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Table of Contents

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Review

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Adult Neurogenesis in the Hippocampus: From Stem Cells to Behavior

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The dentate gyrus of the mammalian hippocampus continuously generates new neurons during adulthood. These adult-born neurons become functionally active and are thought to contribute to learning and memory, especially during their maturation phase, when they have extraordinary plasticity. In this Review, we discuss the molecular machinery involved in the generation of new neurons from a pool of adult neural stem cells and their integration into functional hippocampal circuits. We also summarize the potential functions of these newborn neurons in the adult brain, their contribution to behavior, and their relevance to disease.

Over 50 years have passed since the first report of neurogenesis in the hippocampal dentate gyrus (DG) of the adult rodent brain (Altman and Das, 1965). Although the scientific consensus of the time was that the adult brain did not generate new neurons, this discovery was confirmed by numerous subsequent studies. It is now widely accepted that adult neurogenesis occurs in the DG of humans (Eriksson et al., 1998; Spalding et al., 2013), as well as most mammals and several other vertebrates. Adult neurogenesis is the most robust form of plasticity in the adult brain and likely contributes to memory formation. In addition, adult-born neurons have been used to study neuronal development, and defects in neurogenesis have been associated with several human neurological and psychiatric diseases. In this review, we summarize the current knowledge about DG neurogenesis, its origins, regulation, and relevance to disease. We also focus on recent findings on the differentiation, network integration, and function of adult-born dentate granule cells (DGCs).

The Subgranular Zone: Adult Neural Stem Cells and Their Niche

The sub-granular zone (SGZ) of the hippocampal DG is one of the stem-cell-containing niches in the adult mammalian brain (Figure 1A). This thin band between the granule cell layer and the hilus provides a unique microenvironment for an adult neural stem cell (NSC) population. The permissive milieu of the SGZ allows NSC proliferation while promoting the specification and differentiation of dentate granule neurons. Adult-born dentate granule neurons pass through several consecutive developmental stages before they become functionally integrated into the hippocampal circuitry. Type 1 radial glia-like cells (RGLs) are thought to represent the NSC population and can generate proliferating intermediate progenitor cells (IPCs, type 2 cells) with transient amplifying characteristics. These type 2 cells can give rise to neuroblasts (type 3) that subsequently differentiate into mature dentate granule neurons (Figure 1B). Apart from the neural progenitor population, this area contains several other cell types that are thought to support neurogenesis, as well as a dense vascular network that is tightly associated with NSCs.

Progenitors: Is This a Homogeneous Population?

Two of the defining characteristics of stem cells are the capacity for self-renewal through cell division and the ability to generate specialized cell types through differentiation. However, stem cell populations are often heterogeneous within a tissue, and distinct stem cells may coexist for the same lineage. Different models of the identity and activities of NSCs in the adult mammalian brain have been proposed. GFAP-, Nestin-, and Sox2-expressing radial RGL cells (type 1 cells) exhibit NSC properties. Clonal analysis of individual RGLs has revealed self-renewal and multipotent capacities in this population (Bonaguidi et al., 2011). Alternative RGL properties have also been reported (Encinas et al., 2011; Sierra et al., 2015), suggesting that heterogeneity among RGLs may exist (Gebara et al., 2016). Whether and how such NSC heterogeneity contributes to varying levels of self-renewal and differentiation capacity among RGLs needs to be addressed. Furthermore, non-radial Sox2-expressing precursors have also been proposed to exhibit multipotent characteristics, and additional proliferating cell populations may act as NSCs under certain conditions. A recent study used single-cell gene expression analysis to elucidate the heterogeneity of NSCs and found that only a few genes were specific to quiescent NSCs (Shin et al., 2015). These results point to a more complex scenario for the developmental sequence in the adult hippocampal lineage than our prevailing simplified model may suggest. In addition, two recent studies demonstrated that single NSCs are not long-term self-renewing (Barbosa et al., 2015; Calzolari et al., 2015), supporting the emerging concept that NSCs may only persist at a population level. The advancement of new in vivo imaging approaches will undoubtedly further help shed light on this question.

The origin of adult NSCs is still only partly understood. According to a prevailing model, adult NSCs originate from the whole

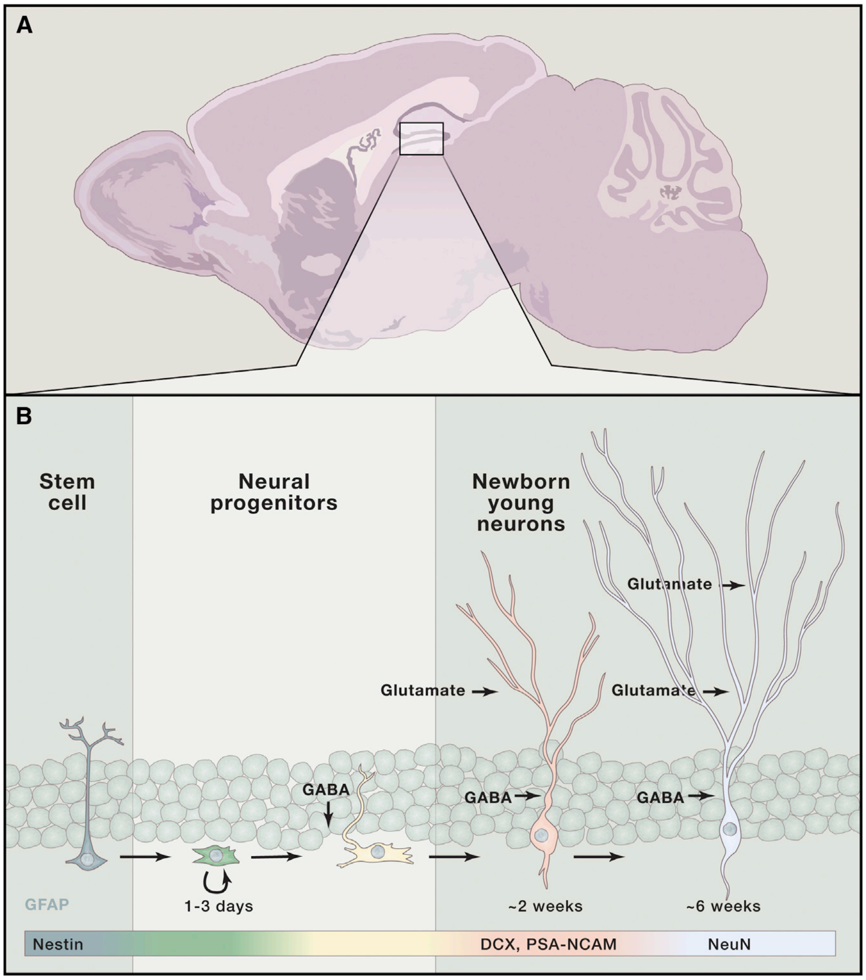


Figure 1. The Adult Hippocampal Niche

(A) Scheme showing the hippocampal formation in the adult rodent brain. The box highlights the SGZ of the dentate gyrus as one of the germinal zones in the adult mammalian brain.

(B) Newborn neurons in the subgranular zone of the dentate gyrus pass through several consecutive developmental stages. Type 1 RGLs can generate proliferating IPCs (type 2 cells) with transient amplifying characteristics. These type 2 cells can give rise to neuroblasts (type 3) to subsequently differentiate into dentate granule neurons. During their maturation, a transition occurs from GABA excitatory to GABA inhibitory and glutamate excitatory inputs around 2–3 weeks after birth. The developmental trajectory is accompanied by subsequent expression of stage-specific molecular markers.

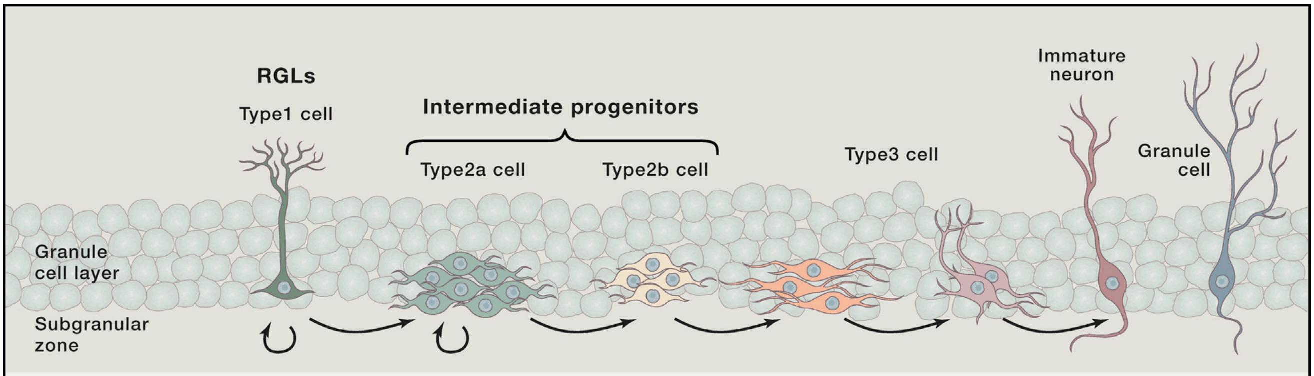
length of the dentate neuroepithelium, which produces both embryonically generated granule neurons and adult NSCs. However, a recent study also proposed that adult NSCs originate during late gestation from a population of sonic hedgehog (Shh)-responsive cells in the ventral hippocampus. The descendants of these cells then relocate into the dorsal hippocampus to become the source for adult NSCs in the SGZ (Li et al., 2013a). The lack of more sophisticated tracing tools still leaves some general questions about their origin unanswered. Do adult precursors arise from neural precursors that are also responsible for embryonic neurogenesis, or do they arise from a quiescent population that is set aside during early development as a reserved pool?

Regulation within a Developmental Continuum: Where and When Do Signals Meet?

Numerous studies over the past decades have revealed several key factors and signaling mechanisms that regulate adult neurogenesis within a defined local microenvironment. As adult stem cells pass through genetically and morphologically identifiable stages, regulation can be targeted at several steps throughout their development. In this review, we discuss our current understanding of the intrinsic and extrinsic signaling mechanisms involved in regulating distinct stages of adult neurogenesis (Figure 2). We also attempt to draw a more unifying picture of how, when, and where canonical signaling pathways crosstalk to facilitate a dynamic modulation of neurogenesis. Signal convergence may occur at several levels within, and in close proximity to, the signal-receiving cell. The surrounding niche provides the environment for a first level of signal integration. Here, local or temporal morphogen gradients could have opposing or cumulative effects on the signaling outcome. A second and more complex level is the network of signaling components existing within a particular context of the signal-receiving cell itself (receptors and intermediate downstream targets). Their different expressions in space and time may set or alter the threshold for certain signals from the niche by integrating or differentiating incoming information. We will start by reviewing the current knowledge about the signaling components (morphogens, growth factors, cytokines, and neurotransmitters), transcription factors, and metabolic components that have been shown to be involved in adult neurogenesis. We will then give an outlook on how this plethora of incoming signals could possibly be integrated into the cellular program.

Notch Signaling

Studies of invertebrates and vertebrates indicate that Notch signaling is highly pleiotropic, as it plays fundamental roles in a wide array of developmental processes. The specific context in which Notch signaling is activated dictates the particular downstream process that is triggered: cell proliferation, cell-fate determination, or apoptosis. The role of Notch signaling has previously been studied during development of the hippocampus, where it appears to be involved in maintaining the proliferative and undifferentiated stages of neural progenitor cells (NPCs) (Breunig et al., 2007). In addition to their developmental functions, Notch pathway components are expressed in the



	Quiescence	Proliferation/ Activation	Fate specification	Morphogenesis and differentiation	Maturation
Signals	BMP, Notch, GABA	Canonical Wnt, IGF, Shh, FGF-2, EGF, Dopamine	Canonical Wnt, NT-3	Wnt/PCP, Notch, BDNF, Reelin, GABA	Glutamate, NRG2, Neuronal activity
Transcription factors	Hes5, FoxO, REST	Sox2, Tlx	Tbr2, Ascl1/Mash1, NeuroD1, Prox1	NeuroD1,Prox1, CREB, AP-1?	CREB
Epigenetic regulation		Gadd45b, LSD1	Fmrp, Mbd1	Gadd45b, MeCP2	MeCP2, HDAC2

Figure 2. Signals, Transcription Factors, and Epigenetic Regulators during Adult Hippocampal Neurogenesis
Stage- and cell-specific effects of different signaling pathways, transcription factors, and epigenetic regulators during lineage progression.

adult nervous system. Various studies have shown that the effects of Notch on adult neurogenesis are context dependent. Notch1 was found to be required for self-renewal and the expansion of nestin-expressing NSCs in the adult hippocampus. In line with these findings, inactivation of the Notch pathway component RBPj resulted in an initial increase in hippocampal neurogenesis by causing premature differentiation of Sox2-positive progenitors, which in turn resulted in depletion of the progenitor cell pool and suppression of adult hippocampal neurogenesis (Ehm et al., 2010). Furthermore, a study focusing on the Notch intracellular domain (NICD) showed that overexpression of this downstream effector induced proliferation and expansion of the NSC pool. The same study demonstrated that Notch signaling also modulated dendritic morphogenesis: conditional knockout of Notch1 resulted in significantly less complex arborization, whereas overexpression increased dendritic complexity (Breunig et al., 2007). The effect on dendritic development seems, however, to be restricted to immature cells, since manipulation of Notch signaling in adult neurons was shown to have no effect on dendritic arborization (Dahlhaus et al., 2008).

Due to its pleiotropic nature, the activity of Notch signaling can have diametrically opposed effects within distinct developmental contexts. Divergent functions of the Notch receptors, as well as differences in the intensity of Notch signaling, are thought to contribute to the heterogeneity in adult NSC behavior. The way in which Notch signaling is integrated with the signals from other pathways could be one possible explanation for its context-dependent roles.

Hedgehog Signaling

Sonic hedgehog (Shh) is the major activating ligand to initiate Hedgehog signaling in the brain and has been shown to play important roles in the formation and patterning of adult germinal niches in the brain. Adult NSCs in the DG appear to originate from Shh-responsive progenitors in the ventral hippocampus (Ahn and Joyner, 2005; Li et al., 2013a). The receptor Patched (Ptc) and the transmembrane protein Smoothened (Smo) are expressed in the adult hippocampus and in progenitors derived from this region (Lai et al., 2003). The sources of Shh have not yet been clearly identified; however, tracing studies using *Gli1-nLacZ* reporter mice have revealed Shh signaling activity in NSCs (Ahn and Joyner, 2005). Exogenous Shh has been shown to directly promote progenitor proliferation in vitro. Overexpression of Shh within the DG using an adeno-associated viral system resulted in a marked increase in hippocampal progenitor cell proliferation in vivo. Pharmacological inhibition of Shh signaling through cyclopamine reduced hippocampal progenitor proliferation when directly delivered into the adult hippocampus (Lai et al., 2003). Postnatal progenitors failed to develop after embryonic ablation of Smo in GFAP+ and Nestin+ neural precursor cells (Han et al., 2008). In contrast, expression of a constitutively active Smo resulted in a marked expansion of the DG, indicating an important role for Shh signaling in the expansion and establishment of postnatal hippocampal progenitors. Interestingly, decreased Shh target gene expression and a similar devastating effect on postnatal neurogenesis were observed in animals lacking primary cilia (Breunig et al., 2008; Han et al., 2008). The selective targeting of the Shh-signaling machinery to cilia is thought to enable RGL precursors to differentially respond to mitogenic Shh signals, thereby functioning as cellular "antennae" (Breunig et al., 2008).

Bone Morphogenetic Protein Signaling

Bone morphogenetic proteins (BMPs) comprise a group of more than 20 ligands that constitute the largest subgroup of the transforming growth factor-beta (TGF-beta) superfamily of cytokines. They are highly expressed in the embryonic and adult nervous system and exert a plethora of effects, including cell survival, proliferation, and fate specification. Negative regulation of BMP activity can be achieved through Chordin, Noggin, and Neurogenesin-1, which bind and antagonize BMPs directly in the extracellular space. In adult neurogenic niches, BMPs can act as short-range morphogens due to a limited spread and their ability to bind to extracellular matrix components. As with many morphogens, the precise action of BMPs depends on the context in which the signaling occurs (context in the niche, as well as within the signal-receiving cell). In the postnatal hippocampus, BMPs are chronically secreted by granule neurons, NSCs, and other niche cells and are essential for regulating the equilibrium between proliferation and quiescence (Bonaguidi et al., 2008; Bond et al., 2014; Mira et al., 2010; Yousef et al., 2015). Not only are BMPs necessary for maintaining quiescence, but they also play crucial roles in controlling the rate at which DGCs mature (Bond et al., 2014). Such a dual role may be explained by a differential expression of the BMP receptors. While NSCs express BMPR-Ia, which is downregulated in IPCs, neurons and neuroblasts express BMPR-Ib (Mira et al., 2010), suggesting a receptor-context-specific signal integration.

Several BMP inhibitors, such as Chordin, Noggin, and Neurogenesin-1, are present in the hippocampal niche and are thought to locally adjust the levels of BMP signaling (Bonaguidi et al., 2008). By adulthood, a strong Noggin signal is concentrated in the DG, which has been shown to be controlled by the RNA binding protein FXR2 (Guo et al., 2011b). BMP signaling, in addition to other pathways, has also been shown to be involved in linking the mechanism of voluntary exercise with changes in neurogenesis. Finally, an age-associated increase in BMP signaling has recently been reported and may partly contribute to the decline of neurogenesis in old animals, suggesting that inhibition of this pathway could potentially allow rescue of this age-related drop (Yousef et al., 2015).

Wnt Signaling

Canonical Wnt signaling is fundamental for the proper development of cortex and hippocampus during development. In addition to promoting self-renewal and maintaining neural progenitors during early neurogenesis, it induces the differentiation of intermediate progenitors during mid and late neurogenesis. Recent work suggests an important function for the Wnt pathway not only during development, but also in the adult brain. Wnt3, which is produced by local hippocampal astrocytes, was shown to stimulate Wnt/β-Catenin signaling in isolated AHPs and induce their differentiation toward the neuronal lineage (Kuwabara et al., 2009; Lie et al., 2005). In vivo experiments further demonstrated the regulative properties of Wnt signaling during adult hippocampal neurogenesis. While activation of Wnt signaling in the SGZ increased neurogenesis, its inhibition caused a reduction in proliferation and neuronal differentiation (Lie et al., 2005). *Prox1* and *Neurod1* were shown to be among the major direct transcriptional targets of Wnt/β-Catenin-TCF/LEF signaling, and they are known to control genes specifically involved in neuronal differentiation (Gao et al., 2009; Kuwabara et al., 2009; Lavado et al., 2010). Gao et al. (2009) demonstrated that *NeuroD1* is required for hippocampal neurogenesis by facilitating survival and maturation. An intriguing link between Wnt/β-Catenin signaling, neuronal differentiation, and the expression of *NeuroD1* was proposed in a study by Kuwabara et al. (2009). Here, the presence of dual regulatory elements within the *NeuroD1* promoter was shown to enable a molecular configuration in which *NeuroD1* transcription was either repressed by *Sox2* in undifferentiated cells or activated by Wnt signaling through TCF/LEF in dividing neuronal progenitors. Despite its pivotal role in promoting neuronal differentiation, activation of the Wnt/β-Catenin signaling pathway was shown to promote proliferation rather than differentiation. However, modulation of the pathway was achieved by injecting lentivirus-expressing shRNAs to suppress expression of Disrupted in Schizophrenia 1 (DISC1), which directly interacts with GSK3β, resulting in its inhibition and subsequent stabilization of β-Catenin (Mao et al., 2009).

While complicating our view of Wnt signaling, the involvement of Wnt signaling in both aspects—progenitor pool maintenance and neuronal cell fate—does not appear to be contradictory. In fact, manipulation of Wnt signaling is a formidable challenge, since the commonly used components (GSK3β, β-Catenin, etc.) are likely to cause pleiotropic effects, as they themselves interact with other signaling pathways. Several studies of Wnt antagonists have shown how aging and neuronal activity dynamically control adult hippocampal neurogenesis through modulation of this central pathway. The expression of Dickkopf-related protein 1 (Dkk1), a secreted Wnt antagonist, was shown to increase with age in the adult hippocampus, and Dkk1 deletion from granule neurons was sufficient to restore neurogenesis in old mice (Seib et al., 2013). In line with these observations, dorsal hippocampal infusion of Dkk1 resulted in impaired object recognition memory consolidation (Fortress et al., 2013). Moreover, secreted frizzled-related protein 3 (Sfrp3) was shown to be secreted by DGCs, and loss of Sfrp3 resulted in the activation of quiescent radial NSCs and a subsequent increase in dendritic complexity (Jang et al., 2013). Neuronal activity, mimicked by electroconvulsive stimulations and optogenetics, was shown to decrease the expression of Sfrp3 (Jang et al., 2013), demonstrating for the first time a link between neuronal activity and Wnt-mediated adult neurogenesis. However, whether these two Wnt antagonists act on the same or different downstream mechanisms remains unknown.

As Wnt signaling alone provides the basis for a wide range of possible interactions, how do these signals converge in space and time to allow a stage-specific regulation? A recent study focusing on the temporal signaling properties revealed a remarkable transition of Wnt signaling responsiveness from the canonical branch (β-Catenin-dependent) to the non-canonical branch (PCP pathway) in the course of neuronal differentiation. While canonical Wnt signaling progressively faded, the emerging non-canonical branch was required for late stages of maturation, such as dendrite initiation, radial migration, and dendritic patterning (Schafer et al., 2015). These results demonstrated that Wnt signals in the hippocampal niche are highly stage dependent and that integration occurs in a context-specific manner within the signal-receiving cell. Careful analysis of Wnt pathway interactors in space and time will undoubtedly help us understand the various interactions and mechanisms involved.

Growth Factors, Neurotrophic Factors, Cytokines, and Neurotransmitters

Numerous growth factors, neurotrophic factors, and neurotransmitters have also been reported to be part of the regulatory signaling macrocosm within the hippocampal niche. For brevity, we will discuss those factors that were studied in the context of adult hippocampal neurogenesis and will refer to more specific literature for further details.

Neurotrophic factors are extracellular signaling proteins that bind to receptor tyrosine kinases known as Trk receptors and their co-receptor p75NTR. Among the four identified neurotrophic factors, the role of brain-derived neurotrophic factor (BDNF) has been studied most extensively. Neuronal maturation—particularly, the dendritic growth of adult-born neurons—is accelerated by behavioral experience, such as exercise and exposure to enriched environments, and the neuronal activity associated with it. This activity-dependent increase in dendrite length and complexity appears to be mediated by the cell-autonomous, autocrine action of BDNF (Wang et al., 2015). Other secreted molecules may also be involved in stimulating the growth and maturation of DGCs in response to neuronal activity; for example, Wnt ligand release is elevated by activity (Wayman et al., 2006). A recent study followed the dendrite growth of adult-born DGCs using longitudinal in vivo imaging over a period of several weeks, thereby capturing the growth, addition, and pruning of dendrite branches in individual neurons (Gonçalves et al., 2016). Exposing the mice to an enriched environment resulted in faster growth and increased branching; however, these changes were countered by earlier and more extensive pruning, so that by the end of the first month post-mitosis, dendritic morphology in enriched environment mice was similar to that of mice reared under standard conditions. Stunting dendritic growth by disrupting Wnt signaling also resulted in dendrites with similar branching structure, albeit with smaller length. Interestingly, newborn neurons that extended more branches underwent more pruning, resulting in a similar dendritic structure for all DGCs. These findings suggest a homeostatic control of dendritic morphology that reverses the activity-dependent changes of dendrite morphology.

Growth factors are a large group of extracellular proteins controlling cell growth and maintenance. Several growth factors have been shown to be involved in regulating adult hippocampal neurogenesis, including fibroblast growth factor-2 (FGF-2), vascular endothelial growth factor (VEGF) and insulin-like growth factor-1 (IGF-1). FGF-2 (Kang and Hébert, 2015) and IGF-1 have both been reported to promote NPC proliferation and production of new neurons. In addition, IGF-1 was found to control subventricular zone (SVZ) neuroblast migration and to instruct adult NPCs in the hippocampus to become oligodendrocytes by inhibiting BMP signaling (Hsieh et al., 2004).

Adult neurogenesis is also strongly modulated by microglia and inflammation. Inflammation is known to sharply inhibit neurogenesis in the adult brain (Ekdahl et al., 2003) through the microglial release of inflammatory cytokines, including interleukin-6 (IL-6) and tumor necrosis factor-α (TNF-α). However, activated microglia do not necessarily inhibit neurogenesis and may even promote neurogenesis if the balance of secreted molecules in the neurogenic niche is anti-inflammatory (Battista et al., 2006). In fact, microglia are thought to be able to promote neurogenesis, for example, in response to exercise (Vukovic et al., 2012), primarily through the fractalkine (CX3CL1) signaling pathway.

Metabolic States in the Adult Hippocampal Lineage

Metabolic control has been identified as an important regulator of stem cell activity in a variety of tissues. Stem cells seem to be in a metabolic state that is different from their progeny (Folmes et al., 2011; Varum et al., 2011). A recent study showed that de novo lipogenesis is crucial for adult stem cell behavior and that proliferation is significantly reduced upon genetic deletion or pharmacological inhibition of the key enzyme fatty acid synthase (Knobloch et al., 2013). Furthermore, physical activity has been shown to improve adult hippocampal neurogenesis, and endurance-related factors reflecting the metabolic state of the muscle are thought to mediate the effects exercise has on adult neurogenesis (Guerrieri and van Praag, 2015; Kobilo et al., 2014). Additionally, recent transcriptomic data suggest that the switch from a glycolytic metabolism to a largely mitochondrial-driven metabolism occurs at a very early stage in the lineage. Stem cells upregulate genes for oxidative phosphorylation at the time they become activated and enter proliferation (Shin et al., 2015).

Many molecular pathways and transcription factors involved in regulating adult neurogenesis have been shown to influence cell metabolism outside the brain. However, it remains unclear whether metabolic changes occur secondary to fate switches or are instructive for adult stem cell behavior. Further studies are needed to shed light on how metabolic states are interconnected with other signaling mechanisms that converge on controlling the balance of stem cell quiescence, activation, and differentiation.

Transcription Factors and Epigenetics

Transcription factors are essential for regulation of gene expression and play a central role in coordinating lineage progression during development. Over the past decades, numerous studies have identified proteins expressed at specific stages of adult hippocampal neurogenesis, which have since been used as markers. Most of these proteins appear to be transcription factors with key functions in controlling the transcriptional program during lineage progression. Here, we discuss some of these major transcription factors with respect to the stage at which they exert a predominant function.

The SRY-related high-mobility group (HMG) box (Sox) family member Sox2 is among the most extensively studied transcription factors in NSC behavior and function. Sox2 is highly expressed in type 1 and type 2a cells and controls the multipotency and proliferative capacities of NSCs (Favaro et al., 2009; Steiner et al., 2006). The transcription factor itself can be regulated by several signaling pathways that are particularly active in type 1 cells. Notch/RBPJk signaling, for example, directly controls the expression of Sox2, and overexpression of Sox2 was shown to be sufficient to rescue the self-renewal defect in RBPJk-deficient stem cells. Thus, Notch/RBPJk-dependent pathways act as essential regulators of adult NSC maintenance through the transcriptional regulation of Sox2 expression (Ehm et al., 2010).

Sox2, on the other hand, controls the expression of several target genes. The nuclear orphan receptor Tlx, which in turn promotes proliferation and self-renewal of adult NSCs through the canonical Wnt pathway, was shown to be positively regulated by Sox2 (Shimozaki et al., 2011). Tlx may also control NSC proliferation by suppressing pathways that promote quiescence, including the p53 pathway, cell-cycle inhibitor p21, and other pathways (Niu et al., 2011). An interaction of Tlx with the histone deacetylases HDAC3 and HDAC5, as well as with the lysine-specific demethylase 1 (LSD1), has been reported to be essential for Tlx-dependent regulation of stem cell proliferation (Sun et al., 2007). Finally, Sox2 was found to modulate Shh signaling by controlling the expression of Shh (Favaro et al., 2009), as well as to inhibit the Wnt signaling-induced transcriptional activation of NeuroD, thereby preventing neuronal differentiation (Kuwabara et al., 2009).

Other transcription factors that are predominantly active in NSCs are those of the Hes family, the Forkhead O-box (FoxO) family, the nuclear factor 1 (NF1) family, the transcriptional regulator Hmga2, and the transcriptional repressor Bmi-1. Common to all is the ability to functionally regulate the expression of differentiation inhibitors, cell-cycle inhibitors, and signaling pathways involved in controlling NSC behavior. The repressor element 1-silencing transcription (REST) factor is a particular case insofar as it is not only expressed in NSCs but also in mature granule neurons (Gao et al., 2011). REST is required to maintain NSCs in a quiescent and undifferentiated state, at least in part by preventing precocious expression of the neuronal differentiation program (Gao et al., 2011; Kim et al., 2015).

Achaete-scute homolog 1 (Ascl1/Mash1) is a member of the basic helix-loop-helix (bHLH) family of transcription factors and is expressed by dividing type 2a cells (Uda et al., 2007). As a proneuronal transcription factor, Ascl1/Mash1 has been shown to play two opposing roles during embryonic neurogenesis: promoting proliferation and driving cell-cycle exit and differentiation. Ascl1/Mash1 operates downstream of Tlx in the control of stem cell proliferation in vitro and closely interacts with Notch signaling in neural precursor cells (Andersen et al., 2014). Interestingly, Hes proteins that are induced by Notch activity act as potent repressors of gene expression, and proneuronal bHLH transcription factors are among their main targets. Due to an auto-regulatory repression and short half-lives, the cellular expression levels of Hes proteins oscillate. This oscillation in turn drives in opposite phase the oscillation of their targets, including Neurogenin 2 (Neurog2) and Ascl1/Mash1. It is noteworthy that the oscillating expression of Ascl1/Mash1 promotes proliferation of neural progenitors, whereas its stable expression drives differentiation (Imayoshi et al., 2013). In the adult hippocampus, Ascl1/Mash1 is indeed increased upon loss of RBKJk, and its expression is confined to about one-third of the activated NSCs, suggesting a dynamic regulation (Andersen et al., 2014).

The T-box transcription factor Tbr2 is another principal regulator of embryonic neurogenesis, controlling the formation of glutamatergic neurons in the developing cerebral cortex (Arnold et al., 2008). In the adult hippocampus, elimination of Tbr2 augmented stem cell proliferation and blocked the generation of late IPCs and dentate granule neurons (Hodge et al., 2008). Tbr2 seems to be crucial for the progression of neuronal fate decisions and was shown to counteract Sox2, the key determinant of NSC identity (Hodge et al., 2012).

A specific feature of the early dentate granule neuron lineage is the simultaneous expression of the bHLH transcription factor NeuroD1 and the homeobox factor Prox1. Both transcription factors are direct targets of canonical Wnt signaling (Gao et al., 2009; Kuwabara et al., 2009). Overexpression of either NeuroD1 or Prox1 promoted neuronal differentiation of NSCs in vivo, and conditional ablation resulted in decreased generation of DCX-positive immature neurons (Gao et al., 2009; Lavado et al., 2010). While Prox1 ablation increased cell death of late-stage precursors (Lavado et al., 2010), NeuroD1 appeared to be crucial for the survival of maturing dentate granule neurons (Gao et al., 2009). Given their simultaneous expression patterns, as well as their mutual operation downstream of Wnt signaling, Prox1 and NeuroD1 appear to be key players in a terminal network specifying the dentate granule neuron subtype. The majority of transcription factors involved in adult neurogenesis exert transient expression patterns. Prox1 seems to deviate from this principle in that its expression is maintained in mature dentate granule neurons after initiation at the stage of type 2b cells. A recent study reported that Prox1 was necessary to maintain the identity of mature dentate granule neurons. Conditional ablation of Prox1 from newly generated mature neurons resulted in reduced levels of Calbindin and aberrant expression of CA3-specific genes (Iwano et al., 2012). These pleiotropic actions of Prox1 could be plausibly explained by the existence of a multitude of Prox1 targets, which may place Prox1 as a central crosstalk anchor between different signaling pathways. Studies from the embryonic brain suggest that Prox1 may be acting at such a crosstalk point between key cell-fate regulators and diverse signaling pathways. However, cell-type- and context-specific interaction studies are needed to reveal the basis of the Prox1-associated transcription network during dentate granule neurogenesis.

Further regulatory properties arise through processes that control gene expression, such as miRNAs (Han et al., 2016) and epigenetic mechanisms, which determine the DNA and histone accessibility of critical genes to shape the cellular transcriptome landscape. Only recently has epigenetic regulation become the focus of attention with regard to adult neurogenesis, especially concerning maintenance and exit from quiescence in adult NSCs. Interestingly, DNA demethylation appears to be induced by neuronal activity in the DG, resulting in the proliferation of neural progenitors and growth of newborn DGCs (Guo et al., 2011a; Ma et al., 2009). For further studies elucidating the importance of epigenetic mechanisms contributing to adult NSC maintenance and lineage progression, we refer the reader to more detailed reviews on this topic.

Molecular Networks: Signal Convergence on a Systems Level

To understand how genes and signals contribute to a complex biological process like neurogenesis, we are faced with the task of assessing phenotypes within the CNS, a complex and highly organized system. Most laboratory experiments currently rely on models that can only account for a few features at a time. To better understand the basis for signal convergence within such a complex biological process, it is necessary to adopt data-driven approaches that permit the measurement of large-scale cellular and molecular phenotypes.

Recent advances in whole-transcriptome single-cell sequencing have laid the groundwork for identifying genome-wide molecular transitions of stem cell behavior. A recent study used a nestin reporter mouse to isolate putative NSCs from the SGZ and developed a single-cell omics analysis for reconstructing the molecular events along a calculated continuous developmental trajectory (Shin et al., 2015). Together with two other studies (Hanchate et al., 2015; Llorens-Bobadilla et al., 2015), these approaches demonstrate that single-cell analysis enables the reconstruction of temporal dynamics and molecular events during lineage progression. A combination of advanced experimental methods and computational tools can help elucidate more precisely the developmental lineages and identify defined or intermediate stages within a developmental continuum. More recently, this approach was used to demonstrate how a continuum of activation stages can be identified even within a defined population of DG neurons following exposure to an enriched environment: by combining cell sorting with single-nuclei RNA sequencing (RNA-seq), the authors were able to capture the transcriptional patterns associated with neuronal activation, including immediate early genes (IEGs) (Lacar et al., 2016). This first set of transcriptomics studies has very recently been complemented by the development of Div-Seq, a method that combines single nucleus RNA-seq with EdU pulse labeling to profile individual dividing cells (Habib et al., 2016).

It is beyond question that the further advancement of high-throughput quantification methods will permit the implementation of a systems biology approach on various levels. The single-cell omics studies are a first step toward such integrative network approaches.

On a molecular level, signaling components, transcription factors, and other molecules may all together be part of a multi-dimensional, partially self-regulatory network program. Cumulative evidence from the last decades of stem cell research suggests that transcription factors are particularly interconnected and form networks with cross-regulatory properties. Such forms of interconnection may provide the basis for a system that is self-sustaining and stable but also prone to unwind through dysregulation of a single interconnected factor (Figures 3A and 3B). As fate decisions, growth rate, and the tempo of maturation are subject to dynamic modulation through extrinsic signals, molecular networks appear to provide an ideal platform for integrating diverging and converging developmental signals into cellular programs (Figure 3B). How these signals are integrated remains largely unknown. However, different extrinsic signals may compete for the rate and tempo of network destabilization, as well as for the recruitment of alternative networks during lineage progression. As cells follow a developmental sequence, with each stage being determined by specific molecular networks, various transient network instability points may exist within intermediate stages (Figure 3C, right). The internal stability of a network at a given time may in turn determine the impact the signal has within that particular stage. Certain signals could benefit from such intermediate instability and gain momentum to dynamically modulate lineage progression. Alternating expression patterns of interconnected transcription factors, for example, as described in the case of the oscillating Hes transcription factor family (Imayoshi et al., 2013; Shimojo et al., 2008), are likely to cause alternating states of network stability and instability (Figure 3C, left). We still do not understand enough to predict such network states, and further studies are needed to combine biological data with computational network theories. Features such as network components (which molecules/genes participate in the network program?), network topology (how is the network organized? Figure 3A), and network logic (what are the internal network rules and what molecules/genes determine the internal stability? Figure 3B) should be implemented to understand network dynamics (Figure 3C). Such a holistic approach will be essential to test and develop hypotheses that look beyond the borders of a still simple developmental model.

Functional Implications of Neurogenesis

As detailed above, molecular networks are involved in controlling the developmental process of adult-born DGCs and are particularly responsive to neuronal activity and environmental factors. This molecular machinery propels adult-born neurons through a maturation period that resembles that of neurons generated around birth, thus providing newborn DGCs with transient functional properties that are unique in the adult brain. In the next sections, we describe the steps in the functional maturation of newborn neurons and how their immature properties may be essential to their role in the adult brain.

Electrophysiology of Adult-Born DGCs

Adult-born DGCs have been shown to differentiate into functional neurons with functional passive membrane properties, synaptic inputs, and action potentials. Their electrophysiological characteristics are initially distinct from those of mature DG neurons: they have higher input resistance, lower threshold voltage, and a slower membrane time constant and they are more prone to long-term potentiation (LTP). As adult-born neurons mature, they are thought to recapitulate embryonic and post-natal developmental steps and eventually become indistinguishable from DGCs born during early development (Espósito et al., 2005; Laplagne et al., 2006). They start by having high input resistance, more depolarized resting membrane potentials, and low-amplitude action potentials. Gamma-aminobutyric acid (GABA) currents are initially excitatory and tonic (Ge et al., 2006). Phasic

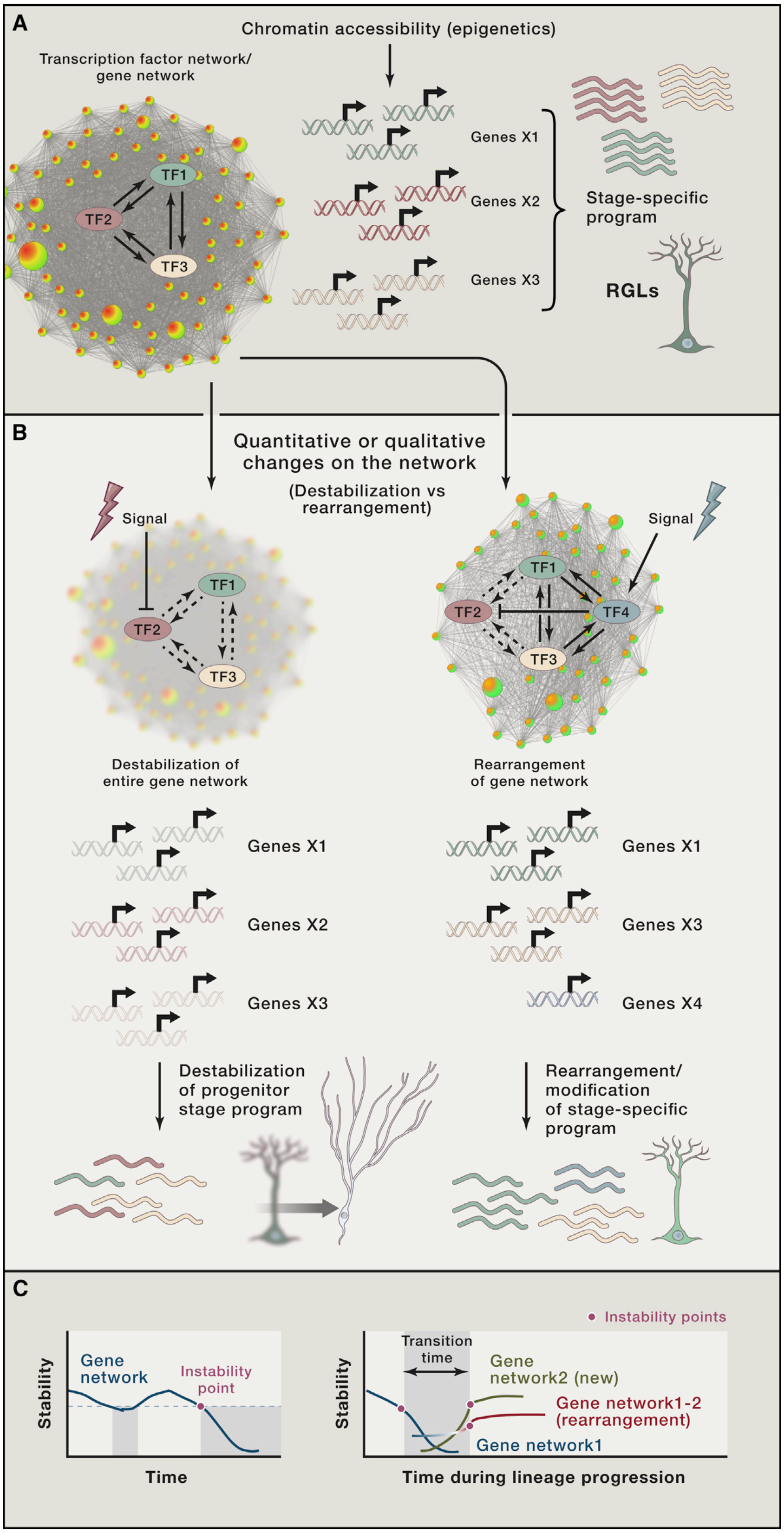


Figure 3. Gene Networks as Platforms for Signal Convergence

(A) Transcription factors are interconnected and form gene networks in which cross-regulation among its network components ensures that the system is self-sustaining and stable. These transcription factor networks result in a stage-specific transcriptional signature (gene-expression program). Different network programs may exist for different stages during lineage progression. Further regulatory properties are given through epigenetic modifications, which determine chromatin accessibility and thereby the ultimate cellular signature.

(B) Transcription factor networks can be modulated via extrinsic signals. Dysregulation of single interconnected transcription factors (in scheme TF1, 2, or 3, left) can result in destabilization of the entire network, which in turn dismantles the cellular program or stage. On the other hand, signals may also induce qualitative changes by rearranging or modifying the gene network (right).

(C) Different extrinsic signals may synergize or compete for the rate and tempo of network destabilization or rearrangement. The term "network dynamics" describes the internal stability of a network at a given time as a function of its topology and logic. Variable states of internal stability (such as those caused by oscillating expression levels of single transcription factors) may determine the impact a signal has on the network. Network states with lower stability (gray) could allow a faster or easier destabilization through certain signals (left). As cells follow a developmental sequence, various transient network instability points may exist between different network programs. Certain signals could benefit from such intermediate instability and gain momentum to dynamically modulate the recruitment of alternative or modified network programs during lineage progression (right).

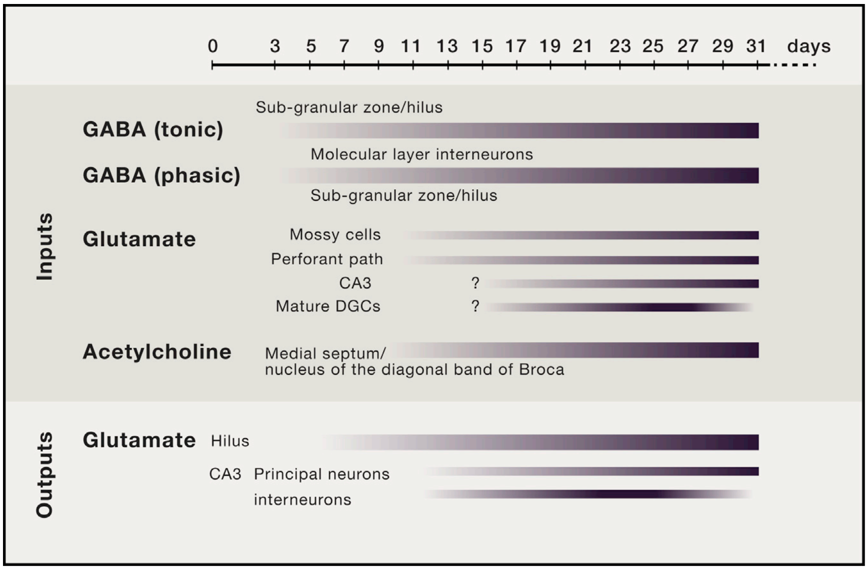


Figure 4. Synaptic Inputs and Outputs of Adult-Born DGCs

Time course of synaptic connectivity in developing adult-born DGCs (adapted from Deshpande et al., 2013, with data from Espósito et al., 2005; Ge et al., 2006; Zhao et al., 2006; Vivar et al., 2012; Chancey et al., 2014; Restivo et al., 2015).

GABA and glutamate post-synaptic currents are present after ∼14 days. Similar to what happens during early postnatal development, the GABA reversal potential is initially higher than the resting membrane potential, resulting in excitatory GABA PSCs. This situation is gradually reversed as the Cl^- transporter, NKCC1, is replaced by KCC2, and by the third week, GABA currents are inhibitory. Early synaptic input is essential for the correct development and synaptic integration of adult-born DGCs, starting with GABA-induced depolarization (Ge et al., 2006).

The first synaptic inputs into newborn cells are thought to be inhibitory interneurons in the SGZ and the hilus (Espósito et al., 2005; Ge et al., 2006), with a tonic GABA component that likely originates from transmitter spillover. Dendritic spines form at 16 days in a process that appears to be controlled by local astrocytes (Sultan et al., 2015; Zhao et al., 2006), but the first glutamatergic inputs into newborn neurons seem to originate as early as 10 days from hilar mossy cells (Deshpande et al., 2013). Inputs from cells in the molecular layer also appear during the second week, as do the first long-range connections from the medial septum and the nucleus of the diagonal band of Broca, providing cholinergic innervation. Inputs from the entorhinal cortex (EC) are present from the third week. Other synaptic inputs include a back-projection from CA3 and a seemingly transient input from mature DGCs that is present during the first month (Vivar et al., 2012), as well as inputs from the subiculum (Figure 4). Interestingly, the connectivity profile of newborn DGCs appears to depend on the behavioral experience of the animal (Bergami et al., 2015). Running and enriched environment exposure during weeks 2–6 were found to result in an increase in otherwise rare inputs from interneurons in CA3 and CA1 and from the mammillary bodies, as well as an increase in connectivity from the hippocampus, subiculum, and cortex. Although these changes were mostly transient, changes in cortical connectivity seemed to persist. Interestingly, voluntary exercise and enriched environment exposure appeared to have different effects on connectivity, with the former increasing connections only from the cortex, but not local and hippocampal connectivity, which could potentially account for the different behavioral consequences of exercise and enrichment. While both approaches resulted in an increase in the number of newborn neurons, mice exposed to an enriched environment outperformed those that engaged in voluntary exercise in challenging contextual fear-conditioning tasks that required discriminating between similar contexts (Clemenson et al., 2015). DGC axons (mossy fibers) make contact with granular cell layer (GCL) interneurons, as well as with interneurons and mossy cells in the hilus and CA3 cells. In newborn cells, DGC axons are found in the hilus as early as 7 days after GFP-expressing retroviral infection and reach CA3 at 10–11 days (Zhao et al., 2006), where they form functional glutamatergic connections as early as 17 days post-mitosis.

Therefore, by the end of the first month, adult-born DGCs are already integrated in the circuitry of the hippocampus, and their morphological growth is mostly complete. They receive incoming synaptic inputs, fire action potentials, and establish functional synapses onto hilus and CA3 cells. However, the electrophysiological features of DGCs at this age are different from those of mature cells, giving them unique properties that are thought to be important for their functional role. First, adult-born neurons are more excitable than mature DGCs between the fourth and sixth week post-mitosis due to a different balance in excitation/inhibition (Table 1). In addition, synaptic plasticity is enhanced: adult-born neurons have reduced LTP induction thresholds and increased LTP amplitude, which is at least partially attributable to a higher contribution of the NR2B-receptor subtype to NMDAR-mediated currents and less feed-forward inhibition at this developmental stage (Ge et al., 2007; Li et al., 2013b). The consequence of these differences in excitability and plasticity is a “critical period” during which immature adult-born neurons respond to a broad range of input stimuli and are quick to reinforce active connections. As newborn neurons mature further, they come under stronger inhibitory control, and the range of stimuli that elicit firing becomes narrower, resulting in sparser activity typical of mature DGCs (Danielson et al., 2016; Marín-Burgin et al., 2012). This period of unusual activity and plasticity is likely to be essential for the function of adult-born neurons, as obtaining these properties transiently in a specific subpopulation of cells is not thought to be easy using standard plasticity mechanisms present elsewhere in the mammalian brain.

Table 1. Selected Electrophysiological Properties of Adult-Born DGCs

Property	Week 4	Mature
Resting membrane potential (mV)	−76 ± 0.5 (Mongiat et al., 2009)	−81 ± 0.5 (Mongiat et al., 2009); −65 ± 4 (Ge et al., 2006); −68 ± 2 (Pernía-Andrade and Jonas, 2014)[a]
Input resistance (MΩ)	519 ± 30 (Mongiat et al., 2009)	224 ± 7 (Mongiat et al., 2009); 143 ± 10.8 (Pernía-Andrade and Jonas, 2014)[a]
GABA current reversal potential (mV)	−56 ± 1 (Marín-Burgin et al., 2012)	−75 ± 6 (Ge et al., 2006)

[a] in vivo, awake recordings.

Dentate Gyrus: From Structure to Function

The DG is an area of the brain characterized by a large, dense population of glutamatergic granule cells with very sparse activity (Chawla et al., 2005; Danielson et al., 2016; Jung and McNaughton, 1993). It is a major input region to the hippocampus and is therefore thought to play an essential role in learning, episodic memory, and spatial navigation tasks associated with that structure. DGCs receive their primary input from perforant path fibers originating in layer II of both lateral entorhinal cortex (LEC) and medial entorhinal cortex (MEC). In addition, they receive commissural inputs from the contralateral hippocampus, diverse neuromodulatory afferents, most notably cholinergic input from the septum, dopaminergic inputs from the midbrain (Du et al., 2016), feedback inputs from CA3 (Vivar et al., 2012), glutamatergic inputs from mossy cells, and inhibitory inputs from interneurons in the hilus, as well as granule and molecular layers. One striking anatomical feature of the DG is the fact that it contains significantly more principal neurons than its input or output regions. The rat DG is composed of around 1 million DGCs, whereas layer II of the EC has ∼0.11 million and CA3 has ∼0.25 million principal cells. Several theoretical studies have associated this disparity in dimensionality of coding and the low firing probability of DGCs with a putative function in discriminating between similar yet different experiences—a task equivalent to the computational concept of pattern separation (O'Reilly and McClelland, 1994; Treves and Rolls, 1994). This hypothesis is supported by studies of hippocampal lesions and manipulations of the electrophysiological properties of DGCs.

Since DGCs have very low firing probabilities, only a small population of DGCs is activated by these inputs at any given time, resulting in sparse representation of contexts and events. The sparseness of these DG representations—also known as "engrams"—is thought to be crucial for creating non-overlapping (or orthogonal) responses to different experiences, thereby keeping memories distinct. The sparseness of coding in the DG is largely due to strong inhibitory inputs from interneuron populations in the DG and hilus, including chandelier cells and the so-called MOPP (molecular layer perforant path-associated) cells (Li et al., 2013b) in the molecular layer, as well as basket cells in the subgranular layer, HIPP (hilar perforant path-associated) cells, and HICAP (hilar commissural-associational pathway-related) cells in the hilus. Remarkably, only ∼2% of DGCs respond when exposed to any given context, as recorded by IEG expression (Chawla et al., 2005), and a recent study has found that the size of neuronal representations (cell ensembles) depends heavily on lateral inhibition from somatostatin-expressing interneurons in the hilus, which tend to be primarily HIPP cells (Stefanelli et al., 2016). Optogenetic stimulation of DGCs active during a context-dependent fear-conditioning task is sufficient to elicit a fear memory (Liu et al., 2012). Yet, it is unclear whether the re-activation of this neuronal population occurs during, and is necessary for, natural memory recall. A study using IEG expression as a proxy for neuronal activity found no preferential re-activation of DG neurons upon re-exposure to the conditioned context, whereas CA1 neurons preferentially reactivated during the same recall test (Deng et al., 2013); on the other hand, optogenetically silencing DG or CA3 cells activated during memory encoding prevented memory recall (Denny et al., 2014).

Other studies have found that the DG is involved in memory retrieval, but not in memory recall; however, it may be difficult to disentangle these two processes. Sparse representations in the DG are relayed to CA3, a hippocampal area characterized by recurrent connections that is hypothesized to function as an auto-association network; it has been shown to play a role in pattern completion, i.e., to recall a memory upon an incomplete cue or only a partial activation of its neuronal representation. However, CA3 is also thought to be able to perform pattern separation, and whether it performs one or the other task seems to depend on the input it receives directly from the EC and, particularly in the case of pattern separation, from the DG. In this manner, the hippocampal memory system is thought to have the flexibility to implement pattern separation and pattern completion, both essential functions for episodic memory formation and recall: the former permits generalization and recall from incomplete inputs, whereas the latter ensures that similar memories are kept distinct from each other. Disrupting DG function results in a decrease in the context specificity of CA3 activity, i.e., a shift from pattern separation to pattern completion (McHugh et al., 2007). Electrophysiological recordings of DG activity are difficult due to the high density of neurons in the granule layer and their low firing rates. Single-unit extracellular recordings have confirmed that DGCs have low firing rates (most cells have mean rates below 0.5 Hz and as low as 0.01 Hz) and exhibit stable place fields—that is, cells fired with high spatial selectivity with respect to the environment the animal moved in (Jung and McNaughton, 1993). Another study has found that small changes in the environment explored by rats resulted in large changes in the firing patterns and correlations of DGCs even when grid fields recorded from the perforant path did not change their firing rates (Leutgeb et al., 2007). These findings further confirmed the role of the DG in pattern separation. The involvement of DG and CA3 in pattern separation has been confirmed in humans by MRI studies done in conjunction with a visual memory task, where subjects were presented with images of common objects. BOLD (blood-oxygen-level-dependent) fMRI responses in DG/CA3 were similar when an image was presented to test subjects for the first time and when highly similar images were presented. A different pattern of activity was seen in DG/CA3 upon presentation of a repeated image, but not in CA1 or EC, indicating that the latter areas do not have the same sensitivity to small differences (Bakker et al., 2008).

Functional Role of Adult-Born Neurons

A better understanding of the contribution of adult neurogenesis to learning and memory has evolved side-by-side with our understanding of DG function. Adult-born neurons are unlikely to influence behavior before they integrate DG networks, fire action potentials, and establish synapses, but their presence is thought to be particularly impactful between the fourth and sixth weeks post-mitosis, as they undergo a period of increased excitability and plasticity (see above). New neurons eventually mature to the point where their properties are similar to those of other DGCs; they are unlikely to have a unique impact on behavior at this stage, as evidenced by the fact that optogenetically silencing newborn neurons at 4 weeks, but not at 2 or 8 weeks, could impair hippocampal memory retrieval (Gu et al., 2012). Early studies of the function of neurogenesis have some discrepancies and sometimes even contradictory findings that can, in hindsight, be attributed to these factors. Likewise, computational modeling of the effects of adult neurogenesis on hippocampal function has generated different theories for the role of newborn neurons. These include encoding of temporal information into memories (Aimone et al., 2006; Becker and Wojtowicz, 2007), avoidance of memory interference and cognitive flexibility during learning of new tasks (Chambers et al., 2004), and balancing pattern separation/integration (Aimone et al., 2009). While there is evidence for many of these functions, consensus on a unified theoretical framework for adult neurogenesis has not been reached and will likely require more experimental data. It might also be the case that adult-born neurons perform distinct functions in the DG depending on the environmental inputs and cognitive demands present during maturation. Experience during this early maturation period changes the timing of the integration of neurons into hippocampal networks and shapes their connectivity (Bergami et al., 2015; Gonçalves et al., 2016; Piatti et al., 2011; Zhao et al., 2006). It is therefore conceivable that distinct demands and distinct connectivity can result in distinct functions for adult-born neurons.

Reducing the number of newborn cells has been found to result in specific cognitive deficits. Spatial memory was affected in many instances, in particular long-term memory retention in the Morris water maze test. Context-dependent memory, and specifically performance in contextual fear conditioning tasks, was also found to depend on neurogenesis (Ko et al., 2009; Saxe et al., 2006; Tronel et al., 2012). There is also some evidence that newborn neurons may be involved in reducing interference between memories that occur at different times (Rangel et al., 2014). Yet another proposed distinct function for adult neurogenesis is cognitive flexibility, that is, the ability to adopt new strategies to successfully complete a previously learned task when contingencies change, such as when a familiar cue no longer indicates the position of the platform in the Morris water maze. However, it can also be argued that this function is a manifestation of improved spatial memory and contextualization.

Several studies have associated adult neurogenesis in the DG with improved performance in pattern-separation behavioral tasks. Pattern separation is defined at a computational level as a process that produces differentiated outputs from similar inputs—in the case of memories, by reducing the overlap in their representations. However, several brain areas may contribute to pattern separation, and in practice, it is impossible to fully characterize memory representations in the brain, thus rendering it impossible to fully characterize the inputs and outputs of the circuits involved in pattern separation. What is possible to record is the behavioral output of mice that attempt to discriminate similar contexts or stimuli. Therefore, these tasks are referred to as "behavioral" pattern-separation tasks, or more specifically as spatial, temporal, or odor pattern separation, depending on the nature of the task. Bussey and collaborators showed that mice with permanently reduced neurogenesis following focal X-ray irradiation or blocking Wnt activity had impaired performance in two tests of spatial pattern separation: a navigational radial arm maze task and an operant chamber, touch screen-based memory task (Clelland et al., 2009). In both cases, mice with ablated neurogenesis had difficulty performing the task at hand when the spatial separation between choices was low, although performance was not reduced when the choices were spatially further apart. Other studies of context discrimination and pattern separation in mice with ablated or silenced newborn neurons had concurring findings (Nakashiba et al., 2012). Similarly, mice with increased neurogenesis, either through behavioral interventions (exercise, enriched environment) or by genetically enhancing the survival of new neurons, performed better in contextual fear-conditioning tasks that required distinguishing between similar environments (Clemenson et al., 2015; Sahay et al., 2011).

Although it is difficult to quantify or manipulate the amount of neurogenesis in human subjects, human neurogenesis is known to decrease with age, as it does in rodents (Spalding et al., 2013). MRI studies in rodents and monkeys have found that cerebral blood volume (CBV) in the DG, a correlate of neurogenesis, is particularly sensitive to aging and is specifically increased by exercise in both rodents and humans (Small et al., 2004). Behavioral pattern separation in humans was shown to undergo an age-related decline in performance, reminiscent of the decay in neurogenesis in the DG (Stark et al., 2010). Interestingly, the ability to recall previously seen images did not vary with age, as older test subjects only had difficulty identifying pictures similar to those they had previously seen. Repeat presentations of the same pictures were easily recognized across age groups, indicating that aging affects pattern-separation tasks, but not recognition memory. Moreover, fMRI studies have shown that the CA3/DG requires a higher degree of dissimilarity in order to display the activity signature of exposure to a novel experience, reflecting impaired pattern separation. The field would greatly benefit from more direct in vivo measurements of neurogenesis in humans. One promising approach came from a report describing the use of magnetic resonance spectroscopy biomarkers for quantifying NSCs and NPCs in human subjects

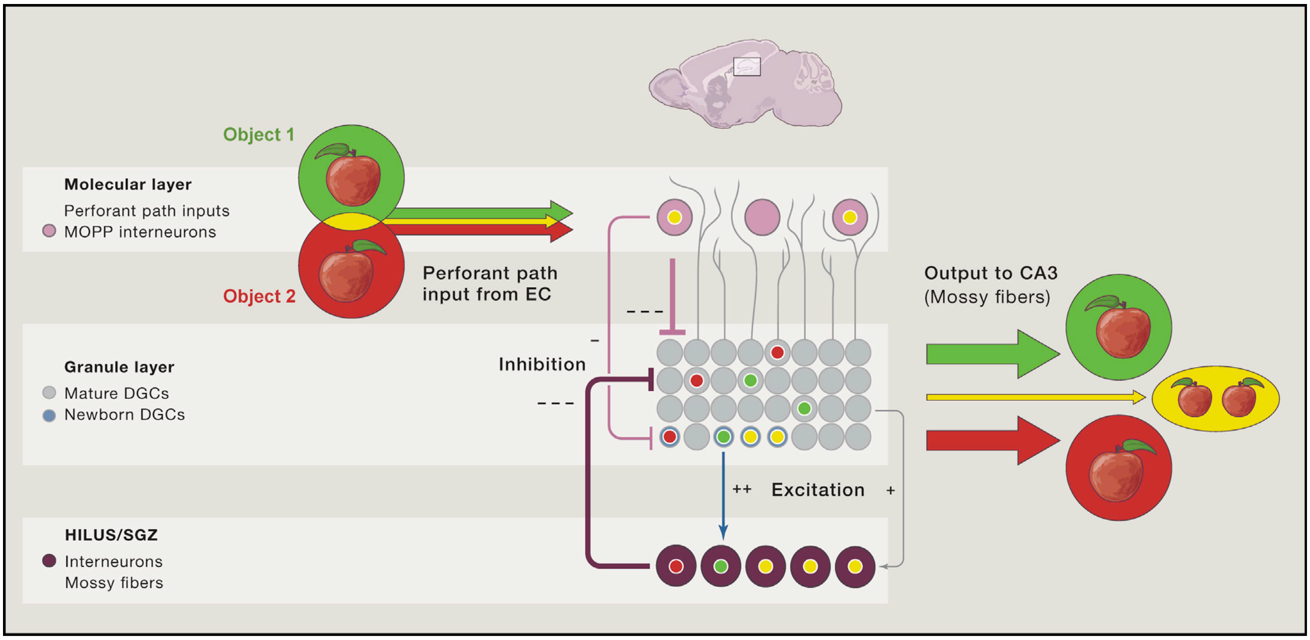


Figure 5. Connectivity of Adult-Born DGCs Potentially Enhances Pattern Separation through Feedback Inhibition

Memories of similar objects or events are thought to be encoded by separate but partially overlapping populations of activated DGCs (red and green, with overlap in yellow), here exemplified by a recall task where the subject is asked to identify which of two images is novel. In this example, the two apples differ only in their green leaves. The more similar the perforant path inputs from the EC, the greater the overlap of their representations in the DG. Mature DGCs (gray) receive strong inhibitory inputs from interneurons (purple) in the hilus, molecular, and sub-granular zones (denoted by – – –). Immature adult-born DGCs (blue) are more active than mature DGCs (gray) due to their intrinsic properties and reduced inhibitory inputs (denoted by –). However, the firing of immature neurons is also thought to strongly enhance feedback inhibition from hilar interneurons, resulting in overall sparser DG responses and, consequently, a decreased overlap of memory representations. Therefore, although the responses of newborn DGCs are less discriminating, with a large overlap between representations, they are thought to enhance pattern separation by minimizing the overlap between object representations of their mature counterparts. These representations are then relayed to CA3 through the mossy fiber outputs. Most mossy fibers respond to only one of the images (red and green arrows), although some, primarily those of newborn neurons, fire in response to both (yellow arrow).

(Manganas et al., 2007), although the results were controversial, indicating that this method may need further refinement before gaining widespread acceptance.

Despite the evidence for a function of adult neurogenesis in behavioral pattern separation, the exact mechanism through which newborn cells enhance DG function is still not known. Immature neurons are more excitable and hence will respond to a broader range of stimuli. It is therefore paradoxical that they would contribute to behavior pattern separation, a function that supposedly requires non-overlapping, finely tuned neuronal responses. However, some studies of DG activity have found that newborn cells contribute to a decrease in DG network activity (Ikrar et al., 2013; Lacefield et al., 2012). This reduction in activity makes DG responses more sparse, which would be advantageous for behavioral pattern-separation tasks. There is substantial evidence that reducing neurogenesis leads to a decrease in inhibition in the DG, whereas increasing neurogenesis leads to the activation of interneurons and sparsification of DG representations (Drew et al., 2016; Singer et al., 2011). Therefore, it appears that one way that immature neurons may contribute to behavioral pattern separation is by modulating feedback inhibitory circuits in the DG so that fewer DGCs, and in particular fewer mature DGCs, respond to incoming stimuli (Figure 5). Nevertheless, further work is needed to characterize the circuits involved in this process and quantify their net effect on DG excitability; experiments in hippocampal slices suggest that immature adult-born neurons are poorly coupled to inhibitory neurons in the DG and hilus (Temprana et al., 2015) while being subject to feedback and feedforward inhibitory inputs themselves (Dieni et al., 2016; Li et al., 2012, 2013b). Moreover, recent work has shown that newborn neurons transiently form strong connections to inhibitory circuits in CA3 (Restivo et al., 2015). Taken together, these data indicate that the inhibitory networks associated with developing adult-born DGCs are complex and dynamic. Ultimately, increases in neurogenesis have been predicted to result in the elimination of more distant memories, either through increased inhibition of mature DGCs, degradation and interference of very sparse representations, or simply competitive rewiring of DG outputs. Interestingly, there is experimental evidence that this elimination of memories may be true (Akers et al., 2014), but forgetting and increased pattern separation may be hard to differentiate experimentally: any small change to a conditioned stimulus will cause it to be perceived by the animal as a novel stimulus, instead of triggering a memory (recall).

Monitoring the activity of DGC populations during behavioral tasks will likely provide invaluable information for understanding the effects of newborn neurons in hippocampal function. Electrophysiological recordings in the DG have not been able to distinguish between mature and immature DGCs, but a recent study has succeeded in recording the activity of genetically labeled newborn and mature neurons using in vivo calcium imaging (Danielson et al., 2016). As expected, immature adult-born DGCs were found to be more active than their mature counterparts. By allowing mice to run under head fixation on a long treadmill with multisensory spatial cues, the authors were able to determine that mature neurons had higher spatial selectivity than newborn cells and underwent remapping of their representations. Optogenetic inactivation of immature DGCs resulted in impaired contextual discrimination, consistent with previous behavioral studies where neurogenesis was ablated and consistent with a role for adult-born cells in behavioral pattern separation. One potential caveat with some methods for imaging the DG in vivo (Danielson et al., 2016; Gonçalves et al., 2016) is that they require the removal of a part of CA1, which could disrupt parts of the circuitry of the hippocampus, but developments in imaging technology seem to have circumvented this limitation and will hopefully soon enable the imaging of multiple hippocampal subfields with minimal damage to brain tissue (Pilz et al., 2016).

Adult Neurogenesis and Diseases of the CNS

Studies aimed at detecting neurogenesis in humans have shifted from merely questioning the existence of neurogenesis to exploring the contribution that adult-born cells make to the function of the human brain in health and disease. However, most of these studies have been based on indirect methods due to the lack of tools to directly observe adult neurogenesis in living humans. In the past, this approach has limited the field to correlating impaired functions from disease states with alterations in adult neurogenesis. Nevertheless, understanding what role adult neurogenesis plays within a disease state, or which consequences arise from its involvement, may help to reveal some basic principles of its physiological functions. To date, there is no clinical evidence of an isolated impairment of adult hippocampal neurogenesis in the absence of other abnormalities, but numerous studies have reported alterations in adult neurogenesis that are associated with several neurological and psychiatric disorders, providing a link between adult neurogenesis and human disease. In some cases, these alterations in neurogenesis are thought to contribute to disease symptoms and even to accelerate disease progression. A possible reason for this is that newborn neurons are thought to account for a disproportionally large fraction of DG activity. In addition, they may regulate DGC firing through feedback inhibition and, since DG responses are so sparse, even small differences in the activity can have a significant impact. In this section, we will briefly discuss the effects of a few pathological conditions on adult neurogenesis in rodent models and human patients, and we refer the reader to further literature for more detail.

Alterations in adult neurogenesis and a reduced size of the hippocampus have been reported for most psychiatric disorders, including schizophrenia, major depression, addiction, and anxiety. A significant subpopulation of patients with major depression, for example, was shown to have a reduced hippocampal volume and cognitive defects. It has been proposed that depressive disorders might be caused by impaired adult hippocampal neurogenesis, partially because of the observation that antidepressants and depressive phenotypes affect levels of SGZ neurogenesis (Miller and Hen, 2015). Moreover, neurogenesis was found to be required for many of the behavioral effects of antidepressants (Santarelli et al., 2003). Evidence from human studies supported the observations made in rodent models; however, limitations in study design and the lack of comprehensive tools highlight the need for further validation to provide evidence for a neurogenic cause of depression.

Schizophrenia is a complex genetic disorder that has variable affective symptoms and cognitive deficits. Several studies have implicated an impairment in adult hippocampal neurogenesis as part of the pathology. Furthermore, several candidate genes have been suggested to play critical roles in adult neurogenesis. Ablation of DISC1, one of the best-characterized susceptibility genes, results in reduced levels of hippocampal neurogenesis, altered morphogenesis, and granule cell positioning, as well as impaired hippocampus-dependent behavior in rodents (Duan et al., 2007; Kvajo et al., 2008). However, DISC1 mutations are not unique to schizophrenia; they are also risk loci for major depression and bipolar disorder. Uncertainty remains about the actual disorder that is being modeled by the DISC1 mutant mouse.

Aberrant neurogenesis is also thought to contribute to mesial temporal lobe epilepsy (mTLE), the most common form of epilepsy in adults. There is evidence that mTLE may be triggered by an increase in neuronal excitability in the DG, in what is known in the field as the dentate gate hypothesis. Seizure activity increases adult neurogenesis but also results in aberrant migration, morphology, and connectivity of newborn cells (Parent et al., 1997). These cells frequently extend projections to the granule layer of the DG and are thereby thought to contribute to an increase in excitability, thus aggravating the disease.

Several neurodegenerative diseases, including Parkinson's disease (PD), Alzheimer's disease (AD) and Huntington's disease (HD), have also been associated with alterations in adult neurogenesis (reviewed in Winner and Winkler [2015]). Mouse models of PD were found to have decreased neurogenesis, primarily due to an increase in cell death. While mouse models of AD were also found to have altered neurogenesis, these changes were not consistent and depended on the type of model, age of the animal, and other factors. Interestingly, knockin mice for the Apolipoprotein E4 (ApoE4) isoform had reduced neurogenesis due to a disruption of GABAergic inputs essential for newborn neuron maturation. These defects, as well as the associated deficits in learning and memory, could be rescued by the transplantation of hilar inhibitory interneurons (Tong et al., 2014). Neurogenesis was also reduced in models of HD due to decreased proliferation of neuronal progenitors, although no defects were found in neuronal differentiation (Lazic et al., 2004).

In vitro disease modeling using induced pluripotent stem cell (iPSC) technology has provided new possibilities for modeling human diseases in a dish. Recent advances in mimicking the region-specific sequence of developmental signaling pathways have led to an in vitro model for human DGC neurogenesis (Yu et al., 2014). This in vitro system has recently been used to model mental disorders such as schizophrenia and bipolar disorder (Mertens et al., 2015; Yu et al., 2014).

Conclusions and Future Directions

The last decade has seen tremendous progress in our understanding of the processes underlying adult neurogenesis and its function in the mammalian brain. Adult-born neurons have been found to contribute to learning and memory in rodents, and there are indications that they may fill a similar role in humans. There is still no consensus as to the exact functional contributions of adult-born DGCs, and it is possible that their role is highly adaptive to cognitive demands, especially since newborn neurons undergo a period of extraordinary plasticity as they mature. Nevertheless, it has become widely recognized that the DG is involved in behavioral pattern-separation tasks, and a growing body of research suggests a role for adult-born neurons in supporting this function. Perhaps the most remarkable feature of adult neurogenesis is that it produces a constant turnover of neurons with unique immature properties. These neurons respond to environmental cues through complex molecular regulatory networks and therefore bear the indelible mark of the environment they mature in. Due to their higher excitability, they are likely to have a significant impact on DG activity, despite their low numbers. Whether they play a role after full maturation remains unknown, but memories are hippocampus-dependent for a relatively short period, anyway, before being consolidated to other brain areas. It is therefore possible that the short-lived critical period of newborn neurons contributes to disambiguating or linking memories of events that occur during this time.

Recent technological developments will drive the next discovery wave of the mechanisms behind the proliferation, differentiation, and function of adult-born neurons. In vivo imaging techniques will likely provide invaluable information about adult NSC exit from quiescence and proliferation and will also enable activity recordings from large populations of identifiable DGCs during behavioral tasks. Optogenetics and engineered receptors now allow the silencing or activation of adult-born neurons in a specific and acute manner, with minimal effects on other cells and without triggering compensatory mechanisms that could otherwise mask the true contribution of newborn neurons to hippocampal function. Progress has also been made in the study of human adult neurogenesis. A recent report confirmed earlier findings of neurogenesis in humans and estimated rates of neuronal birth and death by measuring the ^{14}C content of genomic DNA in neurons from post-mortem tissue (Spalding et al., 2013). Additionally, MRI data and cognitive testing have advanced our understanding of human DG function while suggesting a possible correlation between neurogenesis and behavioral pattern separation in humans, but new approaches are needed for quantifying neurogenesis in human subjects in vivo, even if through indirect or correlative measurements. Recent efforts in this direction, for example, using PET imaging (Tamura et al., 2016), hold significant promise. Finally, advances in the analysis of gene expression have already provided a new insight into the molecular mechanisms and signaling cascades involved in the differentiation and functional activation of individual newborn neurons. These advances will foreseeably lead to new potential therapeutic targets for stimulating neurogenesis and modulating the activity of adult-born DGCs, and they may eventually contribute to future regenerative approaches for treating neurological disease.

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Form Follows Function: Bridging Neuroscience and Architecture

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Sustainable Environmental Design in Architecture: Impacts on Health

INTRODUCTION

“Primum non nocere”, the guiding principle of medicine credited to Hippocrates, emphatically asks that we first do no harm; our architectural principles must serve the same goal. Yet, too often the form and function of architectural environments neglect to take into account the influence of the built setting on human responses and indeed, on human health itself. How can we assess this influence in an objective, consistent manner? Can we predict what this influence in the early stages of design and before the structure is built? An emerging discipline, one that bridges neuroscience and architecture, is beginning to provide more rigorous methodologies and a growing number of research reports that explores the interaction between brain, body, building and the environment.

Neuroscience encompasses a range of disciplines that study the multiple functions of our brains, and how these functions change from birth to death and are affected by disease. Our brains survey our environments through multiple sensory organs, and generate appropriate behaviors, conscious and unconscious. Neuroscientific research reveals how dynamic and plastic our brains are, and informs us about how different our capacities to respond to our environments are as children and as adults, and how exposure to environmental conditions influence such capacities. Coupled with this new knowledge are advances in several technologies for measurement of human brain responses to external stimuli that can provide architects with the tools to perform more objective studies, indeed to quantify how their built products engage and affect the human mind and body. The products of such studies are beginning to inform sustainable guidelines and enhance human health and function within the built environment.

It is often suggested that the complexity of architecture makes impossible the reduction of the human interaction with built settings to measurable parts. However, scientific studies combined with rigorous social and cultural observations can be applied to architectural evaluations to yield greater analytic power. For example, it is now possible to measure the electrical activity of the brain with a wearable multi-electrode array that can transmit data wirelessly to a computer, leaving the subject of study relatively unencumbered and free to move in space. Together with parallel physiological measurements obtained with eye movement, heart rate and skin conductivity sensors, the sum of the gathered data can yield critical information about attention, stress, learning, mental state, etc., that can be analyzed with respect to the audiovisual and physical inputs that are being perceived. These human monitoring techniques joined with advanced auditory and visual virtual reality (VR) environments can provide a means to test designs and to acquire objective evidence for evaluating a priori and a posteriori the influence of architecture in human terms.

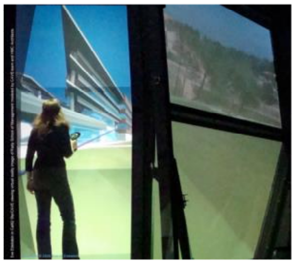

Figure 1: An immersive 3-D virtual reality CAVE allows viewers to move through full-scale building models while movement and physiological responses are synchronously monitored.

NEUROSCIENTIFIC METHODS

In the domain of architecture, a scientifically derived “neuro-architectural” hypothesis may be used to articulate a testable idea about how a specific feature of design may influence psychological or physiological processes that may in turn be associated with measurable changes that reveal the impact of the built environment on human health.

Historically, architectural research relied on philosophical constructs or analysis of behavior patterns in order to relate human responses to design. Psychological studies using subjective methods, such as surveys or interviews, have also been used to test such relationships; however, these methods rely on the subject’s understanding or ability to articulate why they respond to a design element in a particular way. In contrast, neuroscientific investigations offer a higher degree of objectivity, providing a number of additional tools that can measure both conscious and sub-conscious responses without the need to interrupt and perhaps bias the subject. Nor do researchers interfere with the results themselves by asking subjects to think about how or why they respond as they do. This is especially important when studying those unable to understand or verbalize their perceptual and emotional responses due to their age, limited abilities or medical conditions. As demographic changes in the elder population indicate an increasing prevalence of dementia and the use of improved diagnostic tools identify larger percentages of children with developmental disabilities such as autism spectrum disorder, considerations of the diversity of user characteristics are increasingly important.

With the inclusion of people with a broad range of abilities in all architectural settings, healthcare, educational, institutional and residential facilities should be designed to support the heterogeneous and dynamically changing nature of the brain’s response to the environment. Particular attention is needed in the design of healthcare facilities where complex cognitive tasks are performed under duress, while serving the most fragile in great need of care. While sustainable guidelines are increasingly incorporating objectives directed at improving both human and environmental outcomes, in healthcare facilities the overwhelming focus of sustainable design must be on the human impact of built spaces.

The confluence between healthy design and sustainable design is most notable in recent developments of sustainable guidelines for healthcare institutions by institutions such as BREEAM for Health, LEED® for Healthcare, AIA Facilities Guidelines Institute, the Joint Commission, and the Global Health and Safety Initiative, among others. International guidelines for health and safety are increasingly focused on minimizing harm resulting from the extreme conditions, materials and procedures required to provide care. These initiatives reflect the urgent need to continue to investigate the effectiveness of sustainable strategies that seek to improve clinical outcomes in medical and all environments, and to reduce the risk of diseases and disorders related to pollutants, toxins and infectious agents from air, water, and physical contact that have been incorporated in sustainable guidelines to date.[i]

This chapter provides examples of how emerging technologies and scientific methods may be applied to neuro-architectural studies, exploring three elements of the physical environment (sound, location and light) that are within the scope of the architects, and have measurable impact on both human outcomes and sustainable objectives. Neuroscientific data offers the means to advance and validate novel additional guidelines, which now can be continually updated based upon measurable evidence. It is critical that best practices and protocols based upon incomplete data inform, rather than prescribe, design rules, and allow architecture to respond as new medical and neuroscientific data are revealed. [ii] In this context, objective measurement of the neural, psychological, and cognitive impact of the built environment becomes feasible and is indeed necessary.

NEUROSCIENTIFIC EVIDENCE

The human brain is the most complex organ in our bodies, comprising 100 billion neurons of many different types, arrayed in dozens of domains with their own unique architectures and patterns of synaptic connections. Electrical and chemical signals course continuously through the brain, parsing, analyzing and storing incoming information from sensory organs that respond to both the external environment (light, sound, smell, taste, touch, temperature, position relative to gravity) and internal parameters (temperature, chemical concentrations, oxygen tension, blood pressure). The brain generates motor and chemical responses that are adaptive for maintenance, survival, procreation and meaningful experiences that create memory, consciousness, a sense of self and history. The field of neuroscience explores the breadth of these input signals and the corresponding outputs that underlie unconscious and conscious thought, physiological, emotional and aesthetic responses.

Highly refined and powerful new tools allow the monitoring of the chemical and electrical signals that are responsible for these properties. For example, functional magnetic resonance imaging (fMRI), allows us to peer into the recruitment of different domains of the brain in perception and decision-making while undergoing sensory stimuli that evoke memories and desires. The use of high definition electroencephalography (HD-EEG) allows for real-time recording of patterns of electrical activity that subserve attention and cognition in way-finding and path selection in a hospital environment, as described in experiments such as those discussed below. EEG methods offer an advantage by revealing the immediate response of neural signals in micro-second time frames as subjects move within and among distinct experimental conditions. Biochemical assays of perspiration currently allow the rapid determination of neuro-hormonal responses to stressful environments, such as those found in healthcare facilities. Electrocardiography (ECG or EKG) allows the measurement of heart rate variability (HRV) that is driven by the autonomic nervous system in order to modulate stress and relaxation in response to light and other environmental changes. In sum, we can now *measure* what our brains are doing, rather than make an educated guess from a verbal exchange or a psychosocial survey of behavior.

Figure 2. A 256 electrode array records and wirelessly transmits electroencephalographic (EEG) responses.

OUR BRAINS ARE DYNAMIC STRUCTURES

When we design a building, we need to take into account the age and health status of the people who will use it, as much as we incorporate criteria for the physical performance and sustainability of the facility and local environmental conditions. At birth the brain is still quite immature, and it will take over 20 years for the maturation process to produce the fully functional brain. From birth to about 6 yrs of age, when the brain reaches about 95% of its adult weight, areas of the cortex called association areas increase their capacities to deal with sensory information, but can be overwhelmed because their selection ability is not fully functional. Voluntary movements, perception and reasoning are evolving rapidly during this period, and frontal regions of the cortex become active and engaged in complex tasks that involve planning, emotional attachment and attention. During adolescence, from about 6 years to early 20s, the addition of cells and growth of neuronal cell arbors and synapses slows in comparison to earlier rates, and yields to a process of pruning and shedding, sculpting the brain into its adult form. Further, myelination of neuronal projections (axons) increases the speed of electrical impulses, and connections are stabilized. The prefrontal areas of the cortex mature, yielding better control of impulsive behavior, judgment and decision-making. From the early 20s to around age 65, brain functions peak and begin to change, with some loss of mass and functional deterioration, particularly in aspects of memory consolidation and recall. But the very common idea that there is a constant loss of neurons seems to be incorrect and a great exaggeration – there is some loss of synapses and connections as a normal part of aging, but only in the case of early-onset dementias and other brain pathologies does the loss of brain mass reflect any serious cell loss. Indeed, the healthy brain continues to remain ‘plastic’ throughout life, generating some new cells in certain domains, while making new and re-wiring old connections.

In this manner, the brain replicates the dictum, “form follows function”, altering its own form as it re-wires itself and modifies its own perception and function in response to architectural settings and environmental exposures. A number of studies demonstrate that both developmental and disease processes are susceptible to the environment in different ways as the body ages. Thus, children may be more susceptible to the noxious or neurotoxic byproducts of industrial or construction processes than are adults, with lifelong effects of exposure revealed only later in adulthood.

EMERGING NEURO-ARCHITECTURAL TOOLS

In order to advance our understanding of scientific principles that may inform designs that sustain and enhance human health, our interdisciplinary teams of neuroscientists, biologists, engineers, designers, visualization and sonification specialists harness emerging technologies to test how features within the scope of architects, such as light, sound and location, may enhance human and environmental health. A unique facility, the Cave Automatic Virtual Environment (CAVE), at the California Institute of Telecommunications and Information Technology (Calit2) at the University of California, San Diego, offers a controlled environment in which physiological and behavioral measures of subjects or patients are synchronously recorded while they are immersed in virtual reality simulations of building scenarios.

The StarCAVE is a five-sided virtual reality room created by 15 back-projection screens that enclose multiple viewers in a space 3 metres in diameter by 3.5 metres in height. Projectors create 3-D stereo, 20/40 vision resolution of over 68 million pixels – 34 million per eye - distributed over the walls and floor. The viewer interacts with the virtual images using a 3-D joystick and a head tracking infrared sensor system that registers the subject's location and orientation in space, and moves 3-D visual fields according to their point of view. The viewer's head and joystick locations are logged over time, dynamically tracking their first-person perspective, position and interactions with the virtual setting. [iii]

A novel computer-aided design software (CAVECAD ™) has been developed that has the capability of altering dynamically the VR environment while subjects stand within the VR model itself. [iv] This approach eliminates the traditional step of creating a 3-D model at a desktop computer, before bringing it into a virtual environment, thus allowing for much shorter turnaround times when changes to the model are to be made. Therefore, a number of design concepts and use cases can be tested while logging subject responses to specific changes in controlled experimental paradigms, and without necessitating the building of or change to mock-ups before further testing proceeds. In addition, Collaborative-CAVE software allows the same virtual model to be projected in many CAVE environments distributed in different global locations, with participants at each site able to control their own movement through the model, while the other teams' viewports move in synchrony. We expect this to become a valuable tool for the architectural profession to design and evaluate complex designs in full-scale and ultra-high quality visualizations. In addition, experts, clinicians and clients are collaborating to use this virtual reality design laboratory to evaluate operational use and programmatic functions within the VR models.

In order to measure the neurological and associated psycho-physiological and behavioral responses to design, the immersive and interactive capabilities of the VR environment are augmented with simultaneous monitoring of the subject's responses to enable a new class of controlled experiments to test design before the first brick is laid. These advances contribute to the mobility and simplicity of objectively recording the subject's experience along with continuous brain and ocular activity while in 3D virtual reality mockups, and in due course, in real architectural environments. Broad-band data emanating from the brain and body are recorded using a newly developed and tested customized non-contact biopotential sensing and logging devices that can detect and collect electroencephalographic (EEG) brain waves, in addition to detecting electrical activities that measure eye movement (electro-oculography - EOG), cardiovascular (electro-cardiography - ECG) and muscular potentials (electro-myography - EMG). Unobtrusive sensors pick up the body's electrical potentials without conductive contact to the skin, and can be mounted over hair or over clothing without gel or other skin preparation. Other versions of the sensor make use of dry-contact sensors as well as conductive fabric to integrate sensing into apparel worn by the user. The EEG/EOG system directly interfaces with the StarCAVE computing platform, and transmits digitize waveforms through a Bluetooth communication link that is synchronized with CAVE data, tracking the location, head position and reaction time of the viewer as she moves within the 3D model. A real-time 'bio-cursor' uses EOG synchronized with VR head tracking to reveal attention to specific elements in the virtual environment, detecting gaze and micro-movements (saccades) in three dimensions.[v]

These technological breakthroughs and the evidence they can reveal hold the promise of the means to validate data that may inform and expand sustainable guidelines that serve human and environmental health.

NEURO-ARCHITECTURAL RESEARCH

Discussion of our recent research describes emerging technologies that provide the means to predict, test, and validate how physical features within the scope of architectural designs, such as sound, location and light, may inform and enhance both human and environmental health. Such controlled laboratory-based studies form the foundation for future research that uses wireless, sensor based technologies in actual built settings, to gain deeper understanding of the impact of architectural conditions and environmental exposure on human and sustainable outcomes.

Sound as an Environmental Stressor

The field of acoustics provides a useful example of the intersection of neuroscience and architecture, as it consolidates knowledge of the physical propagation of sound with understanding of the human response to speech, background sounds and the impact of unwanted noise. Noise is a well-recognized environmental stressor that puts all users at risk. Beyond acoustic guidelines already considered in sustainable programs, ongoing research reveals that unwanted noise, at intensity levels below those known to cause noise-induced hearing loss, may disturb immune, cardiovascular, endocrine, sleep, emotional and cognitive responses. [vi] Even low sound levels, if unwanted, competing or disturbing, may be associated with diminished speech intelligibility, lowered cognition and lack of rest, along with increased stress responses. [vii] The Environmental Expert Council found a consistent trend towards an increased cardiovascular risk if the daytime noise levels exceed 65 dB(A).[viii] Chronic stress reactions, such as cortisol disturbances, have been observed in children with long-term low frequency traffic noise exposure averaged at less than 55dB(A).[ix]

The influence of unwanted noise on human health is of greatest importance in healthcare settings where diminished speech intelligibility, cognitive function, and stress status may directly impact the quality of care and healing processes. Edelstein et al. (2008) logged continuous sound levels in emergency and intensive care units and found average levels ranging from 75-85 Leq dB(A), with impulse levels from 85-100 dB(A), peaking at 120 dB(A) during shift change.[x] Averaged sound pressure levels in intensive care units were up to ten times greater than conversational speech. Indeed, recent findings show that background noise levels in healthcare environments have been steadily increasing over the past 50 years, with no single facility operating within the sound levels recommended by the World Health Organization. [xi]

The acoustic profile of healthcare spaces may introduce direct and measurable risks of doing harm if ambient noises mask the perception of body sounds.[xii] Neuroscientific and clinical studies clearly demonstrate that competing sounds or noise, wanted or unwanted, mask perception and attention to speech and sound signals. [xiii] Clinical studies confirm that diagnostic accuracy by means of stethoscope auscultation is diminished in flight or ambulances. [xiv] However, there is a scarcity of research into diagnostic accuracy during masking from ambient HVAC, clinical or equipment sounds within architectural settings. Of equal concern is the risk that elevated sound levels from competing alarms, equipment, conversations and mechanical systems may interfere with speech intelligibility, and be a factor in "look-alike-sound-alike" medication errors.[xv]

Although sustainable guidelines increasingly call for acoustic design that reduces unwanted noise, and an "Integrated Project Team" approach that includes acoustic consultants on the design team, most acoustic modeling systems currently available have greatest predictive accuracy for large theatre and concert spaces, yet low accuracy for small spaces such as patient rooms or emergency bays.

To advance understanding of these vital issues, the research team at UCSD created a virtual sound simulation environment to enable architects and users to see *and hear* in advance the consequences of design choices. CAVE and Sound Labs technologies were integrated to create SoniCAVE™ in which ultra-high definition recordings and sound simulations of real environments are merged with ultra-high resolution, full-scale visualizations. Emerging software-controlled audio rendering environments are being developed to create accurate, predictive auditory scenes, derived from computer-aided design models, photographic images, objects, avatars, 'real-world' audio samples, and design materials databases, leveraging spatial auralization and 3D scientific visualization to evaluate entirely new contexts. These new developments provide virtual reality environments in which users and architects may predict and measure neurological, cognitive, stress and performance measures as their teams interact in realistic healthcare scenarios.

Immersive 3D VR "sound-scenes" are used to investigate the impact of acoustical design elements on speech perception and cognitive error, using simulations and recordings of actual clinical conversations, equipment alarms, and mechanicals sound. Demonstrations using spatially-distributed multiple sound sources reveal how discrimination of heart sounds, recordings of medication orders, and "sound-alike" pharmaceuticals are made indistinguishable when masked by realistic clinical sounds.[xvi] This is clearly an area that requires far greater attention and experimentation. Emerging techniques for sound abatement while making critical sounds available in specific locations and directions (e.g., reducing sound reaching the patient while allowing patient sounds to reach the nurse) need to be validated in terms of stress and cognition in order to inform sustainable acoustic design in all architectural contexts, where communication and relaxation have direct impact on outcomes.

Figure 3.
A subject testing visibility of adjacent hospital rooms from a shared nurse's station while testing effects of conflicting sound environments.

Neural Substrates of Wayfinding

Immersive 3-D VR architectural scenes have also be used to gain a deeper understanding of the neural bases of "wayfinding", and can be used to test the effectiveness of visual and auditory cues in forming a memory of space and place. Several decades of research have investigated "place cells" within the hippocampus in the temporal lobe that are responsive to previous experience in a specific location, direction, and orientation.[xvii] More recent findings reveal a hexagonal network of "grid cells" in the nearby entorhinal cortex that associates memories of landmarks and self-motion to create a "cognitive map" of places and events.[xviii] Imaging and electrophysiological studies indicate that the hippocampus plays similar roles in humans. Thus, disoriented patients with temporal lobe disorders revealed that some are unable to recognize or perceive landmarks, while others have no deficits in object or spatial perception, but cannot associate landmarks with directional information, relying heavily on maps and plans that they may draw for themselves. [xix] Although earlier studies focused on two alternate navigation strategies, egocentric versus bird's eye (allocentric) mental mapping methods, emerging concepts suggest that multiple factors influence an individual's strategy for integrating visual and movement cues into cognitive maps.

A StarCAVE study utilized concurrent recordings of brain activity and ocular attention to test navigation strategies while subjects move freely through realistic, human scale, 3D virtual reality environments. Event-related spectral perturbations brainwaves, derived from independent component analysis (ICA) reveal differences in brain dynamics when subjects know their location compared with EEG components when they are lost. Differences in EEG responses associated with spaces rich with visual cues versus ambiguous spaces devoid of cues were found in parietal and occipitotemporal cortex. A significantly stronger synchronization in theta waves and stronger desynchronization in the lower alpha band of EEG frequencies was observed. This pattern likely reflects the involvement of parts of the brain involved in navigation and visual orientation, including the parietal cortex, that uses visuo-spatial information from a first person perspective, along with parietal and occipitotemporal areas involved in processing heading changes and planning of future paths. Disorientation in spaces with less visuo-spatial information was associated with increased alpha wave desynchronization, likely reflecting increased attentional demands. [xx] Figure 4 shows a subject in an early experiment wearing an array of EEG electrodes connected to the laptop while navigating through an area displayed in the immersive VR StarCave at UCSD/Calit2.

Figure 4.
The EEG responses shown on the laptop are compared as subjects navigate through spaces with and without wayfinding cues.

These early results indicated a progressively subtle use of visual cues as subjects navigated the ambiguous space. In the case where obvious cue were not presented, subjects looked for any distinguishing features that might indicate location, including shadows around doors, or patterned finishes. This suggests a continuum of cue effectiveness dependent on the surrounding context and the opportunity to repeatedly search for cues. This technology is expected to become a valuable tool to create virtual reality mockups in which wayfinding systems can be tested at the scale of a building or an urban environment and inform sustainable objectives that promote walking and exercise, and the reduction of reliance on transportation systems that use non-renewable fuels or create pollutants.

Design for effective navigation has value beyond circulation and cognitive mapping strategies. McCarthy (2004) reported that in one hospital, 4,500 hours each year were spent by staff giving directions to lost patients, with an associated cost equivalent of $220,000 per annum.[xxi] In addition to the reduction of stress or anxiety so often experienced when one feels lost, the consequence of ineffective wayfinding design may have more severe consequences, and may even prove fatal during infectious epidemics, should the separation between clean and contaminated spaces be compromised.

It is also proposed that neuroscientific methodologies and emerging technologies will serve investigation of the most effective navigation cues, in multiple modalities, for people with a range of abilities and disabilities including those associated with dementia, Alzheimer's disease and other dementias or with other disorders that interfere with memory formation.

The Influence of Light on Human Health and Function

A long history of research, dating to ancient texts and reports from the beginning of the 17th century, reveals that exposure to light has significant impact on human outcomes.[xxii] Advances in research into the brain's neural "clock", located in the supra-chiasmatic nucleus and associated pineal and endocrine systems, reveal multiple oscillatory systems that modulate human responses to changing light patterns. The solar cycle of daylight and darkness over approximately 24 hours is the primary stimulus that synchronizes biological and behavioral rhythms in response to daily (circadian) and seasonal (circannual) variations in light. For example, diurnal and nocturnal fluctuations in melatonin modulates sleep and wakefulness, while elevated cortisol levels in the morning prime the body for activity, and lower cortisol levels at night encourage relaxation. Recent discoveries of special photoreceptive ganglion cells in the retina reveal how slowly changing light regulates a complex system of neural hormone responses to synchronize psycho-physiological responses with the time of day. [xxiii] [xxiv] Recent studies indicate that the cones, previously thought to function solely as vision receptors, also play a role in eliciting such non-visual responses, in certain conditions. [xxv]

Short-term electrical light exposure also influences human responses, and if excessive, may comprise an environmental health risk. Edelstein et al. (2007) [xxvi] demonstrated that heart rate variability, a well-established indicator of health risk, morbidity, and mortality [xxvii] was highly significantly different during memory task performance during brief exposure (less than 15 minutes) to red, bright white and dark conditions. Whereas many studies have focused on the influence of blue and bright white light of melatonin responses, this experiment demonstrated that red light regulated cardiac responses, with appropriate HRV relaxation during rest and activation during the memory task. In contrast, bright white light with a blue peak was associated with constant heart rate activation throughout the experiment.[xxviii] In a parallel study, brainwaves recorded via a 256 electrode EEG array tended to be different during red versus bright white light conditions in a single subject self-control study.[xxix] Other studies reveal that green light also stimulates circadian responses under certain conditions.[xxx] It should be noted that the influence of "full spectrum" electrical lighting, which has a limited number of spectral peaks within the range of visible light, has yet to be established.[xxxi]

Research suggests that the dynamic manipulation of light and darkness may impose some risk to mental and physical health. For example, epidemiological studies suggest that cancer rates in night-shift workers, including flight crew, factory workers and nurses, may be related to an abnormal pattern of light/dark exposure.[xxxii] [xxxiii] Low levels of lighting during the day has been associated with mental health status, including seasonal affective disorder and longer recovery times for mental health patients.[xxxiv] Diminished cognitive function has also been associated with inadequate lighting, such that pharmaceutical medication error rates have been correlated with seasonal reduction in light.[xxxv]

Most sustainable programs include guidelines that access to daylight. For example, rating systems such as LEED ® encourage access to daylight in "regularly occupied areas" with 90% of "inpatient staff and public areas" required to have design and materials that provide both daylight and natural views.[xxxvi] Design recommendations include the solar orientation of buildings, control of light pollution, and innovative electrical lighting.[xxxvii]

However, an approach that gives credit to the proportion of space with daylight, rather than crediting adjustable lighting systems that provide for individual needs, is unlikely to address the range of human conditions, and the dynamically changing nature of functions that take place in architectural settings. While ongoing neuroscientific research will continue to reveal the parameters of light and dark that best serve human outcomes, the natural pattern and spectrum of solar light should continue to inspire and guide lighting for human health.[xxxviii]

CONCLUSIONS

Much has been made of the development and implementation of standard criteria that measure the performance of a building in relation to the physical environment. Designers, architects and builders strive to achieve the highest level of certification from regional or international sustainable ranking programs to demonstrate excellence in concern for the environments in which they build. A similar concern and aspiration needs to be developed for building performance with respect to user benefits. The approach we have discussed, using contemporary high technology to measure user responses to the buildings in which they work, live, learn and seek better health, parallels the green initiative and puts concern for the user on a par with concern for the physical environment. Recent developments in sensor technology and wireless communication provide a means to implement wearable monitoring devices that leave the subject both unencumbered and able to move both within virtual and real built environments. These advances allow the possibility of recording real-time neurological and physiological data from human subjects while testing how they respond to stimuli.

The general premise that looks to the natural environment as the "gold-standard" for healthy architectural and ecological design has guided sustainable programs to date. In relation to this metric, it is of great importance that rigorous research continues to inform sustainable guidelines that seek to assess and minimize the risks from exposure to pollutants or infectious agents in air, water, and materials. Beyond reduction in exposure to neurotoxins, pollutants and harmful byproducts of the building profession and industrial processes, the fusion of architectural, scientific and medical knowledge can accelerate the development of sustainable objectives that enhance human experience, performance, and health outcomes.

Architects and their clients are increasingly asking for rigorous and trustworthy data to support their design decisions. We suggest that the application of new approaches created at the interface between neuroscience and architecture will be the best source for the "evidence" in evidence-based design. Such evidence, from multidisciplinary studies of human development, neurology, physiology and psychology that assess the impact of the environment on human health and well being, should complement parallel studies of the reverse influence, that of humans on their environments. Ultimately, our goal must be to implement guidelines for sustaining and enhancing human health that serve the range of human needs from birth to death, and for the most fragile as well as the most gifted.

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When Neuroscience 'Touches' Architecture: From Hapticity to a Supramodal Functioning of the Human Brain

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In the last decades, the rapid growth of functional brain imaging methodologies allowed cognitive neuroscience to address open questions in philosophy and social sciences. At the same time, novel insights from cognitive neuroscience research have begun to influence various disciplines, leading to a turn to cognition and emotion in the fields of planning and architectural design. Since 2003, the Academy of Neuroscience for Architecture has been supporting 'neuro-architecture' as a way to connect neuroscience and the study of behavioral responses to the built environment. Among the many topics related to multisensory perceptual integration and embodiment, the concept of hapticity was recently introduced, suggesting a pivotal role of tactile perception and haptic imagery in architectural appraisal. Arguments have thus risen in favor of the existence of shared cognitive foundations between hapticity and the supramodal functional architecture of the human brain. Precisely, supramodality refers to the functional feature of defined brain regions to process and represent specific information content in a more abstract way, independently of the sensory modality conveying such information to the brain. Here, we highlight some commonalities and differences between the concepts of hapticity and supramodality according to the distinctive perspectives of architecture and cognitive neuroscience. This comparison and connection between these two different approaches may lead to novel observations in regard to people–environment relationships, and even provide empirical foundations for a renewed evidence-based design theory.

Keywords: neuroscience, architecture and design, sensory perception, vision, touch, hapticity, supramodality, review

In recent years, novel methodologies to explore the neurobiological bases of mind and behavior have inspired the fields of architecture (e.g., Mallgrave, 2011), planning and urban studies (Portugali, 2004, 2011; van der Veen, 2012; de Lange, 2013), geography (Anderson and Smith, 2001), social sciences and the humanities (Leys, 2002) to open toward cognitive neuroscience and, more specifically, to brain imaging. Novel interdisciplinary fields with the ‘neuro-’ prefix have thus recently emerged, such as *neuro*-economy, *neuro*-law, *neuro*-marketing, and even *neuro*-architecture. A neuroscientific approach to the most diverse fields has proven to be able to offer experimental-based pieces of evidence to different domains, often confirming, reviewing or integrating previous theoretical notions. Yet, when promoting any dialog among disciplines, caution must be urged against certain conceptual ambiguities, as we shall see in this commentary.

NEUROSCIENCE AND ARCHITECTURE

In architecture, new awareness of the complexity of cognitive and emotional processes involved in the daily experience of designed environments has rapidly grown. Such interest also led to the foundation of the Academy of Neuroscience for Architecture (ANFA) in 2003 in San Diego. Since then, various important contributions have emerged from both fields (Eberhard, 2008; Mallgrave, 2011; Robinson and Pallasmaa, 2015).

Provocatively, we may argue that neurophysiology and design started influencing one another during the Renaissance, when anatomists and designers shared their education, studies and the same cultural *milieu*: while Vesalius, Descartes and Willis explored the functional and structural characteristics of the central nervous system, laying the grounds for the subsequent scientific revolution, artists such as Leonardo Da Vinci and Andrea Mantegna spent their days in anatomical observations, visionary hydraulic projects, painting and architectural design.

Since then, design studies and life sciences have been continuously inspiring each other, but only recently have they started to truly share interdisciplinary theoretical and methodological perspectives. Nowadays, the contribution of neuroscientists is actively influencing the architectural debate. For instance, Albright (2015) is approaching design with a neuroscientific perspective on perception and aesthetics. Suggestions on the role of *embodied cognition* through the mirror neuron system in aesthetic response (Freedberg and Gallese, 2007) are taken into account in architectural essays (Mallgrave, 2012; Pallasmaa, 2012; Robinson and Pallasmaa, 2015), and Zeki’s neuroaesthetic theories are being discussed within the architectural field (Mallgrave, 2011). Arbib (2012, 2015) is directly addressing designers with suggestions on sensory perception that could have an impact on design practice.

A specific topic now emerging in the neuro-architectural debate deals with the relationship between sensory experience and architectural perception. The role of non-visual perceptual modalities, and specifically of touch, is currently arousing great interest (e.g., Pallasmaa, 2005). Here, we specifically focus on how the recent neuroscientific evidence of a modality-independent processing of sensory information could actually lead to a ‘sensory intensification’ (i.e., visual and non-visual appreciation of designed spaces) in architectural design.

SENSORY INTENSIFICATION IN ARCHITECTURAL THEORY: THE CONCEPT OF HAPTICITY

In the past, many architectural theorists already speculated about the body-architecture relationship, usually in formal theories lacking any experiential or perceptual bases, as in the famous cases of the ‘golden-ratio’ (Markowsky, 1992; Höge, 1995; Falbo, 2005) or other ‘natural’ formal principles, such as those inspired by the supposed preference for natural, living forms (the so-called ‘biophilia hypothesis’ – for a critical assessment see Joye and De Block, 2011).

The phenomenological philosophy of Maurice Merleau-Ponty (1964) initiated a theory postulating the embodiment of the built environment into our daily sensorial experience. Similarly, the Danish architect Steen Eiler Rasmussen (1964) favored the importance of perceiving and appreciating architectural features through different sensory modalities, such as in the subtle haptic cues mediated by visual perception: for instance, visual cues on textures and shapes are also able to convey haptic information, as roughness, smoothness or weight, and thus to gratify the eye through sensorimotor imagery (**Figure 1A**). Other authors supported an even tighter relationship between architectural design and embodied cognition, as well as architectural experience and bodily self-consciousness (Mallgrave, 2011; Pasqualini et al., 2013). For instance, the architect Yudell claimed that the visual rhythm of the urban landscape could actually affect body motion (e.g., our walking pace) and excite our imagination toward an enhanced interaction with environmental elements, as in fantasizing about climbing non-existent steps when looking at the unusually textured facade of a skyscraper (in: Bloomer and Moore, 1977).

Currently, multisensory perceptual integration and the role of the sense of touch in architectural design are being explored through the notion of *hapticity*. The term *hapticity* is commonly defined as “the sensory integration of bodily percepts” (Pallasmaa, 2005, 2000) and it suggests a pivotal role of tactile-based (i.e., generally non-visually based) perception and imagery in the architectural experience. The Finnish architect and theorist Pallasmaa hypothesizes the existence of an “unconscious tactile ingredient in vision” (Pallasmaa, 2005) that would be fundamental in architectural appreciation and would exalt touch as the primordial sensory modality.

In this view, even though touch and vision remain intrinsically interwoven in object form and spatial perception, tactile sensations would constitute the core of architectural appraisal (**Figure 1B**). In this sense, for example, it is common to refer to a comfortable and relaxing space as a ‘warm’ place. In this regard, Pallasmaa just recently stressed the importance of sensory experience and our ability to catch complex atmospheres and moods “through simultaneous multi-sensory sensing” (Pallasmaa, 2012). The anthropologist Hall (1966) also emphasized the lack of appeal among designers for the role of haptic sensations, even when visually presented, in bonding people with their environment. Similarly, the architect

FIGURE 1 | (A) According to the notion of *hapticity*, visual cues (e.g., textures or shapes) are able to convey tactile information (e.g., roughness or consistency). Left, top and bottom: edgy shape and texture. Right, top and bottom: smooth shape and texture. Of note, neuroscientific observations showed that the same perceptual information is often processed in a *supramodal* manner, i.e., independently of the modality through which that sensory content is acquired. **(B)** What are the implications of supramodal processing when perceiving architecture, such as the facades of the Beauvais Cathedral (Beauvais, France – on the left) or of the Casa Milà (Barcelona, Spain – on the right)? Has visual appreciation of architecture any non-visual (e.g., tactile) implications as well?

Sara Robinson (2015) recently reconsidered the privileged link between haptic sensations and emotion.

Consistently, theorists in the architectural field recently advised against the overemphasis on vision as the primary source of aesthetic appreciation, which may result in biased design methodology (O'Neill, 2001; Mallgrave, 2011). Similarly, the neuro-architectural framework claims that the lack of expertise on multi-sensorial appreciation represents a serious limitation in the current design methodology and struggles for a "sensory intensification" in architectural design (Van Kreij, 2008). On the contrary, most practicing architects typically rely on visual representations both during the design process (e.g., sketches and technical drawings) and the subsequent phase of project communication to the public or the client (e.g., 3D models and renders). Moreover, architects rely almost solely on pictures and drawings (in architectural magazines or books) to establish their personal aesthetics and design method (Wastiels et al., 2013).

NON-VISUAL PERCEPTION AND SUPRAMODALITY IN THE HUMAN BRAIN

Visual information plays a crucial role in shaping the manner in which we represent and interact with the world around us. In fact, for sighted people, vision is so pervasive that they find it hard to imagine a world that does not reach them through their eyes. Thanks to the omnipresence of such kind of perceptual information, sighted people tend to think of themselves as 'visual beings.' Through preferred metaphors, languages often suggest the dominance of vision over other modalities to construct conceptual knowledge. In English, for example, *knowing* and *seeing* are often used interchangeably in daily conversation, with expressions such as '*I see what you mean,*' '*can you see my point?*' or '*seeing is believing.*' In ancient Greek, the verb root 'to know' was used as the past tense of the verb root 'to see,' which lacked its own past tense, so that "I saw" was the equivalent of "I knew."

Consequently, the great majority of psychophysical and neuroscientific studies have been historically focused on the characterization of visual perception and on the dissection of the different steps of visual information processing (e.g., Firestein, 2012) and only recently has non-visual perception started to attract some attention (e.g., Klatzky and Lederman, 2011; Ricciardi and Pietrini, 2011; Ricciardi et al., 2014a; Lacey and Sathian, 2015).

In particular, although vision offers distinctive and unique pieces of information (e.g., colors, perspective, shadows, etc.), several observations indicate that vision might not be so necessary to form a proficient mental representation of the world around us. Indeed, individuals who are visually deprived since birth show perceptual, cognitive, and social skills comparable to those found in sighted individuals (Ricciardi et al., 2006, 2009, 2014a,b; Cattaneo et al., 2008; Pietrini et al., 2009; Ricciardi and Pietrini, 2011; Handjaras et al., 2012, 2016; Heimler et al., 2015). Chris Downey is an architect, Esref Armagan is a painter, Peter Eckert is a photographer: all of them are blind people and yet perfectly capable of successfully conducting their professional lives.

In recent years, functional brain imaging allowed neuroscientists to look at the brains of visually deprived individuals *in vivo* to explore the effects of lack of vision on the formation of proper mental representations. Notably, the question of the extent to which vision is really necessary for the human brain to function, and thus to represent the surrounding world, has recently extended its reach toward a few architectural theorists (Robinson and Pallasmaa, 2015).

Most neuroscientific studies conducted on blind individuals have primarily focused on the structural and functional compensatory plastic rearrangements occurring as a consequence of sensory loss. In sight-deprived individuals, the 'unisensory' visual occipital cortex structurally rewires to accommodate non-visual sensory inputs (e.g., Cecchetti et al., 2015), while showing functional cross-modal responses to several non-visual perceptual and cognitive tasks (e.g., Amedi et al., 2005; Frasnelli et al., 2011; Heimler et al., 2014). The loss of a specific sensory modality, such as vision, represents a unique opportunity to understand the real extent to which the brain morphological and functional architecture is programmed to develop independently of any visual experience. Neuroimaging protocols have been suggesting that distinct perceptual tasks evoke comparable patterns of brain responses between congenitally blind and sighted individuals: for instance, both groups show overlapping responses in the ventral temporo-occipital cortex when visually or non-visually recognizing object forms, in the middle temporal area when discriminating motion across sensory modalities and in the dorsal occipito-parietal region when processing spatial information and spatial representations (Amedi et al., 2001, 2002; Pietrini et al., 2004; Ricciardi et al., 2007; Bonino et al., 2008, 2015; for a review: Cattaneo and Vecchi, 2008; Cattaneo et al., 2008; Ricciardi and Pietrini, 2011; Handjaras et al., 2012, 2016; Heimler et al., 2014; Ricciardi et al., 2014a,b).

The sharing of an active 'visual' area both in sighted and blind participants across visual and tactile task modalities implies a more abstract, *supramodal* representation of specific information content. Supramodal brain regions may share a representation of the perceived stimuli independent of the input format from the sensory modality conveying the information to the brain (**Figure 2**).

As vision has long been considered crucial to explore and represent external sensory stimuli (that are processed along a segregated, but hierarchically organized, network of brain areas), supramodal responses were first assessed within the well-known visual functional pathways (e.g., Milner and Goodale, 1995; Goodale and Milner, 2006; Handjaras et al., 2012).

Supramodality has more recently been shown to be involved in integrated semantic representations and affective processing, ranging from action understanding to emotional and social functioning (Ricciardi et al., 2013, 2014a,b; Handjaras et al., 2015; Handjaras et al., 2016; Leo et al., 2016). Consequently, a more general 'supramodal mechanism' advances from simpler low-level to more complex sensory information toward more abstract, 'conceptual' representations.

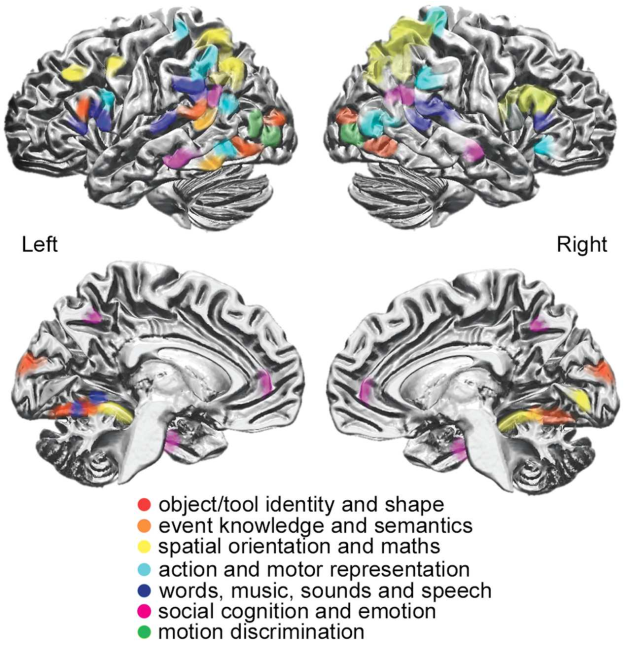

FIGURE 2 | Supramodal areas showing functional responses to different perceptual, cognitive, and affective stimuli (as shown through different colors), independently from the sensory modality that conveys the information to the brain [modified from Ricciardi et al. (2014a)].

WHEN NEUROSCIENCE 'TOUCHES' ARCHITECTURE: DO WE REALLY NEED VISION?

Therefore, according to this perspective, distinct elements of form and space in architectural perception may be processed and represented in highly specialized brain regions in a sensory modality-independent manner. In this sense, assessing the consistency or roughness of a material may recruit a supramodal neural content independently of the sense involved. The same may happen when exploring a complex object only by actively touching it. Rasmussen (1964) provided many examples which could be construed as supramodal architectural experiences *ante litteram*: he claimed, for instance, that just looking at the surface of a wall could evoke sensations of weightiness or lightness, hardness or softness.

On these premises, Mallgrave (2011) approached the *supramodal hypothesis* as a possible neural explanation of hapticity. As a matter of fact, by supporting the view of a more abstract nature of information representation, supramodality could theoretically comprehend and thus represent the neural correlate of hapticity and consequently provide the theoretical basis for its empirical investigation.

Nonetheless, if it is evident that vision is not solely responsible for spatial appraisal and perception as hapticity would imply, the notion of supramodality, in line with the intuition of a 'sensory intensification' in architectural appraisal (Van Kreij, 2008), further implies a more comprehensive overview on the embodiment of architectural experiences, shifting the balance beyond immediate sensory perception – not limited to a single sensory modality – toward higher cognitive, more abstract representations involving semantic, emotional and even social processing.

The conceptual potential of hapticity may have not been fully characterized yet, and therefore not fully exploited by architects. In addition, stating the predominance of the tactile sensory modality may be wrong. In fact, touch is constrained both spatially and temporally, as compared to vision. By definition, haptic perception happens in sequence, within a limited perceptual range and only through direct contact with the perceived object (Pons et al., 1987). In addition, the sense of touch relies more on specific properties, such as surface texture, than global ones, such as shape or localization in space (e.g., Lakatos and Marks, 1999; Podrebarac et al., 2014). On the other hand, vision relies on a parallel sensory processing, able to provide a comprehensive, *'gestaltic'* perception over a distance and on a wider spatial extent (e.g., Gibson, 1979). Furthermore, functional neuroanatomy and psychophysiology demonstrated a perceptual and cognitive dominance of vision over other sensory modalities (Sereno et al., 1995; Gross, 1998).

Nonetheless, neuroscientists have recently referred to touch in a way that may take hapticity into account. From a phylogenetic perspective touch is an 'earlier' sense, developing prior to vision (even bacteria have it). Touch is a key element in communicating emotions and intimacy, maintaining and reinforcing social bonds (Suvilehto et al., 2015) and evidence shows that tactile stimulation accelerates brain development in infants (Guzzetta et al., 2009). Touch could even entail emotional involvement with inanimate objects (e.g., Hornik, 1992) and, from a functional perspective, it has been proven that the somatosensory cortices and the action recognition network show vicarious activations during non-visual socially relevant interactions (for a review: Keysers et al., 2010). Most importantly, haptic perception is crucial in determining a 'sense of presence,' which refers to the perception "of being immersed in the surrounding environment," whereas vision often does not (Bracewell et al., 2008; Slater et al., 2009). As neuroscientists and architectural designers, we may ask ourselves whether environment appraisal indeed relies on such sensation of 'being there' (or 'in touch,' as it were) as the notion of hapticity seems to indicate, and to what extent it does so. Because the theorists of hapticity supported their idea of a multimodal sensing in the architectural experience by relying on the neuroscientific evidence that visual and non-visual information is equally processed and represented in the human brain, design decisions can truly integrate such knowledge to enhance architectural experience embracing the whole of the different sensory modalities. For instance, a recent study showed that symmetry is represented in the lateral occipital cortex in a supramodal fashion (Bauer et al., 2015) and many other design-relevant properties await to be investigated.

TOWARD AN EMPIRICAL *RESPONSIBILITY PRINCIPLE* IN ARCHITECTURE?

Since we spend the most part of our lives in buildings, our environment would greatly benefit from a perspective on architectural and urban design that is shared by both the architect and the neuroscientist. However, we must bear in mind that when dealing with the scientific method that characterizes life sciences, as suggested by Mallgrave (2015), architects must be prepared to address unexpected and possibly unwelcome empirical realities.

In fact, while the 'neuro-turn' has been welcomed by some architects as a way to "humanize" buildings (Pallasmaa, 2012) or to enhance architectural experience (Mallgrave, 2011), in other fields the same shift provoked an opposite reaction: some historians and sociologists see the fascination for neurosciences as a menace to human diversity and creativity (Fitzgerald and Callard, 2014), as a deeper knowledge of the molecular and neural correlates of human mind and behavior would prompt stereotyped approaches to design.

Many socially relevant research questions could be explored by neuroscience and architecture in synergy (see for instance: Pasqualini et al., 2013; Vartanian et al., 2013, 2015; Choo et al., 2016). Whereas currently the outcomes of this dialog and contamination between architecture and neuroscience are hardly predictable, we believe in the paramount importance of sharing knowledge among disciplines. Actually, the dialectics between the notions of hapticity and supramodality that we have described in this essay is a clear example of the weaknesses and potential strength of sharing theoretical models and terms. So, although hapticity suggests a primacy of touch that evidence from neuroscience does not fully support, it also highlights the urge for a deeper understanding of processing or integration of multiple sensory modalities in environmental perception and appraisal. Actually, the comparison between these two different, but complementary approaches, may lead to novel observations regarding the people–environment relationships (e.g., concerning the architectural elements that may evoke the 'sense of presence'), and even provide empirical foundations for a renewed evidence-based design theory (e.g., characterizing which visual and haptic cues evoke similar percepts or dissecting the role of each sensory modality in processing spatial information).

Such ambiguity of terms demands clarity. Many scientific fields that have matured toward the establishment of accepted methods had to come to terms with theoretical uncertainties such as those faced by architectural theorists and researchers right now. In scientific investigation, more accurate conceptual and linguistic choices should be made, in order to provide a common ground for the involved disciplines: specific terms must be preferred to fashionable and evocative ones, and evidence-based demonstrations should overcome speculations [Lilienfeld et al., 2015; see Franz (2005) as an example of such approach].

No infatuation for neuroscience will bring beneficial change to the architectural field if even eminent theorists still rely on verbal descriptions and speculations. On the contrary, if a paradigm shift awaits architecture, it cannot rely on a turn to neuroscience alone: architectural researchers now need to embody the *ethos* of empirical responsibility.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

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THE DYNAMICS OF ARCHITECTURAL FORM

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I. ELEMENTS OF SPACE

WHAT IS space? There are two ready answers to this question. One of them is spontaneously plausible. It conceives of space as a self-contained entity, infinite or finite, an empty vehicle, ready and having the capacity to be filled with things. Consciously or not, people derive this notion of space from the world as they see it, and unless they are psychologists, artists, or architects, they are unlikely ever to be confronted with the challenge of questioning it. Plato spoke in the *Timaeus* of space as "the mother and receptacle of all created and visible and in any way sensible things." He thought of it as "the universal nature which receives all bodies —that must be always called the same; for while receiving all things she never departs at all from her own nature and never in any way or at any time assumes a form like that of any of the things which enter into her; she is the natural recipient of all impressions, and is stirred and informed by them, and appears different from time to time by reason of them." Space was for Plato a nothingness existing as an entity in the outer world, like the objects it could hold. In the absence of such objects, space would still exist, as an empty, boundless container.

SPACE CREATED BY THINGS

Spontaneously, then, space is experienced as the given that precedes the objects in it, as the setting in which every thing takes its place. Without paying our respects to this spontaneous and universal manner of looking at the world, we could not hope to understand the nature of architecture as an arrangement of buildings placed within a given, continuous space. Nevertheless, this conception neither reflects the knowledge of modern physics nor describes the way the perception of space comes about psychologically.

Physically, space is defined by the extension of material bodies or fields bordering on each other, e.g., a landscape of earth and stones adjoining bodies of water and air. The measurable distances within such a rag rug of different materials are aspects of physical space. Beyond that it is the mutual influences of material things that determine the space between them: distance can be described by the amount of light energy that reaches an object from a light source, or by the strength of the gravitational attraction exerted by one body upon another, or by the time it takes for one thing to travel to the next. Apart from the energy that pervades it, however, space cannot be said to exist physically.

The same is true psychologically for the origin of space perception. Although space, once it is established, is experienced as an always present and self-sufficient given, the experience is generated only through the interrelation of objects. This is the second answer to the question: What is space? Space perception occurs only in the presence of perceivable things.

The difference between the two conceptions of space has fundamental consequences. The notion of space as a container that would exist even if it were completely empty is reflected in the Newtonian assumption of an absolute base of reference, against which all distances, velocities, or sizes have equally absolute measurements. Geometrically this corresponds to a system of Cartesian coordinates, to which all locations, sizes, or movements in a three-dimensional space can be related. If, for example, nothing but a single ball-shaped object is given, its spatial position with regard to the framework can be determined by three coordinates indicating the distances from the frame of reference.

This sort of construct makes no sense when we deny the existence of absolute space and instead consider space the creation of existing objects. In this view, no three-dimensional framework exists for the solitary ball suspended in emptiness. There is no up or down, no left or right, neither size nor velocity, and no determinable distance of any kind. Instead there is a single center surrounded quite symmetrically by emptiness in that no direction is distinguishable in any way from any other, and consequently the notion of direction does not come up at all. Space is, in this case, a centrically symmetrical sphere of infinite expanse. It should be noted that the situation I am describing here is not simply physical but experiential, presupposing a consciousness of space that somehow inheres in that single, ball-shaped object.

We can go a step further and separate that consciousness from the target of its attention by assuming the existence of two objects in empty space, an observer and something he observes. Let us assume that astronauts are approaching the earth and, for the time being, have wiped the memory of all other heavenly bodies from their minds. A linear connection forms itself spontaneously between observer and earth, and this connection constitutes the axis of a one-dimensional world. Along this axis there are distances, directions, and velocities, and the empty environment arranges itself symmetrically around the axis in the form of a cylinder of infinite size.

A roughly comparable experience can occur in our terrestrial environment. For example, as one approaches a building towering over a fairly empty plain, the perceptual relation is essentially between the viewer and the target, especially when the building is the person's destination. The horizontal surface of the plain, although perceived, does not modify the relation between viewer and tower and therefore does not actively enter his spatial conception of the situation. Nor does this happen only when the environment is unoccupied. A stranger trying to reach the one tall building that rises above the city may walk in the direction of his visual target, selecting street after street as it seems to lead him in the right direction, without any more conscious apprehension of the pattern of streets he is traversing than if he were hacking a path through a jungle. Even though a complex physical structure is physically present, the experience is dominated by the primary goal and the single-minded effort to reach it.

Note that the connection established by the observer between himself and his target is experienced as a straight line. In principle, that connection could take any shape among an infinite number of curves, twists, and loops of the most irrational kind. The economical choice of the shortest connection is an elementary application of gestalt psychology's principle of simplicity: any pattern created, adopted, or selected by the nervous system will be as simple as the given conditions permit.

The effects of this principle are better appreciated when we now take a further step and consider a configuration of three, rather than two, points in space (Fig. 2). Suppose a spaceship is navigating in relation to a planet and the sun. According to the principle of simplicity this situation will create a triangular structure in the minds of the astronauts. A flat triangle is the simplest structure compatible with three points. As the astronauts concentrate their attention on their relations to the planet and the sun, their world is no longer one-dimensional but two-dimensional. Functionally, no third dimension exists. For example, the question of how the triangular plane is

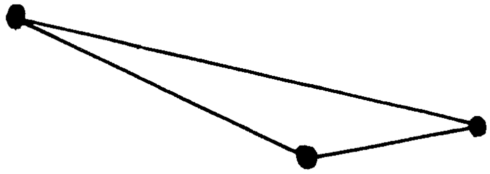
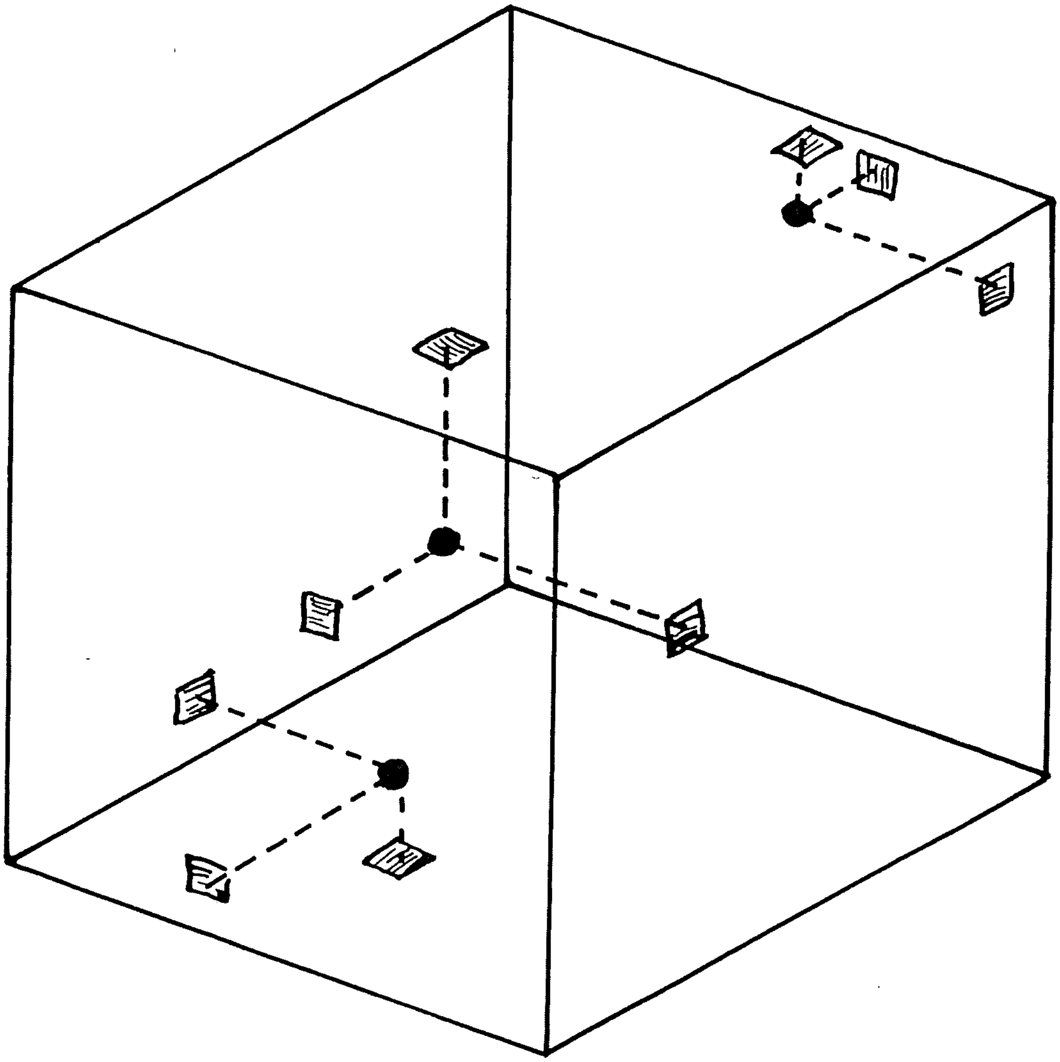


Figure 2

Figure 3



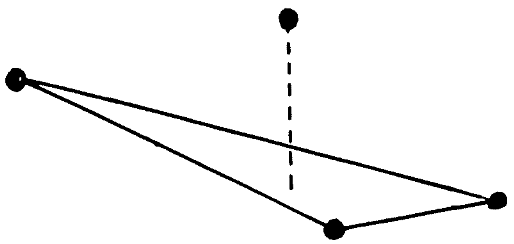


Figure 4

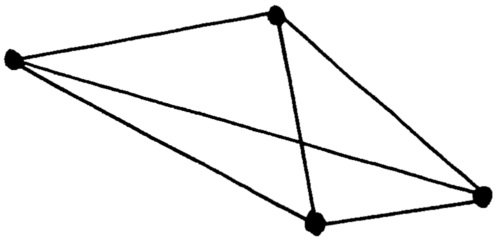


Figure 5

located in space, whether it is oriented horizontally or vertically, or tilted obliquely, has no meaning. Notice here that if space were not created by the three objects involved, but in relation to an external framework of Cartesian coordinates, a different set of spatial relations would result, which could totally exclude the triangular connection between the objects (Fig. 3).

Since we are dealing with the psychological experience of space, much depends on how an observer conceives of and therefore structures the situation. If, for example, further objects venture into the range of the three, the role and function accorded them will influence the resulting constellation. The relative strength of the contending parties will matter. A small asteroid would probably not upset the flatness of the triangular situation, but would be seen as located at some angle to that base (Fig. 4). If, however, the new fourth object is strong, it may create a fuller realization of the now three-dimensional setup: the triangular plane may be replaced by a four-cornered polyhedron (Fig. 5).

ARCHITECTURAL IMPLICATIONS

By way of lofty abstraction we have come across a fundamental principle of practical importance to the architect. In spite of what spontaneous perception indicates, space is in no way given by itself. It is created by a particular constellation of natural and man-made objects, to which the architect contributes. In the mind of the creator, user, or beholder, every architectural constellation establishes its own spatial framework. This framework derives from the simplest structural skeleton compatible with the physical and psychological situation. Under elementary conditions the structure established by the architectural layout as a whole may rule uncontested. For example, in a linear village surrounded by cultivated fields, the main street may serve as a one-dimensional spine to which all particular locations and spatial orientations conform. Usually the situation is more complex. Some components of the whole establish their own spatial framework. A church oriented along an

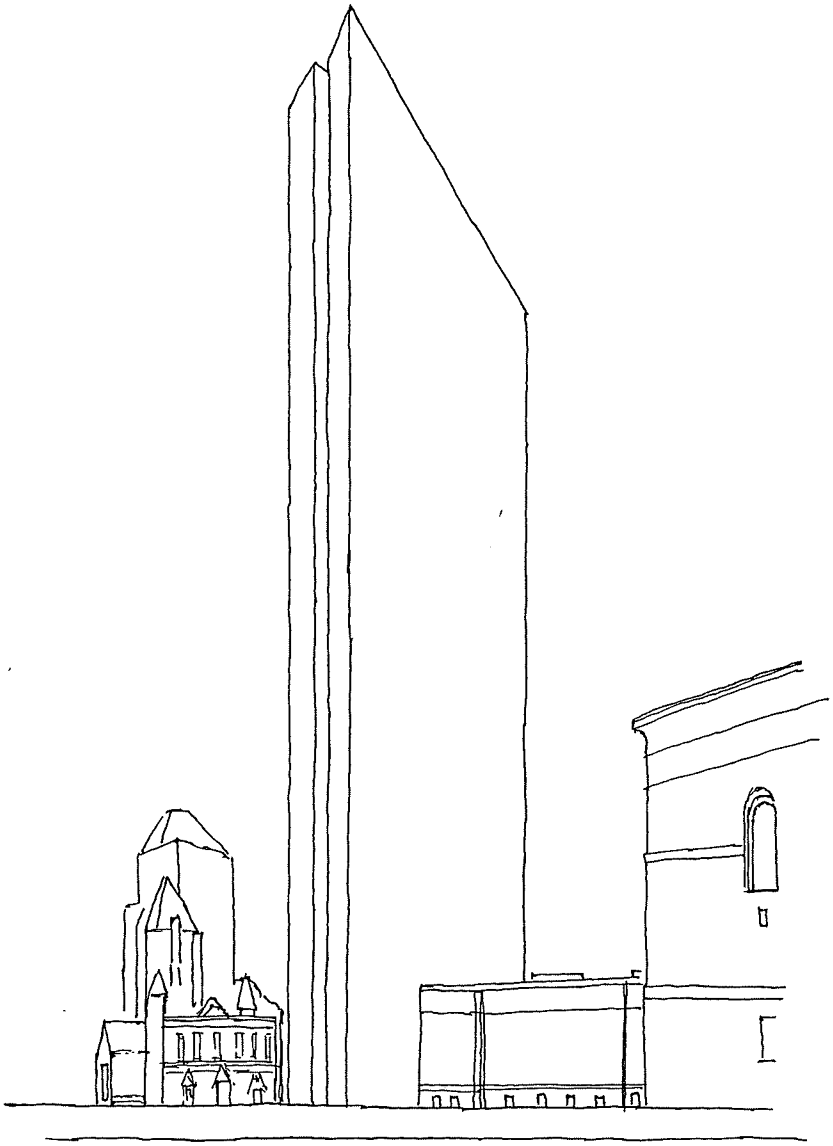


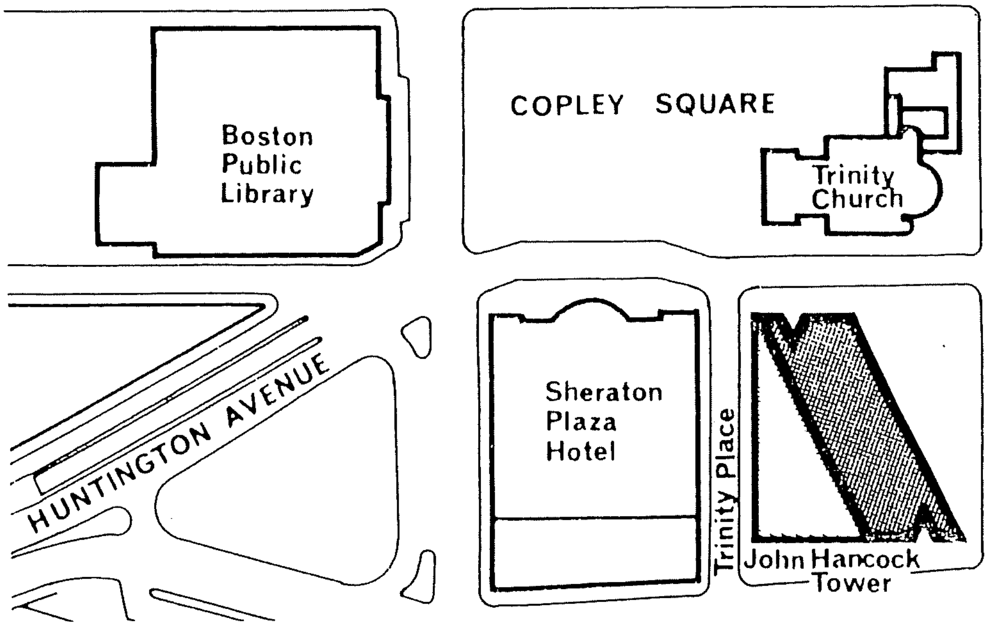
Figure 6

east-west axis may oppose the overall orientation of its environment, and the relation between the two may be complex or even unmanageable, in which case the spatial order comes apart. Take the following recent and particularly dramatic example. The quadrilateral symmetry of Boston's Copley Square, on which H. H. Richardson's Trinity Church and the public library of McKim, Mead, and White face each other, has been pierced visually by a diagonal wedge nearby, the huge rhomboid skyscraper of the John Hancock Tower (Figs. 6 and 7). In such cases the addition may be simply absorbed and subordinated by the existing setting–an unlikely possibility in this case because of the mass and height of the intruder. Or the new structure and the old may reorganize themselves into a new configuration of unified shape. Most probably the clash of two incompatible patterns will result in mutual denial—a disorder that spells visual destruction.

Almost any architectural setting is a highly complex constellation of such spatial systems, some subordinated, some coordinated, some bordering upon each other, some crossing or surrounding others. At its most comprehensive level the setting may be the shape of an entire city, composed of distinguishable boroughs, each of which is made up of isolable parts, with these in turn being subdivided into single streets, squares, buildings. Each building is a constellation of its own, and the subdivision leads all the way down to the furnishings of a single room, in which tables, shelves, or beds each propose a particular spatial framework.

Kevin Lynch's classical description of urban settings makes it clear that at their various levels these spatial systems may be either highly ordered or chaotic. It stands to reason that environments planned as a whole are likely to display a more consistent order than the piecemeal accretions by which most communities grow, although the latter do not necessarily produce disorder. Lynch's analyses show that the more orderly the objectively given spatial structure, the more agreement there is in the images people form of the setting. The more ambiguous the structure, the more the resulting image depends on where an observer happens to anchor his attention, how well acquainted he is with various sections, and so forth.

Figure 7



More will be said on this subject in a discussion of order and disorder in Chapter VI. Let me add here that the complexity of the space created by architecture is in part what psychologists call a developmental matter. Three-dimensional space is directly given to the mind only in its crudest extent; the finer interplay of dimensions must be gradually conceived by it. Early spatial conceptions are therefore simple. This is not always evident in the actual constructions since in practice the developmental factor can be overlaid by technical, historical, or personal influences. But it is useful to realize that one of the components at work is a tendency of the mind to proceed from the simplest spatial constructs to increasingly complex ones. In a relatively pure state we may find this tendency manifest in children's block play, in the early experiments of architectural students, or in primitive huts. Psychologically, a first phase may consist in the placement of a single object in neutral space. At a somewhat more developed stage, the relations between objects as well as those between the components of a single object may be essentially two-dimensional, conceived in terms of a flat plane, whether horizontal or vertical. Within such a plane, relations may be limited at first to right-angular ones, proceeding to more intricate obliqueness only later. Similarly, true three-dimensionality limits itself at an early level to right-angular relations, for example in the shape of a cube or an arrangement of cubes.

In this way one can try to establish a scale of increasing complexity, by which spatial imagination proceeds from the simplest structures to the most complex. Of course, in a purely physical sense even the simplest architectural act involves three-dimensionality, since a single brick is a three-dimensional object. But it is essential for the understanding of architectural form to realize that the mere handling of objects in the physical world does not by itself provide an active conception of the dimensions and inherent possibilities of space. This holds true for every human occupation dealing with space, be it engineering, mathematics, physics, medicine, games, or the arts. Spatial imagination must be acquired step by step. In some persons or cultural periods it never reaches beyond fairly elementary relations, either because development stops at an early level or because greater complexity would serve no good purpose. In a few instances, spatial imagination attains the dizzy intricacy displayed by a Borromini or Le Corbusier.

THE FIELDS IN BETWEEN

Let me return to the two conceptions of space from which we started. Spontaneous perception, we said, presents space as a container existing prior to, and independently of, the physical bodies that find their place within it. In such a view, the spaces between things are empty. Everyday experience distinguishes between impenetrable matter, such as mountains or tree trunks or the walls of buildings, and openings that we can pass through. This distinction is fundamental for the architect, since he constantly seeks the proper ratio between the two.

At the same time, however, the architect must be aware of the second conception, suggested to him by the physicist and the psychologist, that space is created as a relation between objects. These relations persist in perceptual experience, even though the man in the street may not spontaneously acknowledge them. There are many aspects of experience of which we are not explicitly conscious that nonetheless tinge our awareness in important ways. The visual relations between objects are of this kind. Space between things turns out not to look simply empty.

Take the example of two buildings, one big and one small, standing at a moderate distance from each other. It is possible to deal with them independently by making statements about one of them without considering the other—for example, by discussing the height of only one of them. That is the sort of disconnected treatment to which we owe the visual, functional, and social chaos of modern life. It derives from the tunnel vision employed for immediate practical ends, especially under social conditions that atomize the human community into a mere aggregate of individuals or small groups, each minding its own business. Perceptually this attitude corresponds to seeing items of the continuous environment in isolation from their context. We readily recognize such dismemberment as a pathological deformation of the natural way of seeing the visual field as a whole. At the less elementary level of viewing social relations, the pathological character of this attitude should be equally evident. Socially as well as perceptually, one cannot understand the nature of either the small house or the large house as long as one considers each only by itself.

Unimpaired vision perceives the two buildings as elements of one image, in which a decrescendo effect leads from the tall house down to the low one, or conversely a crescendo makes our eyes rise from low to high. Also the big mass of the one building is seen as contrasting with the small mass of the other, and vice versa, as the viewer's glance moves back and forth between them. Looking at the two is an eminently dynamic experience, in which the space between the buildings is an inseparable part of the image. Far from being empty, that interstitial space is pervaded by gradients. If the width of the interval were to change, i.e., if the buildings were to be closer together or farther apart, the slope of the gradients would change concomitantly. So would the contrast between the buildings.

It may seem paradoxical that space has a perceptual presence of its own, even though it is not explicitly constructed by the builder and does not appear among the objects constituting the inventory of the visual image. But it is quite common for visual percepts to contain more than what is given in the physical stimulus pattern. A configuration of four dots on a paper may be seen as a square, even though no connections between the dots are drawn in. Perhaps the following example will persuade the reader that what is made does not necessarily correspond to what is seen. For the decoration of an early type of Greek vases, black figures were painted on the red ceramic ground. The inverse procedure was used in later times: the background was covered with black paint, and the figures remained red. If we simplify the technical process somewhat, we may say that on the red-figured vases the artist painted only the background but obtained the figure. Inversely, the architect does not build space but creates it just the same.

A good way to demonstrate that interspaces are not empty is referring to what may be called their density. If one makes small models of our two buildings and moves them back and forth, closer together and farther apart, one observes that the interspace looks looser and thinner as the distance between the buildings increases. Conversely, the interspace becomes denser as the distance diminishes. The observer experiences perceptual compression or decompression in the interval. To my knowledge, this phenomenon has never been systematically investigated, and its conditions are likely to be complex. Although the observed density may be a simple function of the distance between the objects, its absolute level of intensity may depend on other perceptual factors, such as the size of the buildings. Furthermore, if there are additional buildings in the neighborhood, the spaces between them will influence the space we are considering (Fig. 8). Interspace *n* will look smaller and denser when compared with *o*; it will look larger and looser when compared with *m*.

The distance between the buildings also influences the degree of their mutual dependence or independence. If the interspace were entirely eliminated, the two buildings would tend to coalesce into one, with the small one looking like a mere appendage of the large one. At the other extreme, a great distance would extinguish most relations between the buildings. The interspace, then, establishes a particular ratio of remoteness and connectedness, which affects the architectural complex as a whole. When we consider

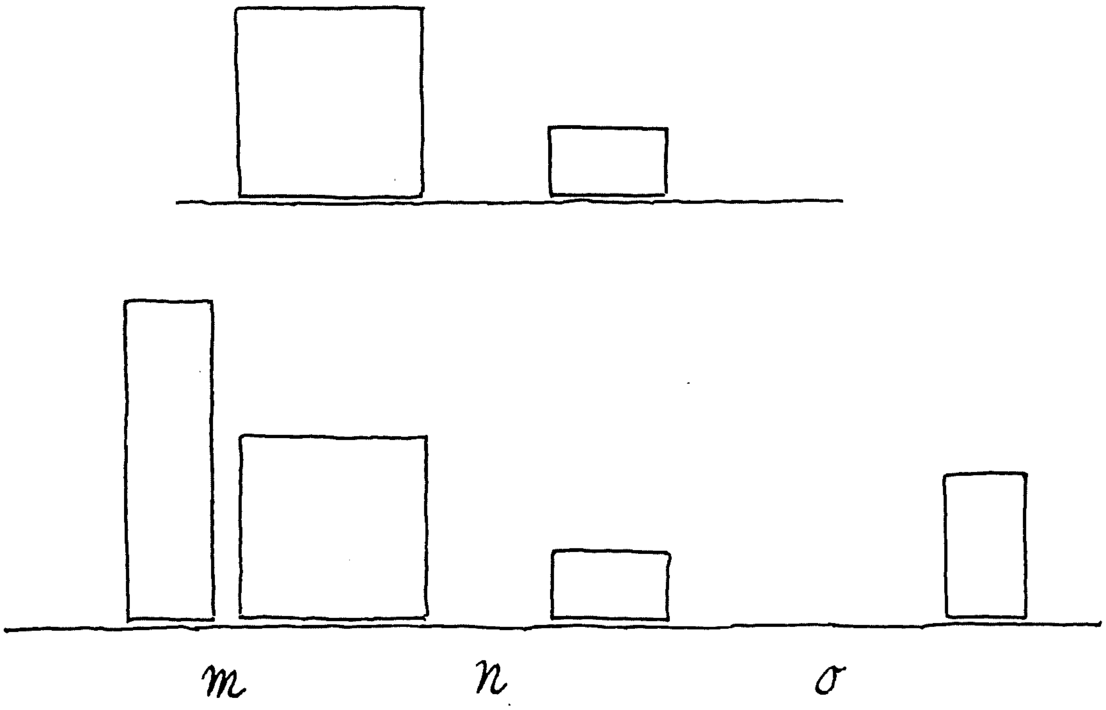


Figure 8

remoteness and connectedness not simply as metric distances but dynamically, we find that they depend on forces of attraction and repulsion. Objects that look "too close" to each other display mutual repulsion: they want to be moved apart. At a somewhat greater distance the interval may look just right or the objects may seem to attract each other.

These forces are at work whenever things are related across space; they determine the spacing of pictures on a wall, the placement of furniture in a room, the proper distances between buildings. We feel impelled to ask whether the distances between the baptistery, the cathedral, and the campanile in Pisa's Piazza del Duomo are just right, and if so, why? What would happen if the distances were altered? The perceptual aspects of the judgments that determine the answers are arrived at intuitively by our sense of sight. They are likely to depend on the strains and stresses activated in the brain field by the particular constellation of stimuli projected upon it by the retinal image. Optimal distances can be measured, but here again the rules governing the phenomenon are not likely to be simple.

In recent years, especially through the work of Edward T. Hall, attention has been drawn to the psychological and social connotations of spatial distances between people in daily intercourse. How close together or far apart people are expected to be when they meet depends on their personal relationship and more generally on the social conventions of the particular cultural setting. These "proxemic" norms influence also the choice of preferred distances between objects, e.g., the placement of furniture, and they are likely to affect the way people determine and evaluate the distances between buildings. What looks oppressively close to one kind of observer may be welcomed as cozily protective by another. These personal and social attitudes overlay and modify the specifically perceptual factors I am discussing here.

Visual distances are judged by the behavior of the perceptual forces generated by them. We feel impelled to juggle the distances between objects until they look just right because we experience these distances as influencing forces of attraction and repulsion. Balancing applies always to forces. If the intervals were experienced as nothing but dead, empty spaces, there would be no criterion, other than practical considerations, for preferring one distance to another. I shall have occasion to make a similar point on the control of proportions in architecture.

EMPTY AND FORLORN

When the distance between buildings increases, the density of the interval lessens and eventually disappears entirely. No longer do we experience any relation between the buildings. It is under such conditions one can say that the space between them is empty. The conditions for perceptual emptiness can be made clear by an analogy to music. Physically, any moment of time during which no music is sounded can be said to be empty. Perceptually, however, the character of such intervals varies greatly. A run of pizzicato notes hangs together like a string of pearls because the small pauses between the tones are entirely absorbed by the continuing sequence. Longer pauses are perceived as silences but nevertheless also as integral parts of the music. During such an interval the tone preceding it acquires its rhythmic weight and meaning by lingering on for the time prescribed by the structure of the composition. These time intervals may be entirely devoid of sound, but they are not empty. They are pervaded by tension. Emptiness, however, is experienced when a movement of a composition comes to an end, its structure is completed, and the performers take a moment's rest and check their instruments before starting again.

This comparison with music shows that the degree to which an interval is filled does not depend simply on its objective length. Visually also, when the two objects bordering on the interval require each other for mutual comple-

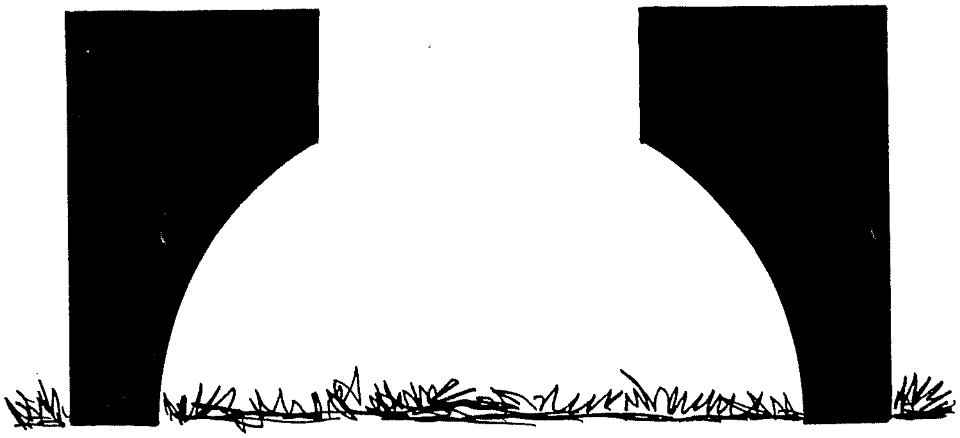
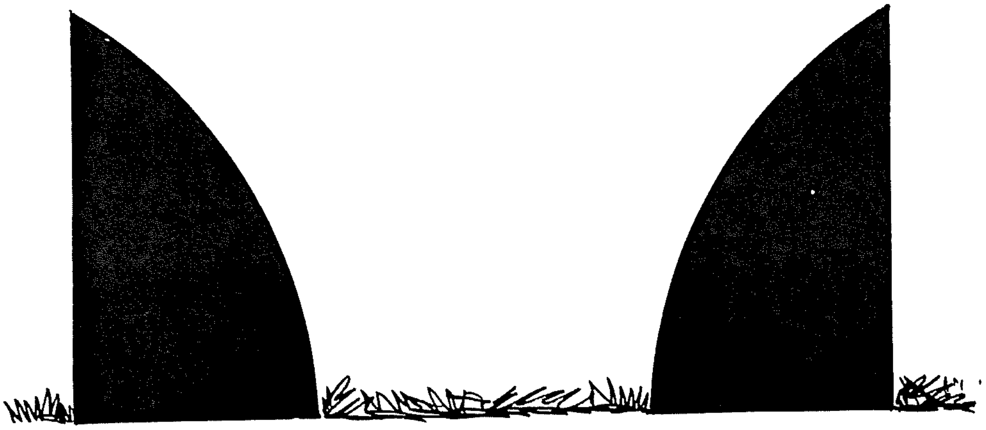


Figure 9a

tion, the interval is more actively and densely filled (Fig. 9a) than if the two shapes are strongly self-contained and independent (Fig. 9b). It follows that perceptual emptiness can be described as a quality of an area whose spatial characteristics are not controlled by the surrounding objects. Extreme emptiness is experienced where there are no objects at all. In darkness, on the ocean, or in outer space, the absence of all points of reference and orientation, the lack of attraction and repulsion, the undefined distances, can cause ultimate terror. Its social equivalent is the experience of a person who feels totally abandoned: the environment is complete without him, nothing refers to him, needs him, calls him, or responds to him. This lack of external definition destroys the internal sense of identity, because a person defines the nature of his own being largely by his place in a network of personal relations.

Figure 9b



To be sure, a strong personality may cope with aloneness by establishing himself or herself as the center and irradiating the surroundings from that center with a sunburst of forces that animate emptiness. Under such conditions the absence of counteracting obstacles may even create an exhilarating sense of freedom. It is the experience of "covering" the world from a mountain top. Similarly, a monument erected in an empty plain may evoke in the surrounding space a field of perceptual forces whose strength diminishes with increasing distance from the center.

Evidently, emptiness is not simply related to the absence of matter. A space on which nothing is built can be pervaded nevertheless by perceptual forces and filled with density, which we might call a visual substance. Conversely, the fenestrated wall of a high-rise building or a large, homogeneous area in a painting may be experienced as empty even though the architect or painter has put something there for us to look at. The effect of emptiness comes about when the surrounding shapes, e.g., the contours, do not impose a structural organization upon the surface in question. The observer's glance finds itself in the same place wherever it tries to anchor, one place being like the next; it feels the lack of spatial coordinates, of a framework for determining distances. In consequence, the viewer experiences a sense of forlornness.

In the examples I just gave, the viewer feels forlorn because he projects himself onto the place that he scans with his glance; he drifts rudderless within the anonymous expanse. This kind of experience can be more intense when the person finds himself bodily at a place that does not define him spatially, for example, on a shapeless city square or in the vast hall of a museum. He can also diagnose an object as looking forlorn in its setting. This may occur when the placement of the object has no recognizable relation to its surroundings. A piece of sculpture placed injudiciously in a living room, a museum, or a landscape may seem lost. It may drift aimlessly, or it may display a tendency to move to a different place, where it can be anticipated to find spatial definition and therefore rest. The central, symmetrical location of the equestrian statue of Marcus Aurelius on Michelangelo's Capitol Square in Rome is the most obvious instance of a sculpture fully anchored in a highly defined space (Fig. 10). A modern example that has assumed almost mythical qualities among students of architecture—especially since the building has been demolished—is the statue by Georg Kolbe placed by Mies van der Rohe in his German Pavilion for the International Exposition in Barcelona, 1929. The life-sized nude, conspicuous as the only organic shape in a building

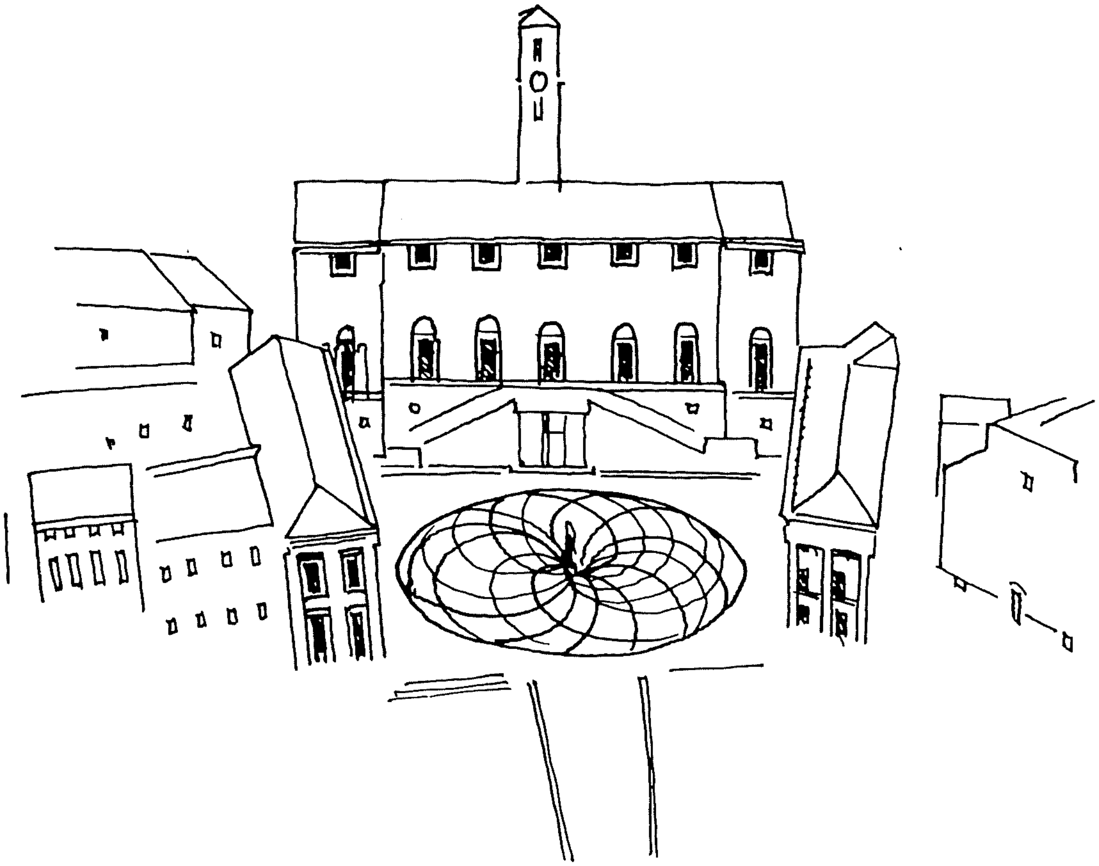


Figure 10

formed of rectangular slabs, stood in a corner that otherwise would have escaped the visitors' attention (Fig. 11*a*). It stood on a terrace in a small pool, which was visible through the glass partition of the large internal space, and it was backed by low walls (Fig. 11*b*). The sculpture pool was accessible through a narrow corridor (Fig. 11*c*) that would have led pointlessly to an empty corner without the statue as its visual focus. By giving a special accent to the far corner of the building, the architect stressed the strongly confined rectangularity of the whole design and underscored the diagonal correspondence between the large pool paralleling the longer side of the building near the open entrance and the small, hidden pool marking the building's shortest side at the remote end.

As this example shows, not only does the setting determine the place of the object, but inversely the object also modifies the structure of the setting. Placed in the corner of a terrace, Kolbe's statue gives the rectangular shape of its more immediate environment an eccentric focus, which contrasts with the

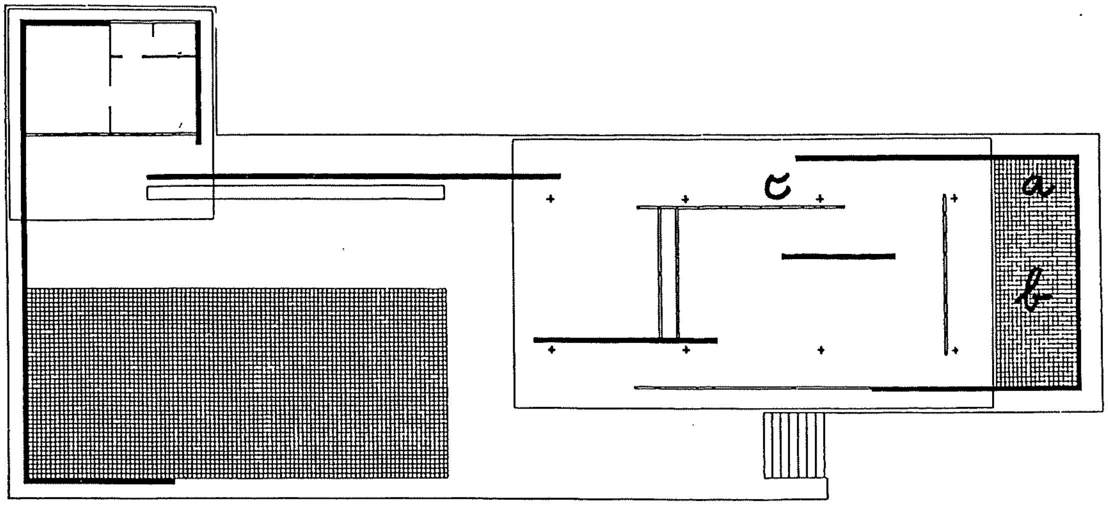


Figure 11

symmetry of the rectangular terrace. The resulting asymmetry creates a tension that must be justified and counterbalanced by the configuration of forces in the building as a whole.

I will report here an experience I had at the time an authentic Japanese house was built in the garden of New York's Museum of Modern Art. The house enclosed a pond of free-form contour, which I admired because, in a way indefinable by measurement and reason, it seemed to establish unalterably a complex spatial relation between the expanse of the water and the landscaping of rocks and shrubs surrounding it. Doubting my judgment, I asked myself whether some arbitrarily different outline might not work equally well. On one visit to the house, however, I noted that somebody had thrown a crumpled-up piece of wrapping paper into the pond. The paper floated on the dark surface of the water as a white patch; and I had to concede that by creating a visually weighty new accent, the intruder had restructured the dynamics of the entire image and disturbed an equilibrium I no longer questioned.

Emptiness and the ensuing sense of forlornness do not come about only when the visual objects needed to determine the field of forces in an open expanse are missing. A similar effect results when such determinants are present but do not add up to an organized structure and thereby cancel one another out. Paul Zucker gives two examples:

> New York's Washington Square is laid out as a regular rectangle, framed by houses on all sides—and yet it is not a "closed" square. For its dimensions are so large, the proportions of many of its surrounding structures are so heterogeneous, so irregular,

> even contradictory, and the location and size of the small triumphal arch are so dissimilar to all the other given factors, that a unified impression cannot result. Disproportion in scale destroys all aesthetic possibilities.
>
> Another factor spoils any aesthetic effect of Trafalgar Square in London: it could have developed into a "nuclear" square had not the tremendous façade of the National Gallery in contrast to the small adjacent blocks of houses and the irregular directions of the streets leading to the "Square" counteracted the effect of the Nelson Column as a space-creating element. But as it is, the column does not become a center of spatial relationships, a kernel of tension.

One could try to describe the disconcerting effect of such a constellation with some precision. One could chart the forces each object generates around itself by its size, mass, location, and direction, and one could show how its particular local field is not supported by those of its neighbors. The object thus does not fit with its neighbors into a superordinate structure, created by them all and containing them as organic parts. The disorientation resulting from a chaos of forces impinging on one another in a disorderly fashion makes it impossible to determine the place and spatial function of any object within the perceptual field. If the observer himself is that object he himself will feel forlorn. A prime source for such perceptual disorientation is the recent fad of reflecting glass walls, which create a surrealistic contradiction between incompatible images. The wall is destroyed, and the reflection shows a space that is not there.

THE DYNAMICS OF SURROUNDING SPACE

Another observation by Zucker suggests that the visual field expands not only in the horizontal dimension but also vertically. He says that an architectural setting induces a definite ceiling to the sky above it:

> The subjective impression of a definite height of the sky is caused by the interplay of the height of the surrounding buildings and of the expansion (width and length) of the floor. It is strongly influenced by the contours of eaves and gables, chimneys and towers. Generally the height above a closed square is imagined as three to four times the height of the tallest building on the square. It seems to be higher above squares which are dominated by one prominent building, whereas over wide-open squares, such as the Place de la Concorde in Paris, the visual distance of the sky is only vaguely perceived.

What Zucker calls the "ceiling" of the sky is what I would describe in dynamic terms as the visual field of forces generated by the heights and masses and probably also by the overall relief of the architectural setting, such as that of a city square. A dynamic interpretation of the phenomenon lets us understand the "height of the sky" as the limit of the field of forces that issues from the architecture on the ground but cannot reach beyond a certain distance. With increasing distance the field peters out into the empty sky. This phenomenon is reflected visually in the shape of skylines. A sharply horizontal boundary tends to produce an abrupt break between architecture and sky. This is not the case when we see irregular contours, which may build to peaking clusters. The diminishing width of spires and towers supports the same visual conception. The architecture diffuses gradually into the sky.

If one turns the shape of a skyline by 90° (Fig. 12), one is reminded that a similar gradual diffusion into the surrounding space is much less appropriate for the vertical boundaries of buildings. This is due to a basic difference between the vertical and the horizontal dimensions, to be discussed in the next chapter. But this difference is also symptomatic of what happens when fields of forces are not permitted to expand unchecked. In such cases, quite common in the horizontal relations between buildings, architectural structures control each other's outreach, the way countries stabilize their boundaries on the political map by power exerted from both sides.

As an example we may look at the size of open spaces bordering on buildings. The parvis in front of Notre-Dame de Paris was originally much smaller than it is now. Even so, it seems to me that the building is well served by the present, rather large, space in front of the façade. The space is large enough to let the structure exert its impact and confined enough to prevent dilution of its intensity. A building with a more open plan, for example, one with wings protruding beyond the center, calls for a more extended "doormat."

What I am describing here as the field of forces surrounding a building should not be taken to refer simply to the distance necessary for an observer to survey the shape of a building. Such proper viewing distances do exist, and I shall refer to them later, but what I am describing here affects the position of the observer in a different way, namely in the sense of "proxemics"—the proper distance prescribed by the nature of a thing or person one is facing. Buildings must maintain a proper distance from one another, and the same rule of conduct holds for an observer. Rembrandt is reported to have said, "You must not sniff at my paints"; and although there can be good reasons for someone to scrutinize a painting or sculpture from close by, there is always something disrespectful and inappropriate about it. The novelist Robert Musil has expressed this aspect of spatial response metaphorically: "Each thing or creature, if it wants to approach another one very closely, has

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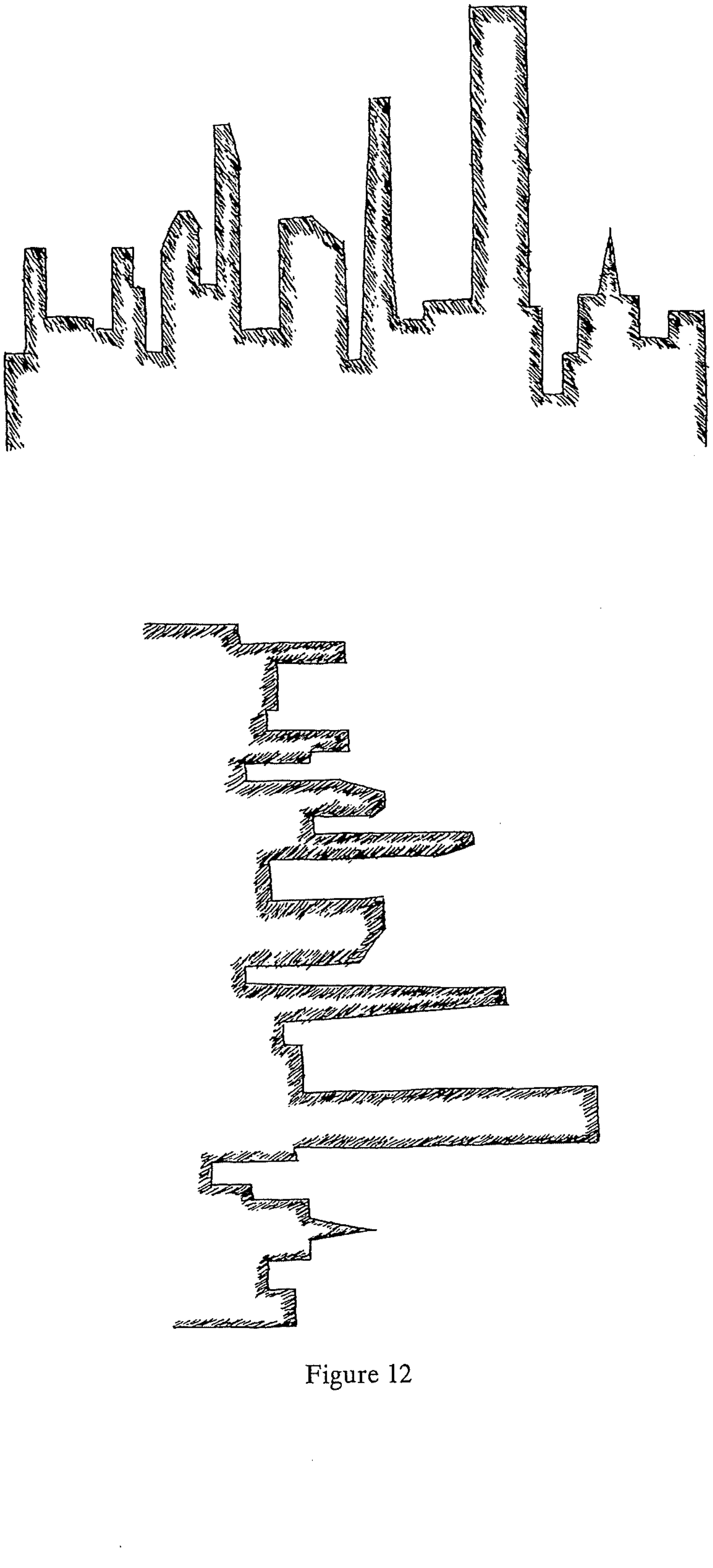

Figure 12

a rubber band tied to it, which tenses when stretched. Otherwise things might end up moving through one another. And so in every motion there is a rubber band that lets one never quite do all one wants to do."

In order for an object to be perceived appropriately, its field of forces must be respected by the viewer, who must stand at the proper distance from it. I would even venture to suggest that it is not only the bulk or height of the object that determines the range of the surrounding field of forces, but also the plainness or richness of its appearance. A very plain façade can be viewed from nearby without offense, whereas one rich in volumes and articulation has more expansive power and thereby asks the viewer to step farther back so that he may assume his proper position, prescribed by the reach of the building's visual dynamics.

As long as the base of a building is in contact with the ground, the need for visual breathing space does not apply to its bottom. However, when it is conceived as a mass suspended above the ground and resting on columns, piers, arches, or pilotis, a proper air space is required for this additional dimension as well. The particular size of such a ground space depends, of course, on the effect the architect intends. If the interspace above the ground level is large, the building may float like an anchored balloon and may even lose its connection with its base. If the space is too small, the visual forces issuing from the building toward the ground may seem constrained to occupy an area that is too small in relation to the building's mass. When Le Corbusier was designing the Carpenter Center for the Visual Arts at Harvard University, it was realized that the horizontal protrusion of the large curved North Studio on the second floor would lose much of its outward thrust unless a larger space beneath it rendered it more independent of the attraction exerted by the ground. For this reason an essentially unfunctional pit was dug beneath the studio area, which, resting on relatively slim pilotis, acquired thereby the necessary dynamic freedom (Fig. 13).

The preceding examples will have made it increasingly clear that in perceptual experience the spaces surrounding buildings and similar structures cannot be considered empty. Instead these spaces are pervaded by visual forces generated by the architectural structures and determined in their particular properties by the size and shape of their generators. Visual forces are not isolated vectors, but must be understood as components of perceptual fields that surround buildings and are also active in interior spaces. Among architects, the importance of these perceptual fields has been acknowledged explicitly by Paolo Portoghesi. Since the notion of

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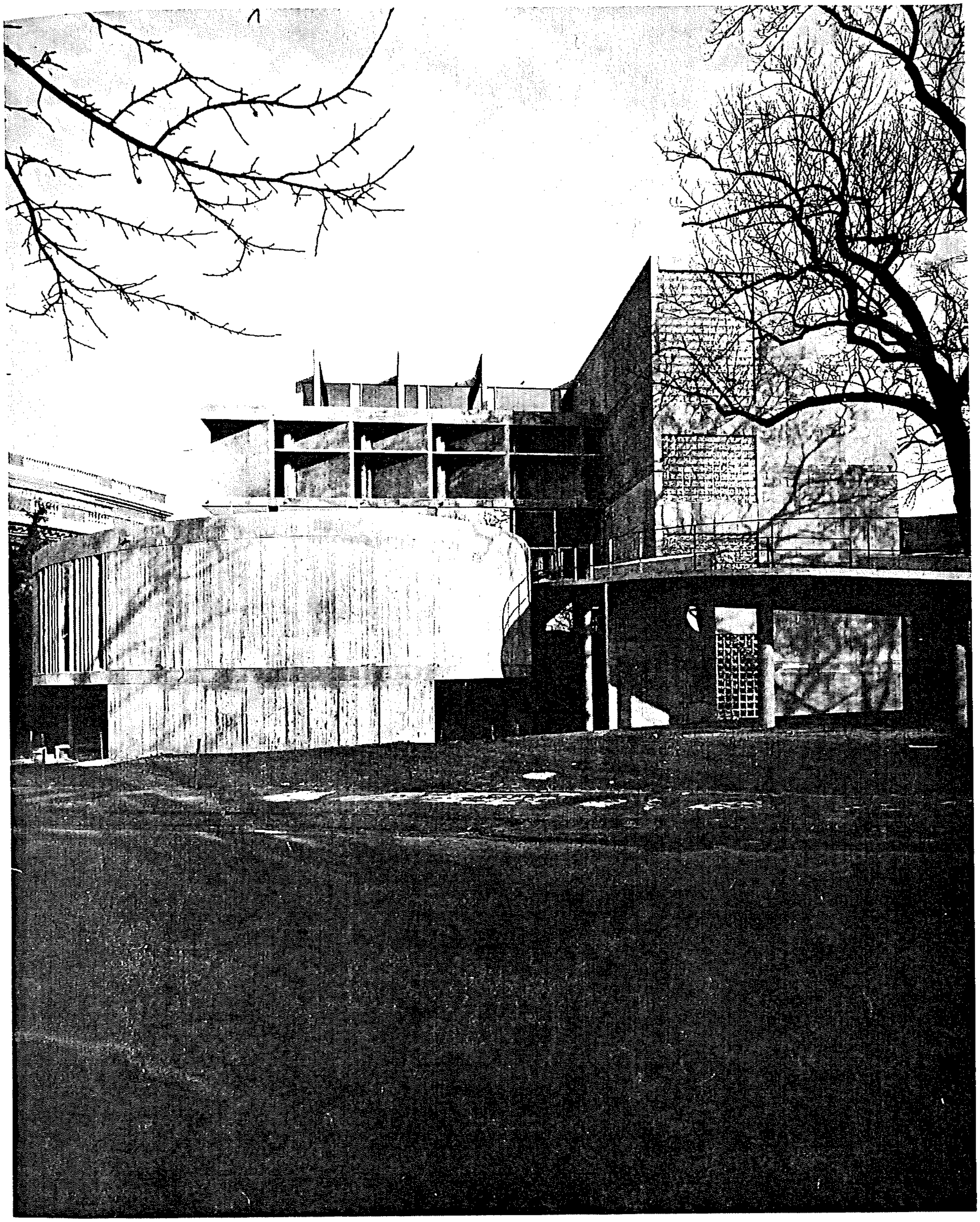


Figure 13. Carpenter Center for the Visual Arts. *Photo*, Harvard News Office.

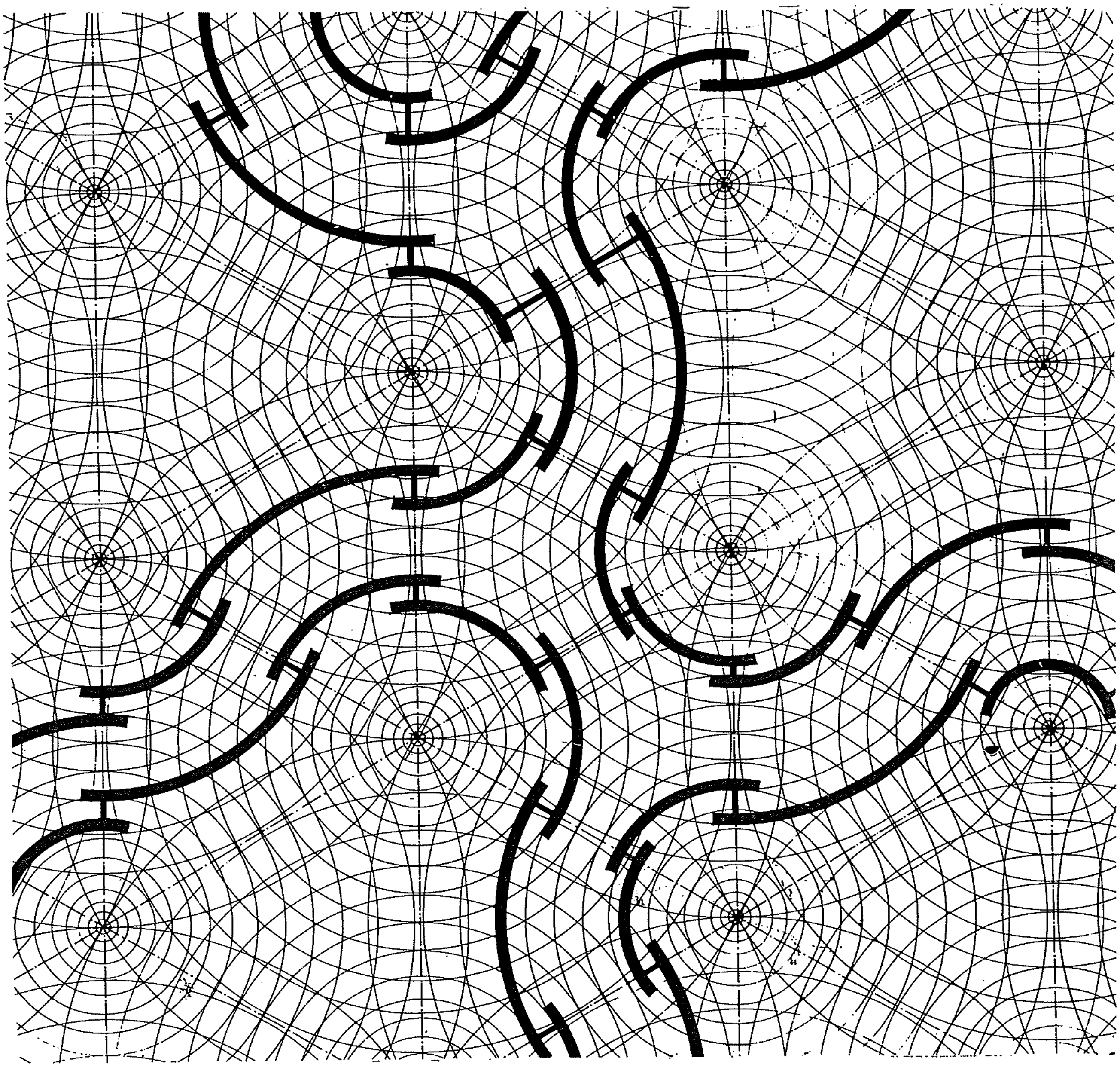
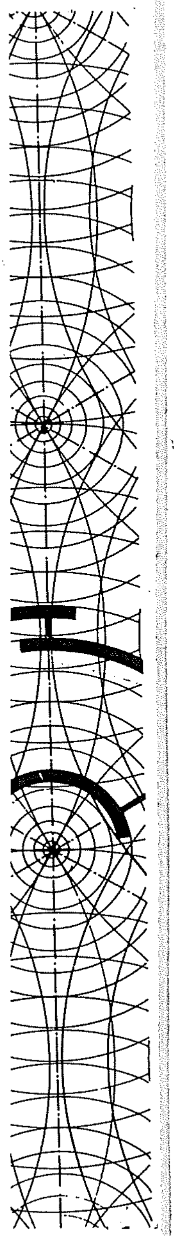


Figure 14. Drawing by Paolo Portoghesi.

perceptual and social fields has been adopted from physics, Portoghesi begins his discussion with a formulation of Albert Einstein's: "We speak of matter when the concentration of energy is high and of fields when the concentration is weaker. But in that case the difference between matter and field appears to be quantitative rather than qualitative." Conceiving of buildings as islands in space, Portoghesi is focusing upon those shapes that indicate the dynamics of fields most directly, namely on patterns of concentric circles, as they appear on the surface of a pond when a stone is dropped



into the water (Fig. 14). Just like its counterpart in hydrodynamics, a field of visual forces in architecture expands from the center and propagates its wave front as far into the surrounding environment as its strength permits. Portoghesi writes:

> By emphasizing the generated field in addition to the architectural object, one raises once more the problem of space, but in different terms by giving the concept a different value. In traditional criticism space is a homogeneous structure, a kind of counterform to the mural envelope, indifferent to the lighting conditions and to its position in relation to the buildings, whereas the notion of field stresses the continuous variability of what surrounds the architectural structures.

Circular buildings expand into the environment, whereas concave walls "open the building toward the urban space." In the latter case the center of the generating field lies outside the architectural structure, which acknowledges the field's presence by yielding to its expansion. These observations go well with what is known about the dynamic effect of concavity and convexity in other perceptual situations, as I will point out later. What needs to be added here is that although circular fields are most easily recognized and described, a field theory of architectural spaces must acknowledge more generally that buildings of any shape create fields of forces around themselves, and that the particular configuration of such a field depends in every case on the form of the generating structure.

The Unknown Space[*]

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In 1948, the philosopher Maurice Merleau-Ponty delivered a series of lectures on French radio where he described a new manner of thinking about the world and the human mind, contrasted with the old "classical" approaches.[1] Merleau-Ponty pointed out that

> *[the] world of perception, or in other words the world which is revealed to us by our senses and in everyday life, seems at first sight to be the one we know best of all. For we need neither to measure nor to calculate in order to gain access to this world, and it would seem that we can fathom it simply by opening our eyes and getting on with our lives. Yet this is a delusion… the world of perception is … unknown territory as long as we remain in the practical or utilitarian attitude.*

Experience of space was Merleau-Ponty's parade example of our deficient understanding of experience. Today, experience of space remains an unknown territory ("opaque" to understanding in Merleau-Ponty's terms) because of the pervasive segregation between two conceptions of space, intellectual and experiential.

Intellectual is the objective, mathematically sophisticated account of space developed by physicists, cosmologists, and philosophers of science. This conception has served us well in physics and engineering, but it has been removed from one's immediate experience of space, here and now. In fact, the segregation of the concepts of physical space and of the space of experience is one of the often-cited reasons for the stunning advancement of physics.

The experiential conception of space has been investigated broadly and often with great insight by phenomenologists and theorists of architecture. Yet their accounts have been speculative: untestable in the sense their predictions were not quantifiable and thus they could not be validated by experiment. In effect, purely phenomenological accounts are largely unsuitable for what Merleau-Ponty called "practical or utilitarian attitude," in contrast to the exacting, predictive theories of physical space.

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[*] This text is a reformatted version of Gepshtein S (2017). The Unknown Space. *Proceedings of the Sixth Professional Lighting Design Convention.* Paris, France, November 1-4, 2017, pp. 88-89.

This situation has to change. Explosive advances in technologies of simulation and the increased sophistication of architectural design are hindered by the rudimentary understanding of spatial experience. Designers want to predict in quantitative detail where and when certain experiences are possible, replacing the exasperating process of trial and error, and ensuring that every desired detail of spatial design contributes to the value of experience.

Here I describe one attempt to develop a quantitative, predictive model of spatial experience that builds on recent advances in sensory neuroscience and psychophysics.[2] A striking (although speculative) precursor of this model is illustrated in Fig. 1. It is an intuition of how sensible features of a built environment affect the perceiver. The thin concentric circles represent the potential perceptual impact of a set of walls (represented by the thick curves). The thin circles suggest a number of zones that create an intricate lacework of potential experiences. Individuals traversing this space would enjoy a series of experiences according to the zones they cross along their path.

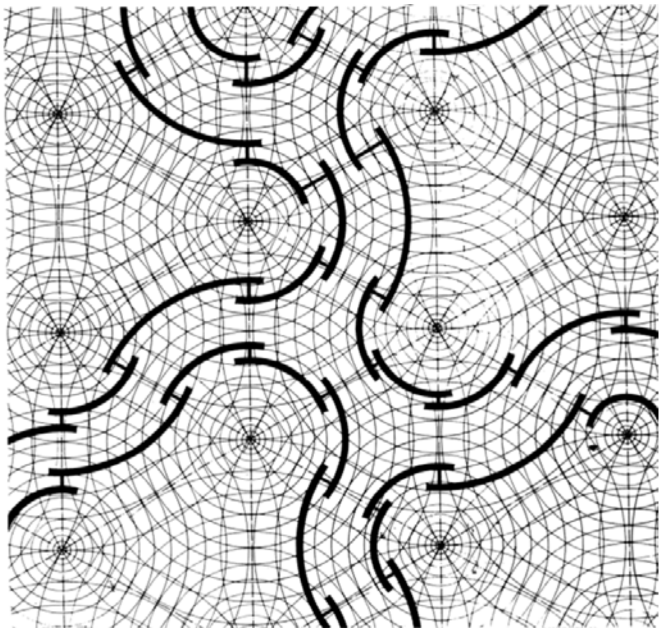

Fig. 1: The hypothetical "perceptual field" of an architectural environment in the plan view. The thick lines represent walls. Each set of concentric curves represents the potential perceptual effect of the corresponding wall. Jointly, the overlapping sets of concentric curves form the "perceptual field." The drawing is by Paolo Portoghesi, reproduced and discussed at length in Rudolf Arnheim's *The Dynamics of Architectural Form*, University of California Press, 1977, p. 30.

A conception similar to that illustrated in Fig. 1 was pursued by an interdisciplinary team at the intersection of neuroscience, architectural design, and narrative design.[3] Inspired by the notion of "behavioral field" in Gestalt theory, and using psychophysical methods for measuring boundaries of experience, the team developed a quantitative model that captures the organization of visual experience in large dynamic environments.

In this model, every environmental feature is deemed to generate a *solid region of visibility*:[4] a pocket of space that contains information about the feature. Such regions for different features can overlap or nest in one another. For example, the two shaded rings in Fig. 2A are horizontal

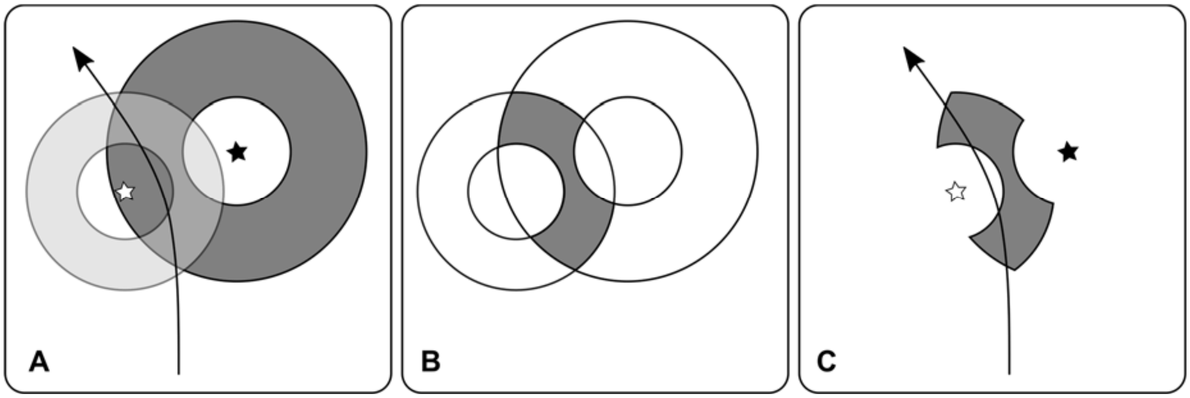

Fig. 2: Ring model of visibility. (A) A plan view of a large area with two objects represented by the black and white stars. The gray rings represent the regions from which the two objects are visible: the white object is visible from the bright ring and the black object is visible from the dark ring. The curved arrow stands for the trajectory of a mobile observer. (B) The dark shape represents the region of joint visibility: the intersection of two rings from panel A. (C) The mobile observer on the trajectory represented by the curved arrow will intermittently enter the region of joint visibility, where the arrow overlaps the dark shape.

sections of two solid regions.[5] In each ring, the outer and inner contours are boundaries of visibility of the features represented by the two stars. The model is derived from extensive prior measurements of visibility in the *cinematic mode* of experience, where optical patterns are viewed on a flat screen from a fixed distance.[6] The new model is designed to predict perception in solid space, i.e., in the *immersive mode* of experience.

Fig. 3: A setup for measuring solid regions of visibility. A screen and projector are mounted on robotic arms at a fixed distance from one another. An observer facing the screen is seated between the rails carrying the robots. Prompted by periodically acoustic signals, the observer reports his experience in response to visual patterns presented on the screen.

First steps in testing the model were entertained in a proof-of-concept study at UCLA Department of Architecture and Urban Design using large-scale robotics (Fig. 3). First, the team measured the solid region of visibility of static optical patterns. Under some conditions, visibility was found to change from zero to maximum over a distance of less than a meter, suggesting that different visual information can be delivered to people stationed at different distances from the same visual panel. Second, visibility was measured for dynamic patterns. Predicted by the model (Endnote 2), boundaries of visibility for dynamic patterns were different from static patterns, allowing for precise control of locations where a pattern is visible by varying the amount of motion.

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[1] The lectures are translated into English as Merleau-Ponty, M (2004). *The World of Perception*. London: Routledge. The lectures summarize Merleau-Ponty's argument about the "primacy of perception" presented in full in his magnum opus *Phenomenology of Perception*. The "opaqueness" of the classical picture of the world is discussed at length in Merleau-Ponty, M (1964). Eye and Mind [L'Œil et l'esprit] in *The Primacy of Perception* ed. by Edie J, Evanston: Northwestern University Press, 1964, pages 159-190.

[2] For example, see Watson AB, Ahumada AJ. (2016). The pyramid of visibility. *Human Vision and Electronic Imaging*, 2016, 1-6, and Gepshtein S, Lesmes LA, Albright TD (2013). Sensory adaptation as optimal resource allocation. *Proceedings of the National Academy of Sciences of the United States of America*, 110(11):4368–4373. Also see Pelli DG, Farell B (2010). Psychophysical methods. In Bass M, DeCusatis C, Enoch J, et al., editors, *Handbook of Optics*, Third Edition, Volume III: *Vision & Vision Optics*, pp. 3.1–12. McGraw-Hill, New York.

[3] The team was led by the scientist Sergei Gepshtein of the Salk institute for Biological Studies, the architect Greg Lynn of the University of California at Los Angeles, and the narrative designer Alex McDowell, RDI, of the University of Southern California. The project was funded in part by the inaugural Harold Hay Research Grant from the Academy of Neuroscience for Architecture.

[4] Here "solid" refers to three-dimensional, volumetric aspects of space.

[5] Such transitions from visible to invisible are gradual (see Endnote 6). Here the transitions are represented by lines instead of gradients for clarity. The lines are placed in the middle of the graded transitions.

[6] Visibility of optical patterns is a graded and readily measurable quantity. An established measure of pattern visibility is *contrast sensitivity*. A fundamental characteristic of vision that describes contrast sensitivity to the full range of standard optical patterns is called *contrast sensitivity function*. The first version of the model described here was derived from this function. For an introduction to the history and methods of measurement of contrast sensitivity, see Robson JG (1993). Contrast sensitivity: One hundred years of clinical measurement. In Shapley RM, Lam D, editors, *Contrast Sensitivity*, pages 253–267. MIT Press. For a review of how contrast sensitivity depends on temporal properties of patterns, see Kelly DH (1979). Motion and vision II. Stabilized spatio-temporal threshold surface. *Journal of the Optical Society of America*, 69 (10):1340–1349.

3

BODY, MIND, AND IMAGINATION: THE MENTAL ESSENCE OF ARCHITECTURE

Juhani Pallasmaa

> *If the body had been easier to understand, nobody would have thought that we had a mind.*[1]
>
> *Richard Rorty*

Instead of stepping on the specialized ground of neuroscience, I wish to elaborate on the specific mental essence of architecture—a realm that is deeply biologically and culturally grounded, although poorly understood in both education and practice. It is my hope that the exciting doors that the biological and neurosciences are now opening will valorize the interaction of architecture and the human mind, and reveal hidden complexities that have thus far escaped measurement and rational analyses. In our postmodern society, dominated by shallow rationality and reliance on the empirical, measurable, and demonstrable, the embodied and mental dimensions of human existence are continually suppressed. I believe that neuroscience can lend support to the mental objectives in design and the arts, which are in danger of being eliminated because of their "practical" uselessness and apparent subjectivity. Architecture has its utilitarian qualities in the realm of rationality and measurability, but its mental value is most often concealed in embodied metaphors and ineffable unconscious interactions—it can only be experienced and encountered. As Jean-Paul Sartre argues, “Essences and facts are incommensurable, and one who begins his inquiry with facts will never arrive at essences … understanding is not a quality coming to human reality from the outside; it is its characteristic way of existing.”[2]

Rather than attempting to highlight the new insights of neuroscience that could be applicable to architecture, I have chosen to focus on the mental dimensions of building that could be valorized by new scientific research. I believe that neuroscience can reveal and reinforce the fundamentally mental, embodied, and biological essence of profound architecture against current tendencies toward increasing materialism, intellectualization, and commodification. I will attempt to illustrate the mental and spiritual qualities of architecture and art side by side, as I see the craft of architecture, in its existential and mental dimensions, also as an art form. No doubt, architecture is ontologically grounded in utility and technological reality, and this makes it equally decisively a nonart. While writing this essay at Taliesin West, Frank Lloyd Wright’s studio in the Arizonan desert, every morning I saw a quote of Frank Lloyd Wright printed on my tea mug: “I believe a house is more a home by being a work of art.”[3] For my purposes in this context, architecture is and is not an art, depending on one’s point of view.

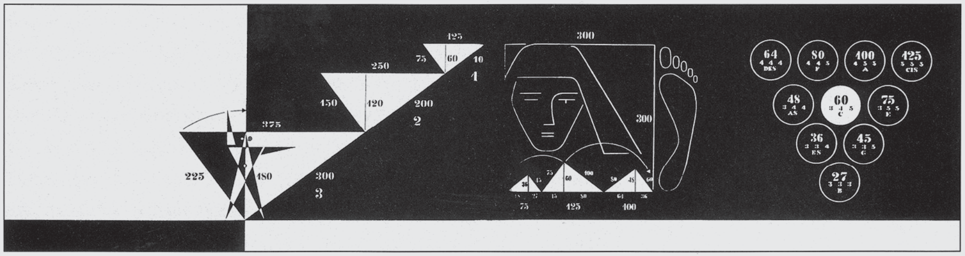
THE TASK OF ARCHITECTURE

The purpose of our buildings is too often understood solely in terms of functional performance, physical comfort, economy, symbolic representation and aesthetic values. However, the task of architecture extends beyond its material, functional, and measurable properties—and even beyond aesthetics—into the mental and existential sphere of life. Buildings do not merely provide physical shelter or facilitate distinct activities. In addition to housing our fragile bodies and actions, they must also house our minds, memories, desires and dreams. Buildings mediate between the world and our consciousness through internalizing the world and externalizing the mind. Structuring and articulating lived existential space and situations of life, architecture constitutes our most important system of externalized order, hierarchy, and memory.

We know and remember who we are as historical beings by means of our constructed settings. Architecture also concretizes “human institutions,” to use a notion of Louis Kahn’s, the layering of cultural structures, as well as the course of time. It is not generally acknowledged that our constructed world also domesticates and scales time for human understanding. Yet, architecture slows down, halts, reverses, or speeds up experiential time, and we can appropriately speak of slow and fast architectures. As the philosopher Karsten Harries suggests, architecture is "a defense against the terror of time."[4] It gives limitless and meaningless space its human measures and meanings, but it also scales endless time down to the limits of human experience; the mere memorized image of the Egyptian pyramids concretizes the distance of four thousand years in our consciousness. It is evident that architecture has the tendency to turn ever faster in our era of speed and acceleration. Finally, Gaston Bachelard assigns a truly monumental task to architecture: the house "is an instrument with which to confront the cosmos."[5] He criticizes the Heideggerian assumption of the basic human frustration arising from "being cast into the world," as, in his view, we are born "in the cradle of architecture,"[6] not cast into meaningless space. Indeed, until the Renaissance, the main mental task of architecture was to mediate between macrocosm and microcosm, the divinities and the mortals. "With the Renaissance revival of the Greek mathematical interpretation of God and the world, and invigorated by the Christian belief that Man as the image of God embodied the harmonies of the Universe, the Vitruvian human figure inscribed in a square and a circle became a symbol of the mathematical sympathy between microcosm and macrocosm," Rudolf Wittkower informs us.[7] Today, architecture has become mere utility, technology and visual aesthetics, and we can sadly conclude that it has abandoned its fundamental metaphysical task.

3.1 In addition to "domesticating" physical space for human use and grasp, architecture "tames" time for human understanding. The Great Pyramids of Gizeh. Photograph by Don Mammoser, Shutterstock.com.

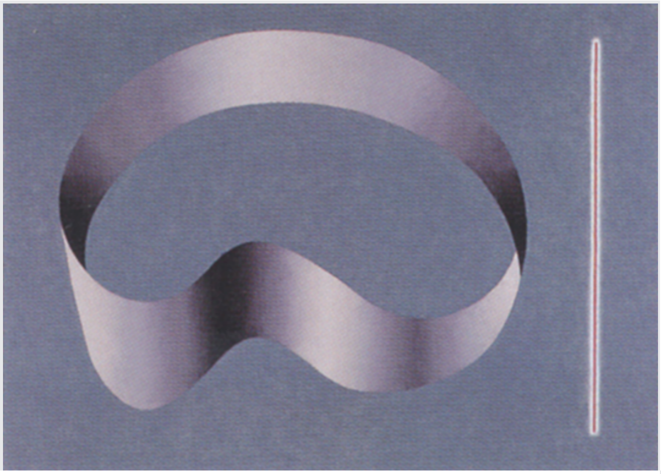
The human essence of architecture cannot be grasped at all unless we acknowledge its metaphoric, mental, and expressive nature. “Architecture is constructed mental space,” Finnish professor Keijo Petäjä used to say.[8] In the Finnish language, this formulation projects two meanings simultaneously: architecture is a materialized expression of human mental space; and our mental space is itself structured and extended by architecture. This idea of a dialectical relationship, or interpenetration of physical and mental space, echoes Maurice Merleau-Ponty’s phenomenological notion “the chiasmatic bind”[9] of the world and physical space, on the one hand, and the self and mental space, on the other. In his view this relationship is a continuum, not a polarity. The chiasmatic continuum of outer physical and inner psychic space can, perhaps, be illustrated by the enigmatic image of the Moebius strip, a looping ring that has only one continuous surface. It is exactly this chiasmatic merging and mirroring of the material and the mental that has rendered artistic and architectural phenomena immune to an empirical scientific approach; the artistic meaning exists in the experience of the material realm, and this experience is always unique, situational, and individual. Artistic meaning exists only on the poetic level in our direct encounter with the work, and it is existential rather than ideational—emotional rather than intellectual. Merleau-Ponty also introduced the suggestive notion of “the flesh of the world,”[10] the continuum of the world, which we are bound to share with our bodies as well as with our architecture. In fact, we can think of works of architecture as specific articulations of this very existential and experiential flesh.



3.2 Pythagorean studies in mathematically based harmony were revitalized during the Renaissance, and again during the twentieth century. The aim of Pythagoreanism is to create a shared harmonic ground for visual phenomena and music. Aulis Blomstedt, Canon 60, around 1960. Professor Blomstedt’s system of measures and proportions is based on ten basic numbers and their musical equivalents. Courtesy of the Aulis Blomstedt Estate, Helsinki.

FORMAL AND EXPERIENTIAL SPACE

Like most architects my age, I was educated to regard our craft primarily as the construction of visual and aestheticized spatial structures possessing distinct formal characteristics and qualities. Gradually, I have learned to confront buildings experientially as encounters between physical structures and my own existential sense through internalizing multisensory perception. This encounter turns physical and geometric space into existential and lived space, and I become myself an ingredient and measure of the experience itself. This understanding puts the experiencing individual in the very center of the experience. In my way of thinking, a sincere architect cannot authentically design a house facing the client as an external other; the architect has to internalize the client, to turn himself into the client, and eventually design the building for him/herself. At the end of the design process, the architect offers the house to the real dweller as a gift. Profound architecture is always a gift of imagination, as it necessarily transcends its given points of departure and factual conditions. It is always bound to contain qualities that no one could have expected or foreseen. This process is similar to the gift a woman makes when she offers her womb to give life to a child on behalf of a woman who is physiologically unable to bear one. Architecture is born of imaginative empathy, and the talent of compassion is as important to the architect as formal fantasy.



3.3 Juhana Blomstedt (painter son of architect Aulis Blomstedt), *Model and the Artist* (1049) from the Moebius Series, 2003. Oil on canvas, 50 × 50 cm. Private collection. Courtesy of Juhana Blomstedt.

BOUNDARIES OF THE SELF

"What else could a poet or painter express than his encounter with the world?" Merleau-Ponty asks.[11] An architect is bound to articulate this very same personal encounter, regardless of the basic utility and rationality of his/her task and the fact that he/she is engaged primarily in creating settings for others. This might sound like a self-centered position, but in fact, it emphasizes and concretizes the subtlety of the designer's human responsibility. In an essay written in memory of Herbert Read, Salman Rushdie suggests: "Literature is made at the boundary between self and the world, and during the creative act this borderline softens, turns penetrable and allows the world to flow into the artist and the artist to flow into the world."[12] Profound works of architecture also sensitize the boundary between the world and ourselves; I experience this moment and my relationship with the world in a deep and meaningful manner. The architectural context gives my experience of being its unique structure and meaning through projecting specific frames and horizons for my perception and understanding of my own existential situation. The poetic experience brings me to a borderline—the boundary of my perception and understanding of self—and this encounter projects a sense of existential meaningfulness.

3.4 Balthus (Balthazar Klossowski de Rola), *Les Beaux Jours* (The Happy Days), 1944–1946. Oil on canvas, 148 × 200 cm. Hirshhorn Museum and Sculpture Garden, Smithsonian Institution, Washington. Courtesy of Harumi Klossowska de Rola.

SELF-EXPRESSION AND ANONYMITY

Particularly in today's artistic world that seeks novelty and effect, the arts and architecture are seen as modes of the artist's and architect's self-expression. I have become increasingly doubtful about this attitude. Balthus (Balthazar Klossowski de Rola), one of the greatest figurative painters of the twentieth century, is critical of the idea of artistic self-expression: “If a work only expresses the person who created it, it was not worth doing. … Expressing the world, understanding it, that is what seems interesting to me.”[13] This is a rather unexpected attitude from an apparently very self-absorbed painter. He goes even further to demand a distinct anonymity in artistic works: “Great painting has to have universal meaning. This is really no longer so today and this is why I want to give painting back its lost universality and anonymity, because the more anonymous painting is, the more real it is.”[14] Again, I suggest that the same criterion applies to the field of architecture, but this is certainly an unfashionable view in today’s world obsessed with formal uniqueness and global star architecture.

UNITING THE OPPOSITES

Merleau-Ponty formulates the idea of the world as the primary subject matter of art (and architecture, we might add) as follows: “We come to see not the work, but the world according to the work.”[15] As we come to see Frank Lloyd Wright’s Taliesin West, we end up experiencing the landscape, as well as our own sense of existence and self altered, refined, and dignified by the magic of architecture. As we enter this compound, we are placed center stage to experience the desert and the sky, light and shadows, intimacy and vastness, materiality and weightlessness, nearness and distance, in a manner that we have not experienced them before. We are invited inside a unique ambience, an artistically structured world of embodied experiences, which addresses our sense of being, balance, horizon, and temporal duration in a way that bypasses rationality and logic. This architecture seems to have been here forever, exuded by the earth itself like the plants of the desert, but the principles and constituents of this convincing unity seem to be beyond rational and verbal analyses. We simply feel it with the same accuracy that we grasp the


3.5 Frank Lloyd Wright’s Taliesin West is simultaneously an integral part of the Arizonan desert landscape and its geometric and tectonic counterpole. Architecture underlines the landscape and heightens its character. Frank Lloyd Wright, Taliesin West Studio, Scottsdale, Arizona, 1937–1938. Courtesy of the Frank Lloyd Wright Foundation.

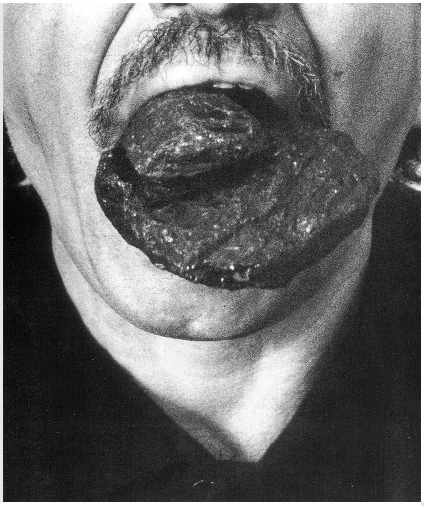
nature of a landscape with all its life forms, or "understand" the weather. As Alvar Aalto, the Finnish master and Wright's friend, once wrote: "In every case [of creative work] one must achieve the simultaneous solution of opposites. Nearly every design task involves tens, often hundreds, sometimes thousands of contradictory elements, which are forced into a functional harmony only by man's will. This harmony cannot be achieved by any other means than those of art."[16]

In the case of the settings of Taliesin West, the opposites of caving in and flight, separation and togetherness, enclosure and vista, gravity and weightlessness, visuality and hapticity, shadow and softened light, give rise to a superbly orchestrated ensemble of experiences. These experiences seem to have the invigorating richness and unpredictability of natural phenomena, held together by an undefinable artistic cohesion, or atmosphere. This place feels like a primordial ritual setting and a utopian community, a futuristic image and a ruin—all at once. It unites earth and sky, the realms of mortals and divinities. Indeed, architecture is logically an "impure" discipline in its fusion of irreconcilable ingredients, facts and beliefs, quantities and qualities, means and ends.

3.6 Wright's architecture is highly atmospheric and projects a haptic feeling with its varied geometry, formal themes, rhythms, tactile materials, and illumination. Frank Lloyd Wright, Taliesin West Residence, Scottsdale, Arizona, 1937–1938. Courtesy of the Frank Lloyd Wright Foundation.

THE SECRET CODE

The mental content and meaning of an architectural experience is not a given set of facts or elements; it is a unique imaginative reinterpretation and re-creation by each individual. The experienced meanings of architecture are not primarily rational, ideational or verbal meanings, as they arise through one's sense of existence by means of embodied and unconscious projections, identifications and empathy. Architecture articulates and "thickens" our sense of being instead of addressing the domain of rational understanding. The British architect, writer, and educator Sir Colin St. John Wilson illuminates this secret, prereflective power of architecture like this: "It is as if I am manipulated by some subliminal code, not to be translated into words, which acts directly on the nervous system and imagination, at the same time stirring intimations of meaning with vivid spatial experience as though they were one thing. It is my belief that the code acts so directly and vividly upon us because it is strangely familiar; it is in fact the first language we ever learned, long before words … now recalled to us through art, which alone holds the key to revive it."[17]



3.7 Art and architecture communicate through an nonverbal and nonideational language that addresses our deeply embodied biocultural memories and instinctual reactions. Jannis Kounellis, *Porta Murata (Walled Door)*, 1990. Carbon, mouth of the artist. Courtesy of Artists Rights Society (ARS), New York/SIAE, Rome. © 2014.

In his book *The Philosophy of No: A Philosophy of the New Scientific Mind*, written in 1940, Gaston Bachelard describes the historical development of scientific thought as a set of progressively more rationalized transitions from animism through realism, positivism, rationalism and complex rationalism, to dialectical rationalism.[18] "The philosophical evolution of a special piece of scientific knowledge is a movement through all those doctrines in the order indicated," the philosopher argues.[19] In my personal view, profound art and architecture struggle to advance in the reverse direction back toward an animistic relationship with the world, in which we project the world, or we are the world, instead of being outsiders and passive observers. Besides, art is more concerned with our past than with the future. A poetic understanding takes place through unconscious identification, simulation, and internalization. While rational understanding calls for a critical distance and separation from the subject, poetic "understanding" requires nearness, identification, and empathy.

IDENTIFICATION AND EMPATHY

As research has recently revealed, we have a surprising capacity to mirror the behavior of others, and even to unconsciously animate inanimate material constructions and objects. According to Joseph Brodsky, the call of a great poem is to "Be like me."[20] A profound building makes a similar suggestion: "Be a bit more sensitive, perceptive and responsible, experience the world through me." The world of art and architecture is fundamentally an animistic world awakened to life by the projection of our own intuitions and feelings. Paul Valéry regards buildings as entities with distinct voices: "Tell me (since you are so sensitive to the effects of architecture), have you not noticed, in walking about this city, that among the buildings with which it is peopled, certain are *mute*; others *speak*; and others, finally—and they are the most rare—*sing*?"[21] In this sense of searching for an animated and lived world, the artistic intention directly conflicts with science's aim to objectify.

We have an amazing capacity to grasp complex environmental entities through simultaneous multisensory sensing of atmospheres, feelings, and moods. This capacity to instantaneously grasp existential essences of vast entities, such as spaces, places, landscapes and entire cities, suggests that we intuit entities before we identify their parts and details. When discussing the roles of the brain's hemispheres, Iain McGilchrist points out: "The right hemisphere understands the whole not simply as the result of assembling a bunch of fragments, but rather as an entity prior to the existence of the fragments. There is a natural hierarchy of attention, global attention coming first. … You have to see it [an image] as a whole first."[22]

Almost eighty years ago, John Dewey, the visionary pragmatist philosopher, pointed out the significance of such a unifying character and cohesive identity: “An experience has a unity that gives it its name. … The existence of this unity is constituted by a single *quality* that pervades the entire experience in spite of the variation of its constituent parts. This unity is neither emotional, practical, nor intellectual, for these terms name distinctions that reflection can make within it.”[23] “The quality of the whole permeates, affects, and controls every detail,” Dewey adds.[24] Sarah Robinson recently pointed out to me a perceptive remark of Frank Lloyd Wright on the power of atmosphere: “Whether people are fully conscious of this or not, they actually derive *countenance* and *sustenance* from the ‘atmosphere’ of things they live in and with.”[25] This view of the dominance of unified entities over “elements” casts serious doubt on the prevailing elementarist theories and teaching methods in education.

THE ATMOSPHERIC SENSE

I have become so impressed with the power of our atmospheric judgment that I want to suggest that this capacity could be named our sixth sense. Thinking only of the five Aristotelian senses in architecture fails to acknowledge the true complexity of the systems through which we are connected to the world. Steinerian philosophy, for instance, deals with twelve senses,[26] whereas a recent book, *The Sixth Sense Reader*, identifies more than thirty categories of sensing through which we relate to and communicate with the world.[27] This idea of a wider human sensorium underlines the fact that our being-in-the-world is much more complex and refined than we tend to understand. That is why understanding architecture solely as a visual art form is hopelessly reductive. Besides, instead of thinking of the senses as isolated systems, we should become more interested in and knowledgeable about their essential interactions and crossovers. Merleau-Ponty emphasizes this essential unity and interaction of the senses: “My perception is … not a sum of visual, tactile, and auditive givens: I perceive in a total way with my whole being. I grasp a unique structure of the thing, a unique way of being, which speaks to all my senses at once.”[28] This flexibility and dynamic of our interaction with the world is one of the important things that neuroscience can illuminate for us. The craft of architecture is deeply embedded in this human sensory and mental complexity.

This criticism of the reductive isolation of the senses also applies to the common understanding of intelligence as a singular intellectual capacity. Contrary to the common understanding of intelligence as a definite cerebral category, psychologist Howard Gardner suggests seven categories of intelligence, namely linguistic, logical-mathematical, musical, bodily-kinesthetic, spatial, interpersonal, and intrapersonal intelligences, to which he later adds three further categories: naturalistic, ethical, and spiritual intelligences.[29] I would add four further categories to Gardner's list: emotional, aesthetic, existential, and atmospheric intelligences. So, we may well have a full spectrum of a dozen modes of intelligence instead of the single quality targeted by IQ tests. The complex field of intelligence also suggests that architectural education, or education at large, faces a much wider task, and at the same time possesses far greater potential, than standard pedagogy has thus far accepted. Education in any creative field must start primarily with the student's sense of self, as only a firm sense of identity and self-awareness can serve as the core around which observation, knowledge, and eventually wisdom can evolve and condense.

HUMAN BIOLOGICAL HISTORICITY

We also need to accept the essential historical and embodied essence of human existence, experience, cognition, and memory. In our bodies we can still identify the remains of the tail from our arboreal life; the pink triangular area in our eye corners, the *plica semilunaris*, is the remnant of our horizontally moving eyelid from the Saurian age; and even the traces of gills derive from our aquatic life hundreds of millions of years ago. We certainly have similar imprints in our mental constitution that derive from our biological and cultural historicity; one aspect of such deeply concealed memory was pointed out by Sigmund Freud and Carl G. Jung—namely, the archetype.[30] I want to add here that Jung defined archetypes dynamically, as certain tendencies for distinct images to evoke certain types of associations and feelings. So, even archetypes are not concrete or given "building blocks" in artistic creation—as postmodernists seemed to believe—but dynamic and interacting mental forces with lives of their own.

Architecture, also, has its roots and mental resonances in our biological historicity. Why do we all sense profound pleasure when sitting by an open fire, if not because fire has offered our predecessors safety, pleasure, and a heightened sense of togetherness for some fifty thousand years? Vitruvius, in fact, dates the beginning of architecture to the domestication of fire. The taming of fire actually gave rise to unexpected changes in the human species and its behavior. "Control over fire changed human anatomy and physiology and became encoded in our evolving genome," argues Stephen Pyne, who attributes the changes in human teeth and intestinal structures to the consequences of eating cooked food.[31] Some linguistic scholars have suggested that language also originates in the primordial act of gathering around the fire. Such biopsychological heritage, especially the polarity of "refuge" and "prospect," has been observed in Frank Lloyd Wright's houses by Grant Hildebrandt.[32] The writer suggests that the master architect intuited the meaning of this spatial polarity decades before ecological psychology touched upon the phenomenon. The studies of the American anthropologist Edward T. Hall, in the 1960s, revealed unbelievably precise unconscious mechanisms in the use of space and its culture-specific parameters.[33] "Proxemics," the new field of study Hall initiated, is based on such unconscious spatial mechanisms. He acknowledges the external communication between our endocrine glands, in opposition to the prevailing scientific view that these glands have only internal metabolic functions—yet another example of the ambiguity of the boundary of the self.[34] In her chapter "Nested Bodies" in this book, Sarah Robinson points out the bioelectric and magnetic fields originating in the body, which extend our bodies beyond the boundary of the skin.[35] Finally, philosopher Martin Jay's remark "With vision we touch the sun and the stars"[36] turns us into true cosmological beings.

3.8 The domestication of fire strengthened the social bond and permitted interaction between the members of the group during the period of darkness. Vitruvius dates the origins of architecture to the taming of fire, while some contemporary scholars suggest that the unifying impact of fire served as a factor in the evolution of language. Image credit: My Good Images/Shutterstock.com.

Such studies are surely only beginning to reconnect modern man, *Homo faber*, back to his biological roots; and we look to neuroscience to valorize the internal workings of these physiological, genetic, and instinctual capacities and reactions. Neurological studies can reveal the neural ground for our fundamental spatial and environmental pleasures and displeasures—as well as our feelings of comfort, safety, and fear.

Merleau-Ponty makes the significant remark: “The painter takes his body with him. … Indeed, we cannot imagine how a mind could paint.”[37] The same must certainly be said about architects, as our craft is unavoidably constituted in our embodied manner of existence; and architecture articulates that very mode of being. In my way of thinking, architecture is more an art of the body and existential sense than one of the eye (even vision serves our existential sense of being)—more one of emotive and unconscious feelings than rational deduction. This is where the logocentric and overintellectualized theorizing of architecture, so popular in the recent past, has gone decisively wrong. But, again, neuroscience can probably valorize these interactions, hierarchies, and priorities. I believe that research in the biological and neurosciences will confirm that our experiences of architecture are in fact grounded in the deep and unconscious layers of our mental life.

3.9 Alvar Aalto’s “Extended Rationalism” and fusion of opposites; the living space of the Villa Mairea merges images of tectonic architectural space and amorphous forest space, modern Utopia and peasant tradition. Alvar Aalto, Villa Mairea, Noormarkku, Finland, 1938–1939. Photograph courtesy of Rauno Träskelin.

I am not speaking against attempts to grasp the structure or logic of experiential phenomena; I am merely concerned about a reductivist or biased understanding of architectural phenomena. The study of artistic phenomena also calls for appropriate methods of study. In the mid-1930s, Alvar Aalto wrote about “an extended Rationalism,” and urged architects to expand rational methods even to the psychological (Aalto used the terms "neurophysiology" and "psychophysical field") and mental areas.[38] Both Wright's and Aalto's masterworks are examples of an architecture that benevolently embraces us, which can hardly be explained intellectually. This is an architecture that is directly connected with our human nature by the architect's own intuited wisdom. No doubt, great architects throughout history have always intuitively grasped the essence of human mental life—both individual and collective. Does not the notion of genius imply capacities of intuiting entities, interrelations, and causalities beyond the boundaries of established knowledge?

We are mentally and emotionally affected by works of architecture and art before we understand them; or, indeed, we usually do not "understand" them at all. I would argue that the greater the artistic work, the less we understand it intellectually. Do we really understand Michelangelo's Rondadini *Pietà*, Giorgione's *Tempest*, or Rembrandt's portraits? No—they will always remain unexplainable jewels of our experiential world. A distinct mental short-circuiting between a lived emotional encounter and intellectual understanding is a constitutive characteristic of the artistic image. Jean-Paul Sartre points out the essential fusion of the object and its experience in the artistic encounter: "Tintoretto did not choose that yellow rift in the sky above Golgotha to signify anguish or to provoke it. Not sky of anguish or anguished sky; it is an anguish become thing, an anguish which has turned into yellow rift of sky. … It is no longer readable."[39] In fact, art is not about understanding at all; an artistic image is an existential encounter which momentarily reorients our entire sense of being: just think of the mysterious powers of music. Great works possess a timeless freshness; they project their enigmas always anew—making us feel each time that we are experiencing the work for the first time. I like to revisit architectural and artistic masterpieces around the world to repeatedly encounter their magical sense of newness and freshness. The greater the work, the

3.10 Tintoretto's painting of a dramatic subject projects a strong atmosphere that unifies the multitude of narrative and pictorial ingredients into a cohesive and emotionally embracing ensemble. The parts cannot be distinguished from the impact of the whole. Jacopo Tintoretto (Jacopo Comin), *Crucifixion*, 1565. 518 × 1224 cm. Scuola di San Rocco, Venice.

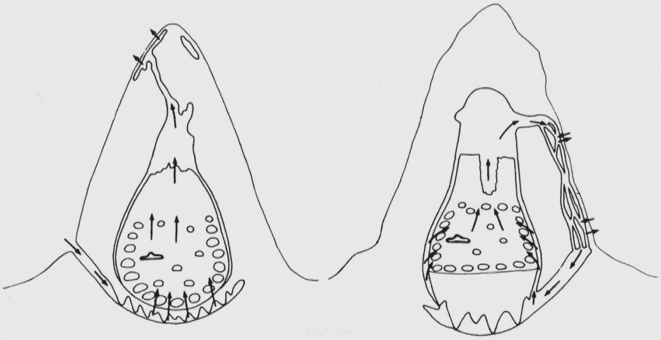
stronger its resistance to time. As Paul Valéry suggests, "An artist is worth a thousand centuries."[40] The hypnotic power of the cave paintings testifies to this longevity of artistic images. The interaction of newness and the primordial in the human mind is yet another aspect of the artistic and architectural image that can be understood through neuroscientific research, I believe. Our neural system seems to be activated by newness, and we seek novel stimuli, whereas the deepest emotive impact arises from the primal layers of our neural system and memory. We humans are essentially creatures suspended between the past and the future more poignantly than other forms of life—it is the task of art to mediate between these polarities.

ARTISTS AS "NEUROLOGISTS"

Semir Zeki, a neurologist who studies the neural ground of artistic image and effect, considers a high degree of ambiguity—such as the unfinished imagery of Michelangelo's slaves, or the ambivalent human narratives of Johannes Vermeer's paintings—to be essential to the greatness of these works.[41] In reference to the great capacity of profound artists to evoke, manipulate, and direct emotions, he posits the surprising argument: "Most painters are also neurologists … they are those who have experimented with and, without ever realizing it, understood something about the organization of the visual brain, though with the techniques that are unique to them."[42] This statement interestingly echoes an argument of the Dutch phenomenologist-therapist J. H. Van den Berg: "All painters and poets are born phenomenologists."[43] Artists and architects are phenomenologists in the sense of being capable of "pure looking," an unbiased and "naive" manner of encountering things. In fact, Bachelard advises practitioners of the phenomenological approach "to be systematically modest" and "to go in the direction of maximum simplicity."[44] A recent book, *Proust Was a Neuroscientist* by Jonah Lehrer, popularizes this topic, arguing that certain masterly artists, such as Walt Whitman, Marcel Proust, Paul Cézanne, Igor Stravinsky, and Gertrude Stein, anticipated some of today's crucial neurological findings through their art more than a century ago.[45] In his important books *The Architect's Brain* and *Architecture and Embodiment*, Harry F. Mallgrave connects the latest findings in the neurosciences with the field of architecture directly in accordance with the objective of this book.[46]

In *Inner Vision*, Semir Zeki suggests the possibility of "a theory of aesthetics that is biologically based."[47] Having studied animal building behavior and the emergence of "aesthetically" motivated choices in the animal world for forty years, I have no doubt about this. What else could beauty be than nature's powerful instrument of selection in the process of evolution? Joseph Brodsky assures us of this with the conviction of a poet: “The purpose of evolution, believe it or not, is beauty.”[48]

It is beyond doubt that nature can teach us great lessons about design, particularly about ecologically adapted design and dynamic processes. This can be seen in emerging fields of study, such as bionics and biomimicry. Several years ago, I had the opportunity to participate in a conference in Venice entitled “What Can We Learn from Swarming Insects?” organized by the European Center for Living Technologies. The participants were biologists, mathematicians, computer scientists, and a couple of architects. The purpose of the encounter was to gain understanding, through recent research findings and computer simulations, of the miraculous capacities of ants, termites, bees, and wasps to construct perfectly adapted nests and wider environmental systems, such as fungus farms and covered road networks. So far, the chain of collective and instinctual actions that enable termites to construct a vault has been simulated, but the embodied collective knowledge that enables them to construct their nest as an artificial lung to sustain the life of a community of millions of individuals remains far beyond our understanding.[49] We can surely expect more of such deliberations in the future. Edward O. Wilson, the world’s leading myrmecologist and pioneer of biophilia, “the new ethics and science of life,” makes the dizzying argument that “the superorganism of a leaf-cutter ant nest is a more complex system in its performance than any human invention, and unimaginably old.”[50]



3.11 Miracles of functional design in the animal world: *Microtermes bellicosus* termite nest from the Ivory Coast (left) and Uganda (right). The arrows indicate the directions of air flows. Termites of a single species living in the coastal and inland climatic conditions seem to be able to construct two different air-conditioning systems for their nest depending on the climate. Courtesy Turid Hölldobler-Forsyth; in Karl von Frisch and Otto von Frisch, *Animal Architecture* (New York: Harcourt Brace Jovanovich, 1974).

In his study on the neurological ground of art, Zeki argues that "art is an extension of the functions of the visual brain in its search for essentials."[51] I see no reason to limit this idea of extension, or externalization, only to the visual field. I believe that art provides momentary extensions of the functions of our perceptual systems, consciousness, memory, emotions, and existential "understanding." The great gift of art is to permit us ordinary mortals to experience something through the perceptual and emotive sensibility of some of the greatest individuals in human history. We can feel through the neural subtlety of Michelangelo, Bach, and Rilke, for instance. And again, we can undoubtedly make the same assumption about meaningful architecture; we can sense our own existence amplified and sensitized by the works of great architects from Ictinus and Callicrates to Frank Lloyd Wright and Louis Kahn.

The role of architecture as a functional and mental extension of our capacities is clear, and in fact Richard Dawkins has described various aspects of this notion among animals in his book *The Extended Phenotype*;[52] he suggests that such fabricated extensions of biological species should be made part of the phenotype of the species in question. So, dams and water regulation systems should be part of the phenotype of the beaver, and the astounding nets of the spider. Works of meaningful architecture intuitively grasp the essence of human nature and behavior, in addition to being sensitive to the hidden biological and mental characteristics of space, form, and materiality. By intuiting this knowledge, sensitive architects are able to create places and atmospheres that make us feel safe, comfortable, invigorated, and dignified without being able to conceptually theorize their skills at all. In this context, I have earlier used the notion "a natural philosophy of architecture," a wisdom that arises directly from an intuitive and lived understanding of human nature, and architecture as an extension of that very nature. Simply, great architecture emanates unspoken but contagious existential wisdom.

THE GIFT OF THE IMAGINATION

The imagination is arguably the most human of our capacities. Although it is often considered to be a kind of daydreaming, and sometimes even as something suspect, our most basic activities, such as perceiving and memorizing places, situations and events, rely on our imagination. The acts of experiencing and memorizing are embodied acts, which evoke imaginative realities with specific meanings. The existence of our ethical sensibility alone calls for imaginative skills, as we could not evaluate our alternative behavioral choices without the ability to imagine their consequences. Recent studies have revealed that the acts of perceiving and imagining take place in the same areas of the brain;

consequently, these act are closely related.[53] "Every act of perception is an act of creation," argues neurophysiologist Gerald Edelman, as Sarah Robinson notes.[54] Or, "attention is a deeply creative act," as McGilchrist points out.[55] Perceptions call for imagination, as percepts are not automatic products of the sensory mechanism; they are essentially interpretations, projections, creations, and products of intentionality and imagination. We could not even see light without our "inner light" and "formative visual imagination," argues the physicist Arthur Zajonc.[56] To conclude: "Reality is a product of the most august imagination," as the poet Wallace Stevens suggests.[57]

We do not judge environments merely by our senses, we also test and evaluate them through our imagination. Comforting and inviting settings inspire our unconscious imagery, daydreams, and fantasies. Sensuous settings sensitize and eroticize our relationship with the world. As Bachelard argues, the "chief benefit of the house [is that] the house shelters daydreaming, the house protects the dreamer, the house allows one to dream in peace. … The house is one of the greatest powers of integration for the thoughts, memories and dreams of mankind."[58]

BODY AND IMAGINATION IN THE ARTS

I have found the study of other art forms very illuminating for the understanding of the mental phenomena in architecture, because the subtleties of our mental reactions are usually confused or suppressed by more practical and rational considerations in the craft of architecture. The processes of literary imagination are interestingly discussed in Elaine Scarry's recent book *Dreaming by the Book*. In her view, great writers—from Homer, Flaubert, and Rilke to today's masters of literature, such as Seamus Heaney—have intuited, through words, how the brain perceives images. She explains the vividness of a profound literary text: "In order to achieve the 'vivacity' of the material world, the verbal arts must somehow also imitate its 'persistence' and, most crucially, its quality of 'givenness.' It seems almost certainly the case that it is the 'instructional' character of the verbal arts that fulfills this mimetic requirement for 'givenness.'"[59] It is the experience of givenness, naturalness, and inevitability that is missing in today's architecture of intellectual games and formal invention.

The Czech writer Bohumil Hrabal vividly describes the concreteness and embodied nature of literary imagination: "When I read, I don't really read: I pop up a beautiful sentence in my mouth and suck it like liqueur until the thought dissolves in me like alcohol, infusing my brain and heart and coursing on through the veins to the root of each blood vessel."[60] Permit me to give yet another example of the embodied nature of poetry. Charles Tomlinson, a poet, observes the bodily basis even of the practices of painting and poetry: "Painting wakes up the hand, draws in your sense of muscular coordination, your sense of the body, if you like. Poetry, also, as it pivots on its stresses, as it rides forward over the line-endings, or comes to rest at pauses in the line, poetry also brings the whole man into play and his bodily sense of himself."[61] Surprisingly, Henry David Thoreau already grasped the significance of the body in poetry: "The poet creates the history of his own body."[62] It is, of course, clear that architecture is the art form that "brings the whole man into play and his bodily sense of himself," exactly in accordance with Tomlinson's description above. Architecture is born of the body, and when we experience profound architecture we return to the body.

3.12 Every significant work of art is a complete microcosm, a metaphoric universe of its own. Morandi's still lifes of timid objects on a table top turn into instruments for intense metaphysical contemplation. Giorgio Morandi, *Still Life*, 1958. Oil on canvas, 25 × 40 cm. Private collection, Bologna. Courtesy of Artists Rights Society (ARS), New York/ SIAE, Rome. © 2014.

As our age seems to value fictions, fantasies, and virtual realities, I wish to include an example of the role of the sense of reality in artistic works. Jorge Luis Borges gives us important advice concerning the requirement for a sense of reality and artistic plausibility: "Reality is not always probable, or likely. But if you're writing a story, you have to make it as plausible as you can, because otherwise the reader's imagination will reject it."[63] Regardless of today's obsession with the fantastic image, architecture is similarly an art form of reality, not fantasy; architecture's task is to reinforce our sense of the real and, through doing that, to liberate our senses and imagination.

Profound works of architecture are not merely imaginary and aestheticized settings or objects; they are complete microcosmic worlds. “If a painter presents us with a field or a vase of flowers, his paintings are windows, which are open on the whole world,” Jean-Paul Sartre avers.[64] A Giorgio Morandi painting with a couple of shy vases and glasses on a table is in fact a metaphysical deliberation which invites the viewer to zoom into the most haunting question of all, that of being: why are there objects and things rather than not? Architecture, also, mediates similarly deep narratives of culture, place, and time, and it is essentially an epic art form, expressive of human life and culture. The content and meaning of art—even the most condensed poem, minimal painting, or simplest hut—is epic in the sense of being a lived metaphor of human existence in the world.

3.13 Louis I. Kahn, Library and Dining Hall, Phillips Exeter Academy, Exeter, New Hampshire, 1965–1972. All imposing works of architecture are spatial mandalas and metaphoric representations of the world. They enable us to feel “how the world touches us,” as Merleau-Ponty said of the paintings of Paul Cézanne. Photograph courtesy of Iwan Baan.

I wish to end with one of the most impressive statements about the mental quality of art that I have read. This poetic requirement distills my arguments about essential artistic condensation, and it also applies fully to architecture. As the master sculptor Constantin Brâncuşi advises us: “The work must give immediately, at once, the shock of life, the sensation of breathing.”[65]

NOTES

1. Richard Rorty, *Philosophy and the Mirror of Nature* (Princeton: Princeton University Press, 1979), 239.

2. Jean-Paul Sartre, *The Emotions: An Outline of a Theory* (New York: Carol Publishing, 1993), 9.

3. Frank Lloyd Wright quote on a teacup purchased at the Taliesin West book and gift shop.

4. Karsten Harries, "Building and the Terror of Time," *Perspecta: The Yale Architecture Journal*, no. 19 (1982).

5. Gaston Bachelard, *The Poetics of Space* (Boston: Beacon Press, 1969), 46.

6. Ibid., 7.

7. Rudolf Wittkower, *Architectural Principles in the Age of Humanism* (New York: Random House, 1965), 16.

8. Keijo Petäjä in numerous conversations with the author during the 1970s. The Finnish original reads: "Arkkitehtuuri on rakennettua mielen tilaa."

9. Maurice Merleau-Ponty, "The Intertwining—The Chiasm," in Merleau-Ponty, *The Visible and the Invisible*, ed. Claude Lefort (Evanston: Northwestern University Press, 1969).

10. Maurice Merleau-Ponty describes the notion of the flesh: "My body is made of the same flesh as the world … and moreover … this flesh of my body is shared by the world" (ibid., 248); and "The flesh [of the world or my own] is … a texture that returns to itself and conforms to itself" (146).

11. Maurice Merleau-Ponty, *Signs* (Evanston: Northwestern University Press, 1982), 56.

12. Salman Rushdie, "Eikö mikään ole pyhää? [Is nothing sacred?]," *Parnasso* (Helsinki) 1 (1996): 8. Trans. Juhani Pallasmaa.

13. Balthus, in Claude Roy, *Balthus* (New York: Little, Brown, 1996), 18.

14. Balthus, in *Balthus in His Own Words: A Conversation with Cristina Carrillo de Albornos* (New York: Assouline, 2001), 6.

15. Maurice Merleau-Ponty, as quoted in Iain McGilchrist, *The Master and His Emissary: The Divided Brain and the Making of the Western World* (New Haven: Yale University Press, 2010), 409.

16. Alvar Aalto, "Taide ja tekniikka" (Art and Technology), lecture, Academy of Finland, October 3, 1955, in Göran Schildt, *Alvar Aalto Luonnoksia* (Helsinki: Otava Publishers, 1972), 87–88. Trans. Juhani Pallasmaa.

17. Sir Colin St. John Wilson, "Architecture—Public Good and Private Necessity," *RIBA Journal* (March 1979): 107–115.

18. Gaston Bachelard, *The Philosophy of No: A Philosophy of the New Scientific Mind* (New York: Orion Press, 1968), 16.

19. Ibid.

20. Joseph Brodsky, "An Immodest Proposal," in Brodsky, *On Grief and Reason* (New York: Farrar, Straus and Giroux, 1997), 206.

21. Paul Valéry, "Eupalinos, or the Architect," in Valéry, *Dialogues* (New York: Pantheon Books, 1956), 83; original emphasis.

22. Iain McGilchrist, "Tending to the World," chapter 5 below.

23. John Dewey, *Art as Experience* (1934; New York: Perigee Books, 1980), 35; original emphasis.

24. Ibid., 73.

25. Frank Lloyd Wright; Sarah Robinson's information in a letter to the author, 20 January 2012. Original emphasis.

26. Albert Soesman, *Our Twelve Senses: Wellsprings of the Soul* (Worcester: Hawthorn Press , Stroud, Gloucestershire, UK, 1998).

27. *The Sixth Sense Reader*, ed. David Howes (New York: Berg, 2011), 23–24.

28. Maurice Merleau-Ponty, "The Film and the New Psychology," in Merleau-Ponty, *Sense and Nonsense* (Evanston: Northwestern University Press, 1964), 50.

29. Howard Gardner, *Intelligence Reframed: Multiple Intelligences for the 21st Century* (New York: Basic Books, 1999).

30. See Carl G. Jung et al., eds., *Man and His Symbols* (New York: Doubleday, 1968), 57.

31. Stephen J. Pyne, *Fire* (London: Reaktion Books, 2012), 47.

32. Grant Hildebrandt, *The Wright Space: Pattern and Meaning in Frank Lloyd Wright's Houses* (Seattle: University of Washington Press, 1992).

33. Edward T. Hall, *The Silent Language* (New York: Anchor Press, 1959); and *The Hidden Dimension* (New York: Doubleday, 1966).

34. Hall, *The Hidden Dimension*, 33–34. The writer refers to endocrinological research by Parkes and Bruce.

35. Sarah Robinson, "Nested Bodies," chapter 7 below.

36. Martin Jay, as quoted in David Michael Levin, ed., *Modernity and the Hegemony of Vision* (Berkeley: University of California Press, 1993), 14.

37. Maurice Merleau-Ponty, *The Primacy of Perception* (Evanston: Northwestern University Press, 1964), 162.

38. Alvar Aalto, "The Humanizing of Architecture," *Technology Review* (November 1940), as reprinted in *Alvar Aalto: Sketches*, ed. Göran Schildt (Cambridge, MA: MIT Press, 1979), 77, 78.

39. Jean-Paul Sartre, *What Is Literature?* (Gloucester, MA: Peter Smith, 1978), 3.

40. Valéry, *Dialogues*, xiii.

41. Semir Zeki, *Inner Vision: An Exploration of Art and the Brain* (Oxford: Oxford University Press, 1999), 22–36.

42. Ibid., 2.

43. J. H. Van den Berg, as quoted in Bachelard, *The Poetics of Space*, xxiv.

44. Bachelard, *The Poetics of Space*, xxi, 107.

45. Jonah Lehrer, *Proust Was a Neuroscientist* (New York: Houghton Mifflin, 2008).

46. Harry Francis Mallgrave, *The Architect's Brain: Neuroscience, Creativity, and Architecture* (Chichester: Wiley-Blackwell, 2010); and *Architecture and Embodiment: The Implications of the New Sciences and Humanities for Design* (Abingdon, UK: Routledge, 2013).

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1

From Neuron to Cognition: An Opening Perspective

MICHAEL A. ARBIB

1.1 Preamble

The title *From Neuron to Cognition via Computational Neuroscience* indicates two overall biases: to move up from neurons toward an understanding of their role in behavior and cognition (with cognition considered in a broad sense which includes action, perception, and diverse forms of memory, as well as planning and decision-making) and to show how computational modeling can complement empirical research in advancing that understanding. We explore how a brain supports behavior through the linkage between perception and action (the *action–perception cycle*), which in turn rests on learning and memory. The aim of this "Opening Perspective" is to provide a framework for reading the chapters which follow. It will show what aspects of cognition we develop in detail, and what we do not—while sketching how what we do cover provides a firm foundation for exploration of the full range of research in cognitive neuroscience, whether computational or not. And in the end we will address that most specifically human form of cognition, namely, language.

A note to the reader: The chapter opens with three sections that offer a shaping perspective for thinking about the brain: "The Maps Are Not the Territory," "Schema Theory and Action-Oriented Perception," and "A Fast Overview of the Human Brain." Thereafter, each section opens with pointers to the chapters that are most relevant to the topic of that section, and a subsection for each chapter will summarize some of its most important data, modeling, and discussions. However, many of these accounts will also include discussion of relevant material from other chapters and observations of my own on the topic at hand. Thus, this "Opening Perspective" can also be used as a reference to enrich the study of particular chapters. The emphasis is not on summarizing what the authors so expertly present but rather on providing a framework which will, I hope, enable the reader to more fully appreciate the contribution each chapter makes to our overall understanding.

As the reader will discover, there are manifold connections between the topics treated in the individual chapters, and so there is no single path through the chapters that best suits all readers. Thus, where some may choose to read the chapters in numerical order, for others this "Opening Perspective" may instead help them define an optimal path tailored to their own interests. In any case, this "Opening Perspective" may well repay being read twice: first before reading the other chapters to get the general ideas involved in the path from neurons (or other aggregates relevant to understanding the brain) to cognition, and then again once one has studied other chapters to more fully appreciate the connections charted here, enriching the second reading with new insights of one's own.

1.2 The Maps Are Not the Territory

It is a truism that "The map is not the territory," but here I want to emphasize that in general a territory can be the basis for multiple maps, each developed to serve different tasks. Consider, for example, traditional paper maps of a region. One would serve motorists and show various roads. To use it to go from A to B you would locate (representations of) A and B on the map and then find a route between them, perhaps choosing between a fast freeway and a slower route that runs alongside a river. Another would serve hikers and would include contour information (missing on the road map) needed to determine where an apparent path might prove too steep. For those who use smartphones instead of paper maps, there may be a loss of overall perspective (getting a sense of the geographical relation between A and B, and the possibilities that lie between them) but a gain in offloading some of the computations to the phone and getting a continual update on what to do next to continue from the present location toward B.

Maps in *the brain:* A crucial organizing principle for the primary sensory and motor areas of the brain and for those subcortical areas with which they are tightly linked is provided by the existence of topographic maps within them (their development is the focus of chapter 13, "Neural Maps: Their Function and Development"). In the visual system, for example, one might test a neuron to determine what type of visual feature best stimulates it and where in the visual field that features elicits the greatest response. The positions where stimuli cause the neuron to fire is called its *receptive field*. Neighboring neurons in the visual areas usually respond to similar regions of the image. Hence these areas are roughly retinotopic in the sense that their spatial organization is similar to that of the image at the retina. This retinotopic structure is strongest in primary visual cortex and gets weaker, and receptive fields get larger, as we ascend the visual hierarchy. In addition to *retinotopic* maps in the visual system, the brain has *somatotopic* maps (organized as a "homunculus" matching the surface of the body in somatosensory cortex), tonotopic or cochleotopic maps (corresponding to the frequency gradient in the cochlea), and whisker barrel maps in rodents (see chapter 16). Motor cortex also contains several "homunculus" maps, but mapping to the muscles and joints of the body, or perhaps to motor actions, rather than to touch receptors in the skin.

Two things to note. First, the "real estate" on each map reflects the functional importance of the area it represents, not its size. Thus, the retinotopic map in visual cortex devotes more space to the foveal region than the far periphery. Similarly, a somatotopic map devotes more space to, for example, the hand than the back. Second, as we move away from the sensory or motor periphery, the notion of "map" becomes less useful. Still, we may find it useful to talk of reference frames to distinguish what aspects of the world best characterize the maximal firing of cells—for example, in reaching to grasp, we can distinguish regions of the brain that code the visual position of a target on the retina from the head-centered position from the position relative to the shoulder that best situates the generation of motor commands. Of course, when we enter more abstract domains of cognition, even the notion of reference frame may become less useful.

Maps of *the brain:* The models developed for computational neuroscience are more akin to maps on a smartphone. Underpinning them is a body of data representing a range of relevant information about the "territory" of interest, but atop them lies a range of "computational routines" that can help us move toward answers to the questions that interest us. However—as is clear from distinguishing the interests of the driver and the hiker—different brain models must be developed to address different issues. The term "neuroscience" suggests a shared interest in neurons, but in fact that interest can take very different forms. Some people might want to develop a drug that ameliorates or cures some disease, and they may find that neurons are too big to interest them and focus all their energies on understanding the role of a specific macromolecule in a synapse, and how genetic defects may impair that role. Another person may find the neuron too small, seeking, for example, to use brain imaging to assess the relative "activity" of different brain regions in some cognitive behavior. Indeed, there are hundreds of relatively distinct niches where a neuroscientist might happily spend a decade or more of his or her career. Each of the 24 subsequent chapters introduces the reader to one or a few such niches, but in each case (as marked by the cross-references) expertise in one area demands at least some knowledge in other areas, and so an education in neuroscience requires the ability to both drill deeply and think broadly.

We saw earlier that a useful map (in the everyday sense of the word) is useful only if it leaves a great deal out so that we can make sense of what we need to know for our current activity. For this reason, a detailed model of all known biochemical processes in the brain (even were it feasible) might obscure rather than illuminate the simulated processes. The strategy in this book is instead to isolate fundamental empirical problems in neuroscience and then seek as simple a model as possible to chart them. As we develop such models, we continually compare them in search of fundamental "brain operating principles." We also assess where features of different models are ripe to be combined into more comprehensive models—but where now the increased complexity is mitigated by our understanding of the way in which the prior brain operating principles find expression in the prior models and thence in the new, more integrated approach.

With our concern for cognition, we must take care to distinguish the brain from the mind (the realm of the "mental," including the cognitive). In great part, brain theory seeks to analyze how the brain guides the behaving organism in its interactions with the dynamic world around it, but much of the control of such interactions is not mental, and much of what is mental is subsymbolic and/or unconscious. Without offering a precise definition of "mental," let's just say that many people can agree on examples of mental activity (perceiving a visual scene, reading, thinking, etc.) even if they take the diametrically opposite philosophical positions of dualism (mind and brain are separate) or monism (mind is a function of brain). They would then agree that some mental activity (e.g., contemplation) need not result in overt interactions with the dynamic external world, and that much of the brain's

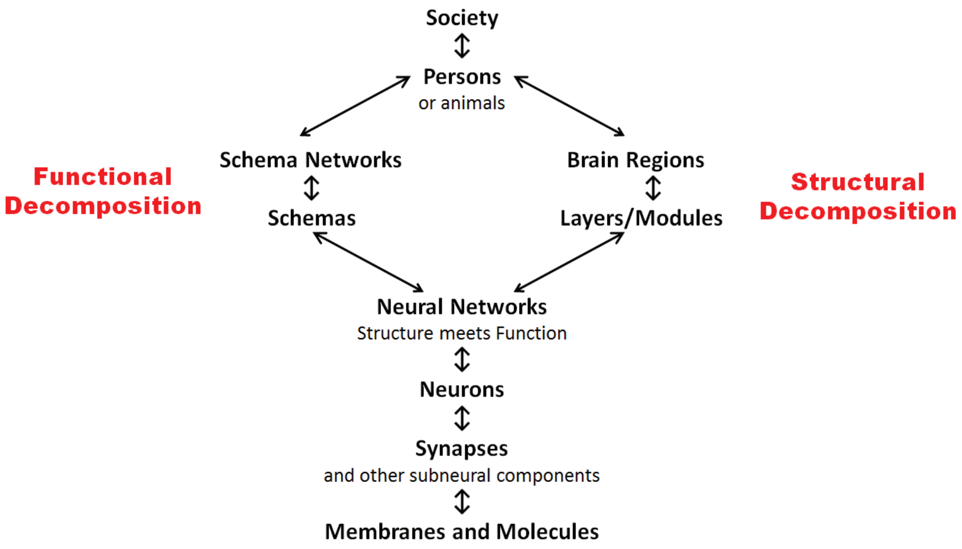

FIGURE 1.1 An overall view of different levels of analysis that may enter into research in neuroscience, proceeding both up and down from neurons, and noting that some overall behavior may be addressed in terms of either constituent *functions* (schemas) or the brain *structures* that implement it, or both. Cautionary note: Behavior in general results from brains within bodies in social interaction. Modeling parts of the brain in isolation can yield important insights but may blind us to key dynamics resulting from brain–body–environment interactions.

activity (e.g., controlling normal breathing) is not mental. This book's hypothesis is that mental processes can all be explained in terms of "brains and bodies in interaction," but many mental phenomena have not yet been explained in this way. This book is a progress report.

Earlier, I placed the term "computational routines" in quotes. This is to emphasize that the way the brain "computes" is very different from the way computation is distributed across the electronic circuits of today's smartphones, computers, and computer networks. Instead, we seek to characterize the way in which the brain's "computations" are distributed across networks of active, interactive, and adaptive entities, whether those be neurons or brain regions or schemas or other structural or functional entities. Nonetheless, just as it is clear that a simulation of an airplane's flight on a digital computer yields invaluable information, so shall we find that our investigations of "how the brain computes" are greatly assisted by the use of simulation on digital computers—without implying that the brain "computes" as such a computer does, any more than we would plan to fly on a computer instead of a plane.

Much of computational neuroscience seeks to provide mathematical abstractions of subneural dynamics—of which the most important is the Hodgkin–Huxley equations—as a basis for creating detailed models of individual neurons which, in turn, underwrite the modeling of relatively specific neural networks. However, subneural modeling will not play the central role in this book (though two chapters will supply the basics of this approach and others will apply them). Instead our primary concern will be with how the brain supports cognition and behavior. Most chapters will focus on how a neural network or a set of interacting networks serves to enable a single human (or animal) to perform just one or two of these functions in interaction with a limited sample of the external world. A quick tour of figure 1.1 will frame our various concerns, and then the rest of the chapter will survey key themes.

The dominant feature of the figure is that it offers two paths to link the "top-down" study of people and animals interacting with their physical and social environment with the "bottom-up" study of how neurons behave when connected into neural networks. The right-hand path of *structural decomposition* is the one more familiar to neuroscientists, dividing the brain into regions such as Brodmann's subdivision of human cerebral cortex (discussed below in relation to figure 1.5), and then dividing the region into subareas, layers, and anatomical modules such as columns. By contrast, the left-hand path of *functional decomposition* starts with some cognitive and behavioral function, such as the visual control of hand movements, and seeks to understand how it can be decomposed into functional units called *schemas*. Such a decomposition may be hierarchical, and the "lowest-level" schemas may be explainable in terms of the activity of neurobiologically defined neural networks. However, in other cases (e.g., in the study of language) this may not yet be possible and matching schemas to the neural level will thus pose challenges for future research.

Working from the bottom up in figure 1.1, our prime concern will be to understand how neurons can be linked together in circuits that do "interesting things." To understand a circuit, we may need to use data on what types of neurons are involved (these may differ in different parts of the brain, and in different animals) and on how they are connected. From the point of view of information processing and learning, the most important synapses are chemical synapses. When an action potential of neuron A arrives at a chemical synapse, a chemical signal (neurotransmitter) is ejected into the synaptic cleft and taken up by receptors embedded into the membrane of the receiving neuron, B. The response of the receiving neuron to presynaptic spike arrival can be measured as an excitatory or inhibitory postsynaptic potential (EPSP or IPSP) at its soma—not a spike so much as a nudge toward (excitation) or away from (inhibition) generation of a spike by neuron B. The strength of a synapse is not fixed but can change (see, e.g., chapter 6, "Hebbian Plasticity and Learning"). In most of the models in this volume, we can simply characterize the synapses by "weights" (a scalar measure of the influence of the presynaptic neuron on the postsynaptic neuron) together with simple learning rules which characterize how those weights may change as the circuit operates. However, there are neurotransmitters that act by changing the dynamic properties of the postsynaptic synapse or neuron. These are called *neuromodulators* (see chapter 7, "Neuromodulation"). One of the most important of these is dopamine, which factors into multiple models because of its role in "Reinforcement Learning" (see chapter 10). A crucial observation is that the effect of a neurotransmitter depends not only on the chemical itself but also on the nature of the receptor in the postsynaptic membrane. Think of a key that opens several locks—each lock may open a door to different pathways. For example, dopamine exerts its post- and presynaptic effects via two families of receptors, the D1 and D2 receptors (and more)—as a result of which a given release of dopamine can yield very different effects in different families of cells, as is documented in chapter 10 and again in chapter 23, "Brain Diseases."

Working from the top down in figure 1.1, we note that animals (and, in particular, humans) have evolved not only to interact with the physical world but also to interact socially with their conspecifics. However, in most of this volume, we will ignore the nascent field of social neuroscience and instead focus on specific functions vital to the animal's interaction with the world and on the brain regions implicated therein. For example, a study of vision might seek to understand how the brain supports schemas for microfunctions like recognizing predator and prey. But this very example makes clear that, while many neuroscientists focus solely on vision, others will seek to learn how the brain can exploit the recognition of predator versus prey to guide the appropriate course of action to capture the prey or escape the predator.

Other neuroscientists may start their investigation with questions inspired by the distinctive anatomy of large-scale structures of the brain. Why, for example, does the cerebellum have its distinctive neural architecture? Such questions become more intriguing when structure meets function. We know that the cerebellum is necessary for us to move gracefully, but we can still move clumsily without it. What other parts of the brain, then, must work in cooperation with the cerebellum in normal behavior? We might address this at the level of human brain imaging, asking how different forms of behavior—some with more emphasis on the planning of action, some with more emphasis on its graceful execution—differentially activate various regions of the brain. Other data, though, will come from animal studies, where single-cell recordings reveal the differential activity of neurons in various parts of the brain during these different conditions.

It is at the confluence of the top-down interest in structure and function and the bottom-up interest in the interactions of neurons that much of our work in this book lies—but, as the rest of this chapter makes clear, by no means all. Our strategy in the next three sections is thus:

- To introduce some key ideas about schemas to establish the mind-set of assessing the processes of competition and cooperation between alternate schemas that may underlie cognition and behavior.
- To provide a quick high-level tour of the human brain to establish the mind-set that the brain involves many different regions with distinct patterns of circuitry, and thus the study of the brain cannot be reduced to the dynamics and adaptive properties of any single formal pattern of neural architecture.
- To look at some classic models of activity in neurons and neural networks to provide basic concepts that will be elaborated upon in later chapters, where complexities will be modeled in light of both bottom-up constraints (e.g., using data from neurophysiology) and top-down constraints (e.g., relative activity of different brain regions, as provided by brain imaging).

In each case, the initial account given here will be enriched by pointers to later chapters. Conversely, some of the linkages suggested here will become more meaningful after the specific viewpoints of several chapters have been understood.

Our cumulative knowledge in neuroscience comes from the study of the brains (or nervous systems) of diverse animals (including humans). We can study the function of human brains through introspection or observation of behavior. This may ground a top-down, schema-style analysis but cannot tell us to what extent the schemas correspond to the function of specific brain regions. The classic data of neuropsychology in the nineteenth and twentieth centuries supported inferences in this direction by studying how function degraded when parts of the brain were damaged, and such observations have been enriched in recent decades by new techniques for imaging the human brain, but such methods look at relative activity in different brain regions, not at the millions of neurons that support that activity. Thus, we turn to other animals for data on neural circuitry. Monkeys, cats, and rats are the source of much neurophysiological data relevant to some aspects of human brain function (though "higher cognitive functions" involve evolutionary variations on general mammalian circuitry) while the classic description of how action potentials propagate in neurons rests on the classic Hodgkin and Huxley experiments on giant axons from squids. It should be added that neuroscientists study the brains (and bodies) of other animals not only to gain lessons for human neuroscience but also to better understand the unique capabilities of other species—whether the flight of birds, the social behavior of ants, or the whisking behavior of rats—and these, in turn, may inform new directions in robotics.

1.2.1 LINKING MODELS WITH EMPIRICAL DATA A brain model may be either an explicit *computational* model, together with computer code and simulations, of how a particular brain system operates at, for example, the level of dynamic interactions in biologically realistic brain regions and neural networks; a *mathematical* model to be explored by, for example, the dynamical system methods of chapter 3 (but it may also be implemented to get further results by simulation); or a *conceptual* model, in which case a "simulation" result may simply be an inference from the verbal formulation of the model. The last is simply a sketch of a "computationally possible" model that may not have been implemented but nonetheless guides experiments. It may serve as the basis for later development of computational models but is itself not yet specific enough for implementation. In each case, a question that will be important to ask of a model is this: Where did the assumptions used in building the model come from, and to what extent do results obtained with the model explain extant empirical data or suggest predictions worth testing with new experiments?

In chapter 5, "Linking Models with Empirical Data: The Brain Operation Database," James J. Bonaiuto and I stress the importance of understanding how models relate to empirical data: assessing which empirical data were used to constrain the design of the model and which were used to test the performance of the model, and the results of those tests. In particular, we introduce the Brain Operation Database, BODB (http://bodb.usc.edu/bodb/), which supports the documentation of models of the structure and performance of models in relation to empirical data. In BODB, each model is linked to *Brain Operating Principles* (BOPs), *Summaries of Empirical Data* (SEDs), and *Summaries of Simulation Results* (SSRs).

A BOP is a general principle of brain operation that is not limited to one experimental protocol or simulation but can be found in multiple regions or in multiple tasks. For example, the Winner-Take-All BOP holds when a neural network (whether in an actual brain or simulated) converts a pattern of activation of its inputs to a peak of excitation that corresponds to the locus of maximal excitation on the inputs. This has been applied to modeling diverse brain regions (including frog tectum and monkey superior colliculus). However, the role of a brain region, and thus the relevant BOPs for modeling it, may vary between different tasks. Indeed, modern brain imaging techniques only work because of such differential involvement of brain regions.

Experimental protocols specify the particular conditions under which a given data set (whether brain imaging, or at the neural, subneural or other levels) is gathered. If we want to develop a model of those brain regions to explain the results of diverse experiments, then each experimental protocol must be translated into a *simulation protocol*. The model can then be tested by comparing the SSRs obtained from a particular simulation protocol with the SEDs obtained with the corresponding experimental protocol.

Some brain models build upon earlier works to increase biological plausibility, explain more SEDs (including new experimental results published since the development of earlier models), or both. In other cases, models that were developed independently may provide complementary or even contradictory views of overlapping sets of empirical results. BODB supports model comparison, or *benchmarking*, in a tabular form based on a comparison of the SEDs used by the models to support their development and the SEDs the model can explain. Two models from chapter 20 are chosen for scrutiny in chapter 5—the so-called MNS and MNS2 models of development of mirror neurons—to present an explicit account of the relevant BOPs, and to illustrate how models may be compared by assessing which SEDs each can explain and which SEDs enter into model design. Whether one uses the tools provided by BODB or not (and several chapters in this book include models documented in BODB), such careful comparison of existing models in the context of available data can be a powerful tool in developing specifications for further models in the area of computational neuroscience to which the models under comparison belong. Chapter 5 also sketches the way in which BODB can support collaboration between modelers and experimentalists—the exchange and linking of experiments with the computational models that may support, explain, contradict, or predict empirical evidence. Collaboration should support not only modelers in grounding computational models in empirical results but also experimentalists in allowing them to contribute summaries of their own data that may challenge modelers.

1.3 Schema Theory and Action-Oriented Perception

In figure 1.1, we introduced the idea of a functional analysis in terms of schemas. In this section, we provide a brief introduction to schema theory. We then turn to the notion of action-oriented perception to offer a framework for studying cognition that is very different from one that roots its study in the notion of thought as purely occurring in some abstract symbolic system.

1.3.1 Introducing Schemas

Frederic Bartlett (1932) studied how we incorporate new memories into our existing body of knowledge. He asked subjects to read stories and then, later, to recall them. Recalled stories became transformed from the original stories because subjects were using their general knowledge and cultural expectations ("schemas") to reconstruct the forgotten links. However, not all schemas are of this form. More generally, a schema is what is learned (or innately given) about some aspect of the world, combining knowledge with the processes for applying it. For example, a *perceptual schema* might support visually recognizing an apple while also generating predictions about touch and taste. But recognizing an apple may be linked to many different courses of action, and these may be linked to one or more different *motor schemas*—for example, to place the apple in one's shopping basket, to place it in a bowl, to pick it up, to peel it, to cook with it, to eat it, to discard a rotten apple, and so forth. Note that, in the list just given, some items are apple specific whereas others invoke generic schemas for reaching and grasping. There is no one grand "apple schema" which links all "apple perception strategies" to "every action that involves an apple." Moreover, in the schema-theoretic approach, "apple perception" is not mere categorization—"This is an apple"—but may provide access to a range of parameters relevant to interaction with the apple at hand.

Clearly, then, multiple schemas must be linked in supporting any given behavior. An example of such linkage, in what we call a *coordinated control program*, is given in figure 1.2, which provides a specific example of top-down schema analysis, based on the empirical work of Jeannerod and Biguer (1982). They charted the way in which the hand, as it moves to grasp a ball, is preshaped so that it is of the right shape and orientation to enclose the ball prior to gripping it firmly. Moreover, they found that, to a first approximation, the movement can be broken into a fast initial movement and a slow approach movement, with the transition from the fast to the slow phase of transport coming just before closing of the fingers from the preshape so that touch may take over in controlling the final grasp. We will relate these phases to feedforward and feedback in our discussion of chapter 9.

Figure 1.2 models this behavior in terms of interacting schemas. This model anticipates the much later discovery, reported in chapter 20 ("Reach and Grasp: Control, Development, and Recognition") of perceptual schemas for grasping located in a specific area of parietal cortex and motor schemas for grasping situated in a related area of premotor cortex. Chapter 20 also takes this high-level view forward in terms of neurobiologically motivated models of the underlying neural networks.

The schemas of figure 1.2 are akin to the blocks in a conventional block diagram for a control system but have the special property that they can be activated and deactivated. Thus, where control theory usually examines the properties of a fixed control system, schema theory allows the control system to expand and contract, adding and deleting subschemas in a task- and data-dependent manner. Solid lines indicate the transfer of data from one schema to another, and dashed lines indicate the transfer of activation. Crucially, then, schemas can be combined to form such *coordinated control programs* which control the phasing in and out of patterns of schema coactivation and the passing of control parameters from perceptual to motor schemas. Moreover, perceptual and motor schemas may be embedded in assemblages embracing more abstract schemas to yield accounts of cognition and language which link psychology to neuroscience. A corollary to this is that knowledge is distributed across multiple regions in the brain so that a multiplicity of different

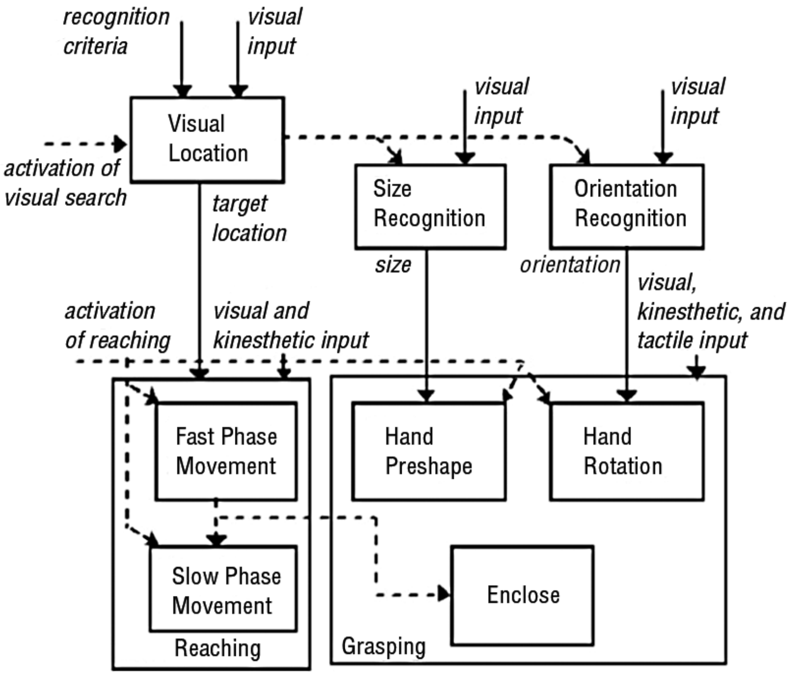

Figure 1.2 Hypothetical coordinated control program for reaching and grasping. Different perceptual schemas (top half of figure) provide input for the motor schemas (bottom half of figure) for the control of "reaching" (arm transport) and "grasping" (controlling the hand to conform to the object). Note, too, the timing relations posited here between subschemas within the reaching motor schema and those within the motor schema for grasping. Dashed lines indicate activation signals; solid lines show transfer of data. Reaching was hypothesized to involve a ballistic phase followed by a feedback phase, with the transition between the two also activating the Enclose motor schema. Adapted from Arbib (1981).

representations must be linked into an integrated whole.

Chapter 25 ("Evolving the Language-Ready Brain") introduces a complementary example of schema processing. Here the challenge is to understand a visual scene. This is done by associating schemas with different portions of the scene. However, this leads us to introduce the notion of *schema instance* as an active deployment of a schema. For example, if there are two cars in a scene, we may want to go beyond simply labeling them as cars to associate each one with a different instance of the schema, each specifying values for parameters such as location, size, make, and color. However, in initial processing of a scene, different schema instances may compete to interpret part of a scene (is that a glimpse of sky or part of another building?) or to choose between motor schemas for different actions (will I pick up the coffee mug or keep typing?). Thus, each schema instance has an associated *activity level*. The activity level of a perceptual schema instance signals the credibility of the hypothesis that what the schema represents is indeed present. The activity level of a motor schema instance may signal its "degree of readiness" to control some course of action.

Each schema (instance) may itself involve the integrated activity of multiple brain regions. The method of interaction of schema instances is *cooperative computation*: competition between discordant schema instances may decrease their activity, cooperation based on coherence between instances may increase their activity, and the process continues until an assemblage of schemas wins the competition to direct perception, thought, and/or action. In this way, "computations" that are often seen as the province of traditional symbol-based processing are instead carried out by distributed "neuron-like" methods which do not involve explicit symbolic control. In chapter 14 ("Schema Theory and Neuropsychology") Richard P. Cooper presents a schema-based system—contention scheduling—for routine behavior, the operation of which is modulated in nonroutine situations by a second system—the supervisory attentional system. His model supports the assessment of data on the effects of brain lesions on human patients.

1.3.2 The Action–Perception Cycle Figure 1.2 showed how a number of perceptual schemas simultaneously activated to characterize properties of an object could activate motor schemas for the coordinated

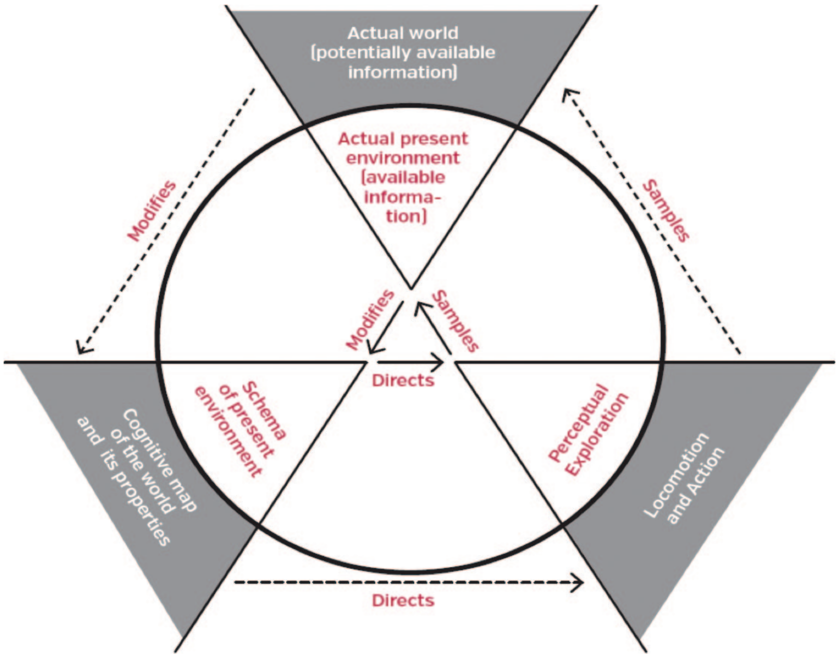

Figure 1.3 The action–perception cycle. The point about a cycle is that one can start anywhere. We can, for example, start tracing each cycle in the actions at lower right: in the inner loop, perceptual exploration shifts our attention to different aspects of the world, thus updating the schema assemblage that represents our current environment; the outer loop stresses those interactions (both physical and social) which may modify the world or our relationship with it; these changes may update our cognitive map of the world, and this in turn may update our (not necessarily conscious) plans for action. Adapted from Neisser (1976).

control of reaching for and grasping the object. An important point is that the set of active motor schemas would change as the coordinated actions progress. Our brief pointer to chapter 25 emphasized that visual perception may do more than characterize a single object—visual input can invoke knowledge coded as a network of schemas in long-term memory to create an assemblage of schema instances that represent aspects of the visual environment. Figure 1.3 integrates these observations into a single perspective, the action–perception cycle (Neisser, 1976). Far from being passive responders to the sensory flow, we actively seek information relevant to our current goals (though, of course, some unexpected events may grab our attention and may even modify our goals). Thus, our actions may either serve to focus attention on sensory data of current interest or change our relation with the physical world, including other people and other creatures. Brains mediate social interactions as well as interactions with the physical (including built) environment.

At any time our current perception of the world combines with our current goals, plans, and motivations to activate certain combinations of motor schemas which determine our actions. Each action may change the world and/or our relationship with the world (contrast opening a door vs. turning one's head just to shift the focus of attention). Thus, the input available about the world at any time will change, both because of our actions (both physical and social) and because the world may be changing anyway. As a result, the assemblage of currently active schemas will be updated and will include perceptions of actions and other relationships, as well as objects and their properties or parameters. The rotating arrows in figure 1.3 indicate that memory structures are invoked in updating our perceptions and our plan of action (further variables relate to the motion and internal state of the body) but also indicate that we continually perceive the consequences of our actions or simply observe correlated changes in the external world so that both our working memory and long-term memory may be modified. Thus, *the action–perception cycle is a learning cycle*, too. As we interact with the world, we are constantly learning, not only laying down memories of specific events (*episodic memory*) but also acquiring and refining diverse skills (*procedural memory*) which are coded at least in part by our perceptual schemas, motor schemas, and the larger structures that integrate them.

1.3.3 Three Flavors of Schema Theory For brain theory, the top-level schemas must be "large" enough to allow an analysis of behavior at or near the psychological level yet also be subject to successive decomposition down to a level that may, in certain cases, be implemented in specific neural networks. One must distinguish a schema as a *functional* unit from a neural network as a *structural* unit. A given schema may be distributed across several neural networks; a given neural network may be involved in the implementation of several different schemas. A top-down analysis (decomposing a function) may suggest that a certain schema is embedded in a certain part of the brain; we can then marshal the available data from anatomy and neurophysiology to assess whether the circuitry can, indeed, subserve an instance of that schema. It often happens that the empirical data are inadequate. We then make hypotheses for experimental confirmation. Alternatively, bottom-up analysis of a brain region (assembling its constituents) may suggest that it subserves a different schema from that originally hypothesized, and we must then conduct a new top-down analysis in the light of these newfound constraints. This discussion supports the following distinction between two "flavors" of schema theory:

Basic schema theory studies schemas as dynamical, interacting systems which underlie cognition and overt behavior (and not just conscious processes). Basic schema theory is defined at a functional level which associates schemas with specific perceptual, motor, and cognitive abilities and then stresses how our mental life results from the dynamic interaction—the competition and cooperation—of many schema instances. It refines and extends an overly phenomenological account of the "mental level."

Neural schema theory: The "downward" extension of schema theory seeks to understand how schemas and their interactions may indeed be played out over neural circuitry—a move from psychology and cognitive science as classically conceived (viewing the mind "from the outside") to cognitive neuroscience. Neural schema theory analyzes data from neurophysiology, lesion studies, and brain imaging to see how schemas may be restructured to relate to distributed neural mechanisms.

A third flavor comes when we seek to distinguish "schemas in the head" from forms of knowledge and action shared by a community:

Social schema theory: The "upward" extension of schema theory seeks to understand how "social schemas" constituted by collective patterns of behavior in a society may provide an external reality for a person's acquisition of schemas "in the head" in the sense of basic schema theory. Conversely, it is the collective effect of behaviors which express schemas within the heads of many individuals that constitutes, and changes, this social reality. Social schemas represent the collective effect of behavior—whether related to everyday events, language, religion, ideology, myth, or scientific paradigm—governed by related schemas (in the sense of basic schema theory) in the individuals of a community (Arbib and Hesse, 1986).

1.4 A Fast Overview of the Human Brain

Figure 1.4 diagrams the cerebral cortex in relation to some (but not all) of the brain regions of importance to us. Cerebral cortex contains excitatory *pyramidal neurons* and a range of inhibitory *interneurons*. Dissection and staining methods have illuminated how the layered structure of cerebral cortex varies from region to region. This *cytoarchitecture* led Brodmann (1909) to parcellate the cerebral cortex as shown in figure 1.5. A few numbers of these Brodmann areas (BAs) are especially worth remembering:

- Vision: Primary visual cortex (BA17) feeds into secondary visual cortex (BA18, BA19).
- Primary somatosensory cortex (BA1), which mediates touch and body sense, feeds into the secondary areas (BA2, BA3).
- Language areas include BA22, Wernicke's area (BA40), and Broca's area (BA44 and BA45).
- Frontal eye fields (BA8) provide a cortical outpost for the control of eye movements.

Brodmann's map of the cerebral cortex (it does not include other brain regions) does not tell us the connectivity (gross neuroanatomy) between these regions of the cortex and with other regions of the brain. Indeed, each region is part of complex patterns of interaction, including interactions with subcortical regions, and so one must not read too much into the functional labels in the above list. Various chapters in this book will focus on specific functions related to cognition and behavior and explore and model the larger networks needed to support them. In general, such models will require us to go beyond the gross neuroanatomy to explore details of neurons and the circuitry in which they are connected.

Functional properties can be investigated through electrophysiological recording methods that allow us to link the firing of one or more neurons to ongoing action, perception, and/or learning. Such methods are rarely justified in humans but yield a wealth of data about animal brains that lets us form hypotheses about mechanisms operative in the human brain. We can learn about animal brains and about human brains

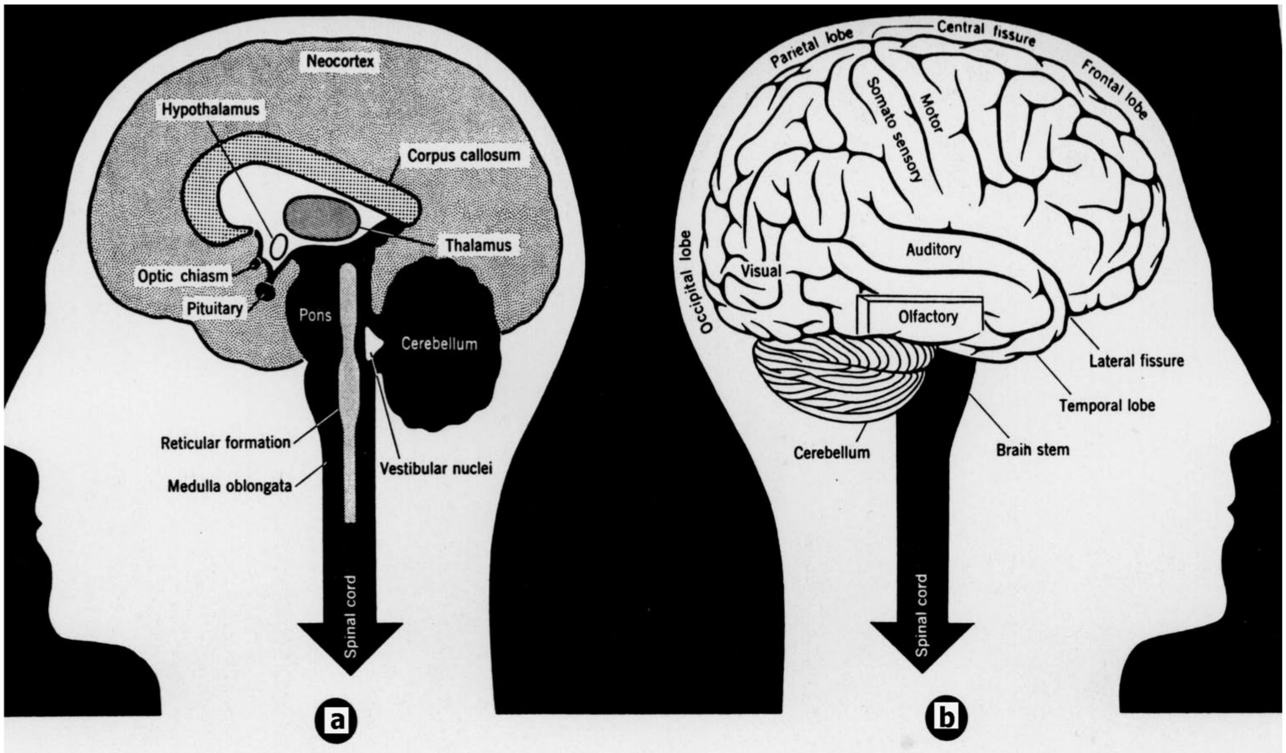

Figure 1.4 Medial (a) and lateral (b) views of the human brain. We see the four lobes (occipital, parietal, temporal, and frontal) of the cerebral cortex with the location of primary sensory cortices for vision, audition, and somatosensation (olfactory cortex is a separate, phylogenetically older structure) as well as the primary motor cortex. The medial view reminds us that there is a lot more to the brain than just the cerebral cortex. We will be particularly attentive to the cerebellum and (not shown in the figure) the basal ganglia and the hippocampus.

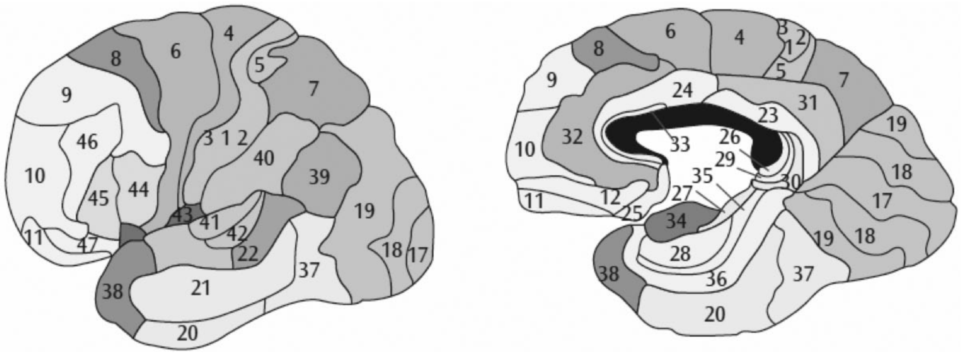

Figure 1.5 Brodmann areas in the human brain. A lateral view of cerebral cortex is shown at left, and a medial view at right. The Brodmann areas are all areas of cerebral cortex. There are many other regions of importance to us, including cerebellum, basal ganglia, and hippocampus.

(affected by disease, tumors, neurosurgery) by studying the effects of damage to, or lesion of, a given cluster or structure. In order to demonstrate the relationship between structure and function, damage to a specific part of the brain should produce a measurable functional deficit, and damage to other structures should not produce the same deficit. Note, though, that loss of a function on excision of a region R does not imply that R by itself supports the missing function (though this is true in some cases), but rather that other regions require interaction with R to jointly support it.

Brain imaging methods are the primary methods for identifying function in the living human brain. In *electroencephalography* (EEG), electrodes are attached to the scalp to measure electrophysiological activity of primarily pyramidal neurons and synchronized brain currents, such as *gamma* and *alpha waves* underneath the skull (see chapter 4, "Neural Rhythms"). *Magnetoencephalography* (MEG) also measures brain activity via accompanying magnetic fields. *Diffusion tensor imaging* (DTI) uses magnetic resonance imaging (MRI) technology to assess white matter connectivity and integrity. Of especial importance in cognitive neuroscience, and a main focus of chapter 15, are positron emission tomography (PET) and functional MRI (fMRI). In both methods, the signal obtained is allocated across an image that covers some area of the brain with three-dimensional "cubes," referred to as *voxels*. The voxels are on the order of several millimeters in each dimension. Both PET and fMRI are thought to reflect synaptic activity more than neuron spiking activity. fMRI measurements typically are relative to a baseline, so that two different cognitive states must be compared against each other. Our present knowledge about the neural basis of human behavior and cognition relies largely on the data from human neuroimaging studies and animal brain neurophysiology studies. Chapter 15 ("Synthetic Brain Imaging") provides more detail on these methods and shows how, for example, fMRI data may be related, via modeling, to the much finer scale activity of neurons in the regions under consideration. A plethora of new experimental methods are becoming available—optogenetics, and mapping of gene expression to name just two—and these each challenge us to develop new modeling techniques that can address the new data and seek explanations that integrate them with the insights gained from other experimental methodologies.

We round out our fast overview of the human brain in two subsections, one looking at two pathways of vision and action (with a brief note on the auditory system) and the other introducing basic anatomical substrates of motivation and emotion. In each case, the subsection ends with an evolutionary perspective, suggesting the ways in which the human brain extends capabilities shared with other species, such as monkeys and rats, respectively.

1.4.1 Two Pathways for Visuomotor Integration

Studies of vision have shown that there is really no single "visual system" in the brain but rather "many visual systems" computing such factors as depth, motion, color and so on—even though we are conscious only of a single integrated visual experience. The visual cortex can be decomposed into a number of visual areas based on anatomical and electrophysiological measurements. Like all areas of the cortex, these regions have a standard six-layer structure. Primary visual cortex, V1, receives retinal input via the lateral geniculate nucleus (LGN) of the thalamus. It then projects directly and indirectly to numerous other "visual areas" of cortex such as V2, V4, and medial temporal (MT), medial superior temporal (MST), and the inferior temporal (IT) cortex. There are numerous interactions between these visual areas, but it is common to concentrate on two hierarchical streams: the *ventral stream*, which consists of V1, V2, V4, and IT, and the *dorsal stream*, which goes from V1 to MT to the parietal cortex.

The thalamocortical pathway via LGN and V1 is not the only way that vision can affect action and perception. Another path from the retina leads to the superior colliculus, a region of the midbrain which plays a critical role in the control of eye movements (see chapter 19, "Saccades and Smooth Pursuit Eye Movements"). However, in terms of cortical processing, it is particularly striking that the ability to use the size of an object to preshape the hand before grasping it (recall the schema model of figure 1.2) can be dissociated by brain lesions from the ability to consciously recognize and describe that size.

Ungerleider and Mishkin (1982) conducted experiments with *monkeys*, using lesions to distinguish the role of the *dorsal* and *ventral* pathways. They showed that a ventral lesion would impair memory of the pattern associated with hidden food while a dorsal lesion would impair memory of where the food had been hidden—and thus spoke of the "what" and "where" pathways, respectively. However, in figure 1.6 we refer to a different paradigm—observations of the effect on reaching and grasping of lesions observed in the brains of *human* neurological patients. Here a ventral lesion affects the ability to name the object ("what"), while a dorsal lesion affects the ability to preshape for grasping or otherwise using the object ("how").

How: Goodale et al. (1991) studied a patient (DF) with damage to the ventral path. When asked to indicate the width of a single block either verbally or by means of her index finger and thumb, DF's finger separation bore no relationship to the dimensions of the object and showed considerable trial to trial variability. Yet when she was asked simply to reach out and pick up the block, the peak aperture (well before contact with the object) between index finger and thumb changed systematically with the width of the object. A similar dissociation was seen in her responses to the orientation of stimuli. In other words, DF could preshape accurately, even though she appeared to have no conscious appreciation (expressible either verbally or in pantomime) of the visual parameters that guided the preshape. This aligns the dorsal path with the schema model of figure 1.2.

What: Jeannerod et al. (1994) report a study of impairment of grasping in a patient (AT) with a bilateral

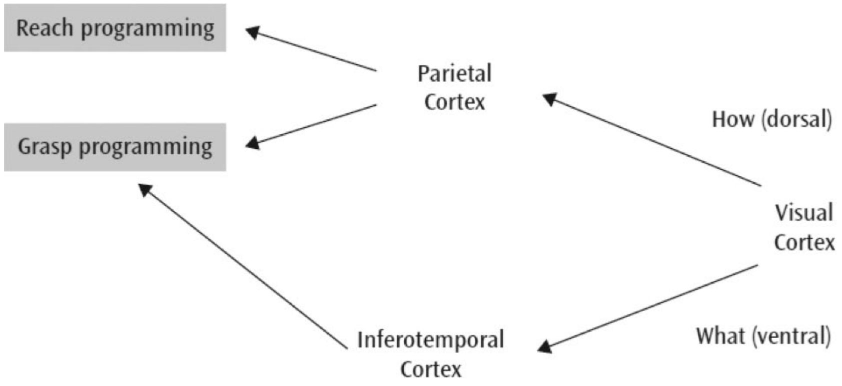

Figure 1.6 The "what" and "how" pathways for visual information involved in successful grasping or manipulation of an object. The "how" pathway from visual cortex travels dorsally, via parietal cortex. The "what" (ventral) path travels via inferotemporal cortex.

posterior parietal lesion that grossly impaired the dorsal pathway. AT is the "opposite" of DF—she can use her hand to pantomime the size of a cylinder, and can reach without deficit toward the location of such an object, but cannot preshape appropriately when asked to grasp it. Surprisingly, however, when the stimulus used for the grasp was not a cylinder (for which the "semantics" contains no information about expected size) but rather a familiar object—such as a reel of thread, or a lipstick—for which the "usual" size is part of the subject's knowledge, AT showed a relatively appropriate preshape. This suggests, as indicated by the arrow at bottom left of figure 1.6, that a pathway from IT cortex provides the parietal areas with "default values" of action-related parameters, that is, values which can serve in place of actual sensory data to represent the approximate parameters of a known object to help the parietofrontal system.

We distinguish *praxic* action, in which the hands (or other effectors) are used to interact physically with objects or other creatures, from *communicative* action (both manual and vocal). Waving good-bye and brushing away a cloud of flies might employ the same motion yet they are different actions, the first communicative, the second praxic. We thus see in the AT and DF data a dissociation between parietal and IT pathways, respectively, for the praxic use of size information (which is why we call the dorsal pathway the "how" pathway) and the communicative "declaration" of that information either verbally or through pantomime (which is why we call the ventral pathway the "what" pathway). Chapter 20, "Reach and Grasp: Control, Development, and Recognition," offers a neurobiological model of the pathways in figure 1.6 as they occur in the monkey (where the ventral pathway is implicated in planning, though not communication); chapter 25, "Evolving the Language-Ready Brain," then suggests how capacities for pantomime and language enrich this mix in the human brain.

Although in this book most examples of perception and of the action–perception cycle emphasize vision, other sensory systems (such as audition, somatosensation, touch, taste, and smell) do of course play a crucial role in animal and human behavior, and these systems have been the focus of important modeling in computational neuroscience. Here we simply offer data on the auditory system that complements our study of the dorsal and the ventral pathways emanating from primary visual cortex. The auditory system must also analyze both the identity and the location of the stimuli it detects. Auditory processing of "what" and "where" involves different structures and pathways even before the signals reach the primary auditory cortex. This is situated in the temporal lobe and has a *tonotopic* organization (i.e., it can be mapped in terms of the predominant frequencies of the sounds to which cells respond) while nonprimary auditory cortex responds to complex sounds. Research on the auditory system in human and nonhuman primates (Rauschecker, 1998; Romanski et al., 1999) showed that there are two pathways for processing auditory input emanating from primary auditory cortex. The *dorsal auditory stream* processes spatial information while the *ventral auditory stream* processes auditory pattern and object information. Auditory objects, including speech sounds, are identified in anterior superior temporal cortex which projects directly to inferior frontal regions. Both streams eventually project to the frontal cortex, which integrates auditory spatial and object information with each other and with visual and other modalities.

Rauschecker (1998) suggests that enhancements in analysis of frequency, FM rate, bandwidth, and timing relative to other primate species have occurred during human evolution—augmenting mechanisms that are

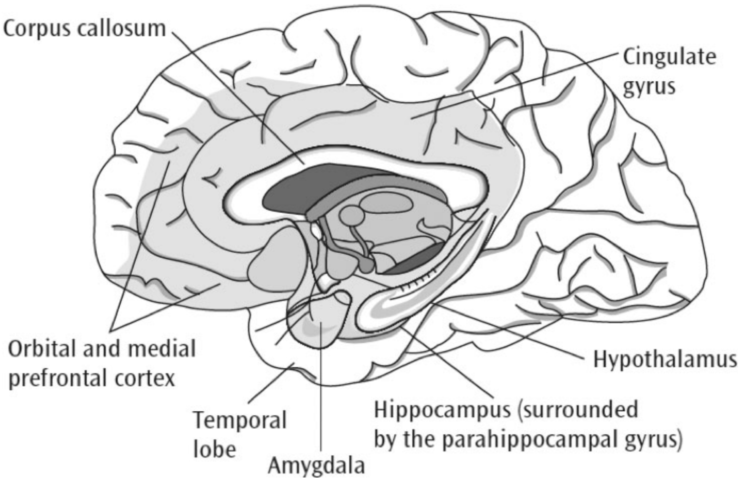

Figure 1.7 A diagram of the limbic system (i.e., the brain regions "that throw their limbs" around the thalamus) showing the relative placement of amygdala (named for its almond shape), hippocampus (named for its sea-horse-like appearance in cross-section), cingulate gyrus, medial prefrontal cortex, and temporal lobe in the human brain. Adapted from Williams et al. (2007).

available in, for example, monkey auditory communication systems. On this basis, speech perception is thought to be possible because it combines a high-resolution system for phonological decoding with more efficient memory mechanisms and an ability for abstraction, both residing in a highly developed and expanded frontal cortex.

1.4.2 Motivation and Emotion Unfortunately, the present book has no explicit chapter on the neuroscience of emotion (see Fellous and Arbib, 2005, for a collection of articles under the banner *Who Needs Emotions: The Brain Meets the Robot*), but the topic deserves brief mention here. Emotion can be analyzed under two headings:

"External" aspect of emotions: Emotional expression for communication and social coordination. If we see that someone is angry, we will interact with that person more cautiously than we would otherwise, or not at all.

"Internal" aspects of emotions: These frequently contribute to the organization of behavior (prioritization, action selection, attention, social coordination, and learning). For example, the actions one is likely to perform vary greatly depending on whether one is angry or sad.

These two aspects have coevolved. Animals need to survive and perform efficiently within their ecological niche, and in each case the patterns of coordination will greatly influence the suite of relevant emotions (if such are indeed needed) and the means whereby they are communicated. The emotional state sets the framework in which the choice (whether conscious or unconscious) of actions will unfold. But emotions, too, are embedded in the action–perception cycle, so that one's emotions may change as the consequence of one's actions become apparent—and our perception of these consequences may well rest on our perception of the emotional response of others to our behavior.

Figure 1.7 sketches a number of brain regions that support motivation and emotion. These regions constitute "limbs" surrounding the thalamus, forming what is called the *limbic system.* (It has nothing to do, directly, with the control of arms and legs.) Animals (including humans) come with an innate set of basic "drives"—for hunger, thirst, sex, self-preservation, and so forth—and these provide *motivation*, the basic motor for behavior. Motivated behavior not only includes bodily behavior (as in feeding and fleeing, orofacial responses, and defensive and mating activities) but also autonomic output (e.g., heart rate and blood pressure) and visceroendocrine output (e.g., adrenaline, release of sex hormones). These lie at the heart [sic] of our emotional repertoire. However, the emotions that we talk about and perceive in others are both more restricted than this (how many people perceive another's cortisol level?) yet also more subtle, intertwining these basic motivations with our complex cognitions of social role and interactions, as in the cases of jealousy and pride.

The core of the motivation system is provided by the nuclei of a deep-seated region of the brain called the *hypothalamus*. These nuclei are devoted to the elaboration and control of specific survival behaviors such as spontaneous locomotion, exploration, and ingestive, defensive, and reproductive behaviors. Basically, the hypothalamus talks "downward" for basic behavioral control and "upward" to involve the cortex in determining when particular behaviors are appropriate. Indeed,

Research-based design:
New approaches to the creation of healthy environments

Technologies are emerging that can reveal the reactions of mind and body to specific features of the designed environment. This paper reviews a selection of these innovations, which can provide the means to conduct pre-design evaluations

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The impact of building-design strategies on non-communicable disorders, unhealthy behaviour and global ecological conditions has recently been recognised in studies by the United Nations, the World Health Organization and the Institute of Medicine.

Such research acknowledges a compelling need to improve our cities and buildings for the benefit of human health and wellbeing. Revelations surrounding the frequency at which unhealthy and adverse events occur in healthcare environments have motivated architects to create design strategies that improve human and sustainable outcomes. These strategies, however, are not always as informed as they could be, because "too often, the form and function of architectural environments neglect to take into account the influence of the built setting on human responses and, indeed, on human health itself".[1]

In response to these needs, a new generation of designers, architects and engineers is embracing an interdisciplinary approach and employing novel technologies to inform salutogenic design. The incorporation of findings from neuroscience, physiology and psychology, along with architectural research models based on philosophical constructs and sociological and ethnographic methods, offer the means to relate human responses to design in a more powerful fashion.

A 'neuro-architectural' approach

The neuro-architectural process informs design by correlating specific measures of the built environment (input) with quantified measures of the brain's and body's responses (neural, physiological and psychological responses), as well as sociological, behavioural and economic outcomes (output). This process gives weight to scientific methods of research, linking input, response and output, and allowing for statistical and critical evaluation of design outcomes.

With the advent of recently developed neuroscientific instrumentation, a higher degree of objectivity enables measurement of both conscious and sub-conscious responses without relying on the subjects' understanding or ability to articulate their cognitive, sensory or emotional response to design. In this way, resulting findings therefore offer greater potential to reveal the needs and preferences of the growing number of individuals with developmental or physical conditions, or those with dementia or cognitive impairment.

The goals of this integrated approach are to understand better how the brain's and body's responses to the environment influence health and wellbeing; and to define and quantify the human, environmental and financial returns on investment in design. The complexity of architectural environments suggests it may be impossible to reduce human interaction with built settings to measurable elements. But the combination of scientific studies with rigorous social and cultural observations can yield greater analytic confidence in the applicability of findings based on physical, physiological, psychological and social (PPPS) measures. These objectives are consistent with the creation of private and social spaces, with natural and innovative features that improve the quality of a place and how users function within it, as well as including salutogenic factors to enhance wellbeing.

Translating the hierarchy of design

A 'hierarchy of design principles' is proposed, translating Maslow's 'hierarchy of needs'[2] into a design process that includes iterative feedback loops to each component of the body, brain and mind that interacts with design features, and consequently drives behaviour. Outcomes that serve salutogenic and economic goals can thus be analysed using the construct of a scientific method applied to design inquiry.

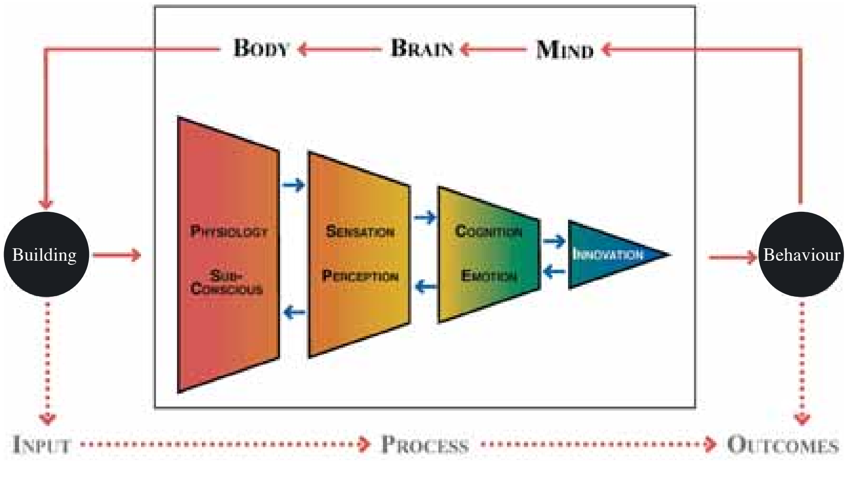

Figure 1: Neuro-architectural design process

Figure 2: Visuo-acoustic simulations in the CAVE evaluate speech intelligibility of doctors reciting 'sound-alike' medication orders when competing with clinical recordings of conversations, ambient noise, equipment alarms and ventilation sounds

The design process is reversed relative to many evidence-based projects; the first step translates clinical and neurophysiological evidence of the impact of physical design components into principles that reflect how the brain and body respond to place. Design that minimises harm in terms of physical health and safety, error and injury is the first priority and considered fundamental to all design decisions. In an iterative feedback loop, the psycho-physiological impact of each design feature is then assessed to 'do no harm' to either mind or body of patients and providers. At this stage, the differing needs of those with specific disabilities or medical conditions are considered. Psycho-physiological responses are considered in terms of their ability to support the quality of care, as well as the quality of work and creativity.

Innovations to enhance outcomes cover all aspects of mind and body. These aspects include sensory, perceptual and cognitive functions for problem-solving and critical decision-making. Socio-cultural constructs inform considerations of private and social spaces to enhance function, engagement and meaning. In this way, design is explored in relation to mind and body as well as health and wellbeing.

Embedded in this approach is the inclusion of guidelines on sustainable design, so that materials, systems and building performance 'do no harm' to the environment or inhabitants. The merger of healthy and sustainable design is evident in the recent development of sustainability guidelines for healthcare facilities, by institutions such as BREEAM for Health, United States Green Building Council, LEED for Healthcare, AIA Facilities Guidelines Institute, the Joint Commission, and the Global Health and Safety Initiative, among others. Most guidelines focus on exposure to pollutants and toxins in air and water, and via physical contact with materials. But design strategies to improve clinical outcomes are equally important and sustainability guidelines should be directed at improving both human and environmental outcomes.[1]

Methods

This scientific research paper reviews the development of several techniques that combine novel biological and environmental sensors in real and virtual simulation settings to test design hypotheses and allow subjects to see and hear the consequences of design. Recent developments in visualisation and acoustic rendering enhance the realism of immersion in virtual mock-ups.

The application of this flexible simulation environment is evaluated below in regard to the impact of sound on medication error and the quality of care; spatial cognition and preference; wayfinding; and the influence of light on human outcomes.

The development of visuo-auditory simulation environments, such as the Cave Automatic Virtual Environments (CAVE), provide controlled settings in which design hypotheses can be tested before design is finalised. Viewers interact with the virtual images using a 3D joystick and a head-tracking infrared sensor system, which registers the subject's location and orientation in space, and moves 3D visual fields according to their point of view. The viewer's head and joystick locations are logged over time, dynamically tracking their first-person perspective, position and interactions within the virtual setting. Use of collaborative-CAVE software also allows visualisation in many environments to be distributed in synch across many locations around the world.[3]

A novel computer-aided design system named CAVECAD allows users to alter dynamically the virtual environment while subjects stand within the stereoscopic model itself. This approach eliminates the need to create a 3D model at a desktop computer before importing it to a virtual environment. Thus, a number of design conditions can be tested without necessitating the building of, or change to, mock-ups prior to further testing. By logging subject responses over a sequence of trials, multiple design changes can be tested, according to controlled protocols and during synchronous recording of brainwave responses.

In CAVE simulation environments and dedicated listening environments, acoustic simulation systems have been developed to test, predict and improve the impact of acoustic design on human responses and function. Using dynamic audio-rendering software (SoniCAVE), scenes of sound can integrate databases of materials, audio samples from real healthcare environments and equipment, and geometric reverberation computations to create accurate predictions of real-life scenarios.[4]

Sound design

An acoustic simulation was designed to model the consequences of noise conditions on work errors. The Center for Quality Improvement and Patient Safety report, and analysis of 26,000 records in a US-wide anonymous error-reporting system (MEDMARX), revealed an increased rate of error in medications with similar-sounding names.[5] The consequences of this issue were demonstrated at a workshop where speech intelligibility and error were presented in three conditions: a dedicated sound lab, an auditorium, and in CAVE virtual simulations.

Sound-alike medications from the National Patient Safety 'sound-alike' medication list[6] were recorded in the presence of, and without, competing sounds (eg recordings of medical-instrument alarms, nearby conversations and HVAC noise). In all conditions, the participants were unable to discriminate between 'sound-alike' names from the list if the competing noises were greater than 15dB above the medication list (played at 65dB(A), the approximate level of conversational speech).

Although the participants were not clinicians, and would therefore be unfamiliar with the medication names, these results are consistent with the body of research that shows intelligibility improves as speech levels rise 15dB, or more, above the background noise level. Even greater separation between speech and noise is required in order to achieve equivalent intelligibility scores for those listening in a second language, and for those with hearing disorders and hearing that has diminished with age.

Unfortunately, the majority of critical-care environments far exceed these levels, dramatically increasing intelligibility and associated error. Figure 3 plots sound levels in a variety of hospital conditions. Using standard protocols for evaluating averaged noise levels, the intensity of sound ranged from 75-85dB(A) Leq in critical-care units such as emergency and intensive-care departments. These findings are consistent with recent studies demonstrating that noise in healthcare environments has been steadily increasing over the past 50 years, with no single facility operating within the sound levels recommended by the World Health Organization.[7] When impulse-sound peaks are measured, using time constants capable of recording sounds from alarms and equipment, a near constant impulse level is seen (in green lines), ranging from 100 to 120dB peak during shift changes.

Exposure to such sound levels increases the risk of noise-induced hearing loss, as well as the likelihood of physiological and psychological changes. Increased cardiovascular risk has been observed when daytime noise levels exceed moderate levels, and stress reactions, such as cortisol disturbances, have been observed in children who are exposed, for long periods, to low-frequency traffic noise averaged at less than 55dB(A).[8] Unwanted noise exposure and lack of speech confidentiality and privacy further diminish performance, communication, satisfaction and the healing quality of healthcare environments.

Findings from surveys of 118 medical practitioners and administrators at the California Institute for Telecommunications and Information Technology (Calit2), at the University of California, San Diego, confirmed concerns regarding acoustic conditions in healthcare settings. The list in Table 1 reveals the priorities for improving sound conditions, among those surveyed. Ordered in a 'hierarchy of care', acoustic modification should first consider the likelihood that unwanted noise may lead to death, or severe adverse events, such as medical or medication error as a result of miscommunication related to competing or high-level sound. The list of needs also considers enhancement of provider performance and the quality of the care environment, in addition to patient needs.

While today's guidelines call for greater attention to acoustic optimisation and acoustic consultation with healthcare design teams, the high sound levels and atypical sound profile generated by equipment and people during the provision of critical care exceed the conditions that minimum acoustic performance standards are designed to address. For example, the recommended wall systems for privacy in standard office spaces are insufficient to ensure confidential-speech privacy – especially in healthcare settings, where voices are often raised to command attention, or to express urgency.

The currently available computational,

Do no harm:
• Improve speech intelligibility to reduce medical and medication error: - enhance intelligibility of sound-alike medication orders - create controlled sound space for communication • Minimise risk of noise-induced hearing impairment or loss: - control sound distribution from helicopters, ambulances, alarms, etc. - reduce the risk of noise-induced hearing loss (e.g. neonates in intensive-care units)
Enhance the quality of care:
• Electro-architectural speech enhancement to improve comprehension: - narrow-beam speech enhancement and noise abatement where and when necessary • Provision of quiet and private spaces for communication: - places for doctors and families to talk - private conversation zones at the bedside to allow visitors to remain during shift reports • Acoustic design enhancements for confidential speech privacy: - clinical and critical-care environments where conversation may be louder than average - sensitive areas, such as financial services, admissions, and multi-patient spaces • Electro-architectural control of unwanted sound distribution: - narrow distribution of masking sounds to minimise unwanted masking of speech - increased speech privacy and confidentiality where clinical information is exchanged
Enhance the quality of work:
• Quiet spaces where concentration can take place (e.g. pharmacy, anesthesia, etc.). • Reduce unwanted or disturbing noise: - improve or control distribution of equipment noise - manage and reduce construction sounds and vibration
Enhance the quality of place:
• Control of sound profile per user: - Narrow-beamed music and sound scenes for each individual patient or provider - Narrow-beamed masking to separate sound sources

Table 1: Innovation-team survey results. The hierarchy of design priorities for acoustic modulation of healthcare environments

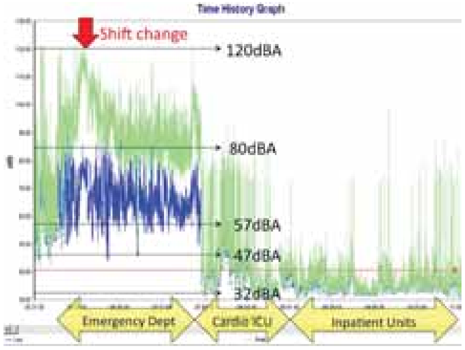

Figure 3: Unacceptable sound levels in critical-care settings. Sound-level equivalent (Leq) averages in decibels (dB(A) = blue lines) and impulse sounds (green lines) as a function of time and clinical-care function

Figure 4: The National Patient Safety list of 'sound-alike' and 'look-alike' medications associated with serious adverse events reveals a great need to create visual (pink labels) and auditory environments to reduce error

digital acoustic-modelling systems are based on algorithms with greater predictive accuracy for large theatre and concert spaces, yet low accuracy for small spaces such as patient rooms or emergency bays. New acoustic modelling software is being developed to overcome these limitations; promising new tunable beam-forming speaker-array systems are being developed to enhance communication more effectively where needed, and masking only where desired, using narrow beams to avoid unwanted masking effects. These techniques will afford designers the means to control unwanted sound distribution without use of walls or physical barriers that impede access, or obscure views.[9]

A view through space

Designers have typically considered the visual domain as the primary stimuli driving the human response to design. Several authors hypothesise that innate responses based on evolutionary pressures may account for design preference. A preference for places of prospect and refuge is thought to derive from adaptation to survival in a savanna ecosystem, where sightlines to predators are essential.[10]

It is further suggested that places of refuge, characterised by visual occlusion, appeal where safety is desired; however, places lacking permeability that limit escape or foresight of oncoming intrusion may induce a sense of fear. Completely enclosed spaces such as rooms with no windows, or confined spaces such as an MRI tube, can elicit a strong sense of discomfort, and evoke agoraphobia or claustrophobia.[11] In contrast, places of prospect, with a broad visual access from a single vantage point, may reduce stress.

It is also hypothesised that the design of spaces with high visibility and connectivity with multiple vantage points may promote environmental comprehension, and entice curiosity and engagement with a place.[12] Varying levels of visual and locomotive permeability have been found to determine probabilistic movement. Biederman and Vessel[13] suggest that the neurobiological system that rewards learning, via endomorphin release in parts of the brain involved in memory of place (parahippocampal cortex), may encourage exploration. Therefore, views that hint of the presence of concealed information and locomotive accessibility may, in fact, entice learning and increase preference of environmental experiences.

Analytic programmes, such as Space Syntax, have been widely used to map the relationship between spatial interconnectivity, visual vantage point and architectural form to the inclination to travel in a particular direction, and predict the aspects of space most likely to be learned.[14] Such methods, however, do not strongly consider the significance of vertical dimension and sense of volume, or the ease with which an observer may acquire spatial knowledge as they move their head position through several vantage points. In order to address these issues, systems have been developed to test the response of subjects to specific features of design while they move through immersive, stereoscopic CAVE visualisations of full-scale photo-realistic buildings.[15] Head-tracking systems allow for more natural exploratory movement and multiple vantage points, in comparison with computer navigation of a digital model on a desktop screen. Several spatial prototypes can be used, each one expressing a different balance between visual permeability and occlusion, and variation in depth layers evaluated.

Hamilton[12] tested this methodology in a pilot evaluation using a virtual model of the Salk Institute for Biological Studies, La Jolla, California, designed by Louis I Kahn (Figure 5). In this case study, specific design attributes were modified to offer different degrees of permeability and occlusion. A forced-choice assessment of paired spaces around a single vantage point indicated initial preference, followed by free movement, a post-test survey and open-ended questions to reveal changes in preference after exploration. Spatial-quality 'measurands' [quantities intended to be measured] were then analysed to determine if qualities other than permeability and occlusion were primary determinants of visual preference.

This study found spaces that achieved a volume of visual permeability from 20 to 40% were preferred. No participant preferred the most occluded space, in which the total volume of visual permeability was only 13%.

There was also a preference for visual volume and permeability that permitted the greatest depth of view. In the post-test survey, trends revealed preference of both visual complexity and order, which may be consistent with the reward for learning in a complex environment, and the desire to

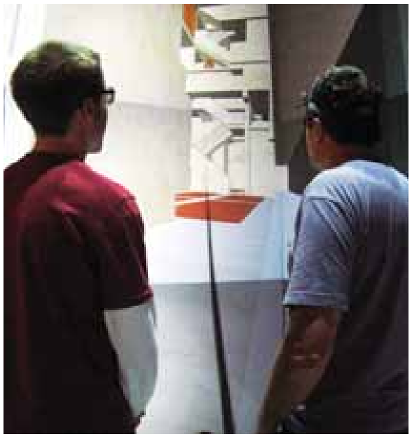

Figure 5: Virtual simulation of the Salk Institute is modified to test preference for permeability and depth

comprehend an ordered, permeable and easy-to-learn environment.

Greater understanding of visual attributes may be gained by emerging technologies using eye-tracking systems that can test visual attention to design features, presented as a factor of depth and visual tracking. For example, Jansen et al.[16] showed that saccadic eye movements tend to follow depth cues. Visual-attention tracking that includes depth, as well as the dimension of time, have been tested in virtual-reality CAVE simulations, where carefully controlled calibration can begin to map visual attention to specific architectural features.[17] Such measures are more accurate than tracking head movements alone, as eye and head movement are not always in alignment. Ongoing studies combining these technologies will add clarity to initial findings and enable more specific exploration of the preferred balance between occlusion and permeability, complexity and order, and a vast range of design attributes.

Memory in real and virtual places

A user's attention to many architectural features (visual, auditory, tactile, kinesthetic, etc.) can be studied by recording the subconscious 'experience' of design. Wearable and wireless bio-sensors, combined with environmental sensors, can track the body, brain and behaviour, as subjects are exposed to controlled elements of real or virtual buildings. For example, technologies that record heart rate and electroencephalographic (EEG) brainwaves can reveal and correlate cognitive reactions to specific design features, during wayfinding strategies, attention, concentration, relaxation or stress. Edelstein et al[17] used a 256-electrode array to reveal activity of individual components of the brain's cortical areas, as subjects navigated through CAVE simulations of real environments. Tracking systems logged the subjects' head position and view angle, as well as movement within the full-scale digital mock-up. Differences were observed in the frequency spectrum and intensity of responses during spatial navigation when the subject was in a space absent of cues to location, versus a setting rich with navigational cues.

In this early study, significantly stronger synchronisation in theta brainwaves and stronger desynchronisation of the lower alpha brainwave frequencies were observed in areas of the cortex that play a role in spatial and visual orientation (parietal and occipitotemporal areas). The parietal cortex uses visuo-spatial information from a first-person perspective, along with parietal and occipitotemporal areas involved in processing changes in direction and planning of future paths. Disorientation associated with increased alpha-wave desynchronisation likely reflected increased demands on attention.

In contrast, most psycho-physiological studies use desktop screens to show small architectural visualisations of 3D digital buildings. In such simulations, the subjects must imagine themselves interacting within the building – a difficult task for many clients, students and professional designers, even. In this way, virtual CAVE simulations, in which micro-sensors monitor subjects as they move through full-scale architectural spaces, clearly offer more 'ecologically relevant' simulations.

Integrating light

The human visual system is not merely engaged in sight but also in the integration of light to assess the body's exposure to diurnal and nocturnal patterns. A body of neuroscientific and clinical research, dating from before the 17th century, reveals that exposure to light has significant impact on mental state, cognitive function, behaviour and physical health. Recent epidemiological studies suggest that elevated cancer rates in nurses, night-shift workers and flight crew may be related to unnatural patterns of light or dark exposure. Measures of neuroendocrine levels reveal the correlation between daily fluctuations in melatonin, which modulates sleep and wakefulness, and elevated cortisol levels, which prepare the body for activity.

Consistent with these findings, Edelstein et al[18] found significant differences in heart-rate variability (HRV) – a well-established indicator of health risk and stress – during performance of memory tasks when subjects were exposed to less than 15 minutes of red light, versus bright white (with a blue peak) light. Whereas many studies have focused on the influence of blue and bright white light on melatonin responses, this experiment demonstrated that red light is associated with changes in cardiac responses. In red light, HRV relaxation was appropriate during rest, and activated only during the memory task. In contrast, bright white light with a blue peak was associated with a constantly active heart rate throughout the experiment. In a parallel study, brainwaves recorded via a 256-electrode EEG array tended to be different during red-light conditions versus bright white-light conditions in a single-subject self-control study.[19]

Such research suggests that sustainable-design guidelines should include findings that reveal the spectral range, intensity and pattern of light important to human health and function, as well as vision. Rather than guidelines that suggest average light levels across an entire building, or propose percentages of exposure, lighting design should respond to the specific needs of the users, in addition to the uses of a space. In this manner, programming of spaces for night-shift workers, such as clinicians, factory workers, aircrew or business travellers, could be prioritised when planning access to spaces with natural light.

Furthermore, spaces for control of light and access to darkness would also drive design decisions. The unwanted distribution of light into places occupied by others should be a primary consideration in lighting design for healthy places. Rather than a 'one size fits all' approach, thoughtful lighting strategies should provide for safety and egress, as well as individual controls to modulate light exposure according to clinical needs, functional tasks and individual circadian status.[19]

Conclusions

Synchronous measurements of human responses, including both biosensors and, environmental sensors, and behavioural-tracking techniques, now offer the means to explore architectural issues that have, to date, remained as design hypotheses. Using a variety of emerging technologies in pre-design studies and post-occupancy evaluations, rigorous research can inform the design of environments that support, rather than impede, health and wellbeing.

An interdisciplinary neuro-architectural framework for design thinking employs such technologies, merging scientific methods with observational, ethnographic, sociological, psychological, physiological and medical results. This approach is particularly relevant to healthcare facilities, which serve the most fragile and most gifted. Moreover, healthcare environments represent all architectural types, being, as they are, places of healing and health, teaching and learning, and business and rest. Similarly, as places that encounter birth, death, discovery and recovery, healthcare facilities must meet the broadest of human challenges.

As healthcare design increasingly incorporates sustainable-design guidelines, we can apply the evidence derived to address human needs that go beyond reduction of noxious and toxic exposures. Architectural, technical and medical knowledge can, in this manner, accelerate such best practice to enhance human experience, performance and health itself. These applications of new technologies sit at the interface between neuroscience and architecture, and enables the provision of more rigorous data for research-based design. The ultimate goal is to support the design of healthy places for all: the healthy, the infirm, the gifted, and those with special needs, and to promote and enhance health and wellbeing across all peoples.

Author

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Figure 6: Dr Edelstein navigates through the virtual-reality stereoscopic model of the Calit2 Atkinson Hall in the StarCAVE

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Simulating Circadian Light: Multi-Dimensional Illuminance Analysis

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Abstract

The effects of building design on human circadian rhythms have been linked to health, behavior, and performance outcomes. Limited options, however, are available for predicting circadian stimuli during the design process, other than via quantification of a single variable known as melanopic illuminance. Several additional circadian illuminance quantities (including rhodopic-, cyanopic-, chloropic-, and erythropic-lux) have not, to date, been utilized in simulating circadian exposure. We demonstrate how daylight, spatial, and material choices may alter the contribution of five currently-known photoreceptor channels to regulating circadian rhythms. This novel 3D rendering system will also support future circadian research and applied solutions.

Introduction

Visual and Non-Visual Responses to Light

There is a mounting body of evidence for lighting's influence on "nearly every physiological, metabolic and behavioral system" (Lucas et al. 2014). Human exposure to light and dark patterns is associated with changes in endocrine function, growth, digestion, core body temperature, reaction times, fatigue, cognitive function and mood states. Research has demonstrated statistically-significant changes in heart rate variability (HRV), a reliable indicator of health risk as well as cognitive engagement, even in the presence of short-term exposure to electrical light (Edelstein et al. 2008). Light therapy has been applied to ameliorate conditions such as seasonal affective disorder (SAD), dementia, the effects of traumatic brain injury, and various sleep disorders; further, it has been used to counteract fatigue from jetlag, night shift work, and even space flight (Zatz [ed.] 2005).

For most of evolutionary history, solar light was the primary stimulus to indicate the time of day, and to entrain human 'circadian rhythms', the biological functions that cycle around the time of day. The advent of electrical lighting at the turn of the 20th century, however, has disrupted this relationship. This presents numerous challenges, as well as potential opportunities, for architectural designs that more effectively serve human wellbeing and performance. Indeed, the American Medical Association (AMA) adopted a policy statement in 2012 citing evidence that links circadian rhythm disruption to impacts on human health, including "cell cycle regulation, DNA damage response, and metabolism" (Stevens et al. 2013). Further, the AMA notes that there is accumulating "epidemiologic support for a link of circadian disruption from light at night to breast cancer" (p. 343).

Historically, the scientific community thought that the conventional visual photoreceptors of the human eye – the rod cells and three types of cone cells in the retina – were responsible for entraining these circadian rhythms. Relatively recently, however, Brainard et al. (2001) and Thapan et al. (2001) discovered a new category of photoreceptors: intrinsically photosensitive retinal ganglion cells (ipRGCs). These cells are primarily responsible for 'non-visual' processing of light integrated over time. These cells – and associated retinal bio-circuitry that include the rods, cones, and various connector cells – transmit neural signals to a part of the brain known as the suprachiasmatic nucleus (SCN), the body's 'master' circadian clock. The SCN, in turn, innervates a complex network of neural and endocrine systems that send hormones coursing through the blood stream, and influence the brain, mind, body, and behavior.

To date, however, most physiological models of human retinal function continue to quantify light in terms of the visual responses of the rods and cones alone. In particular, the commonly-used photopic spectral sensitivity function (also known as the 'luminosity' function in color science and related disciplines) describes the contributions of mostly long- and middle-wavelength cone cells to an aspect of visual function that hardly includes shorter wavelengths of light. This photopic function ($V(\lambda)$, or $\bar{y}(\lambda)$) is derived from the CIE RGB model of color perception, and used as the color matching function for the Y channel in the tristimulus CIE XYZ color space model, first published by the *Commission Internationale de L'Éclairage* (CIE) in 1932. Although updates have been made, the original RGB and XYZ models are still widely used in colorimetric applications, and still remain the basis for the *Systéme International* (SI) photometric units.

Visual Lighting Simulation and Rendering Systems

As a result of this narrow focus, a majority of conventional lighting simulation software platforms compute the

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appearance of light and materials in the form of red, green and blue (RGB) color channels. The behavior of light in the real world however, is a complex interplay of various wavelengths of light being emitted from, transmitted through, and reflected off various physical objects in the environment. Although it is computationally efficient to collapse the representation of light into three primary values – as opposed to performing raytracing calculations for every wavelength of light at every point in a given field of view – tristimulus-based simulations pose known discrepancies in relation to the accurate simulation or perception of light. Since it is possible for two materials with different spectral reflectances to correspond to the same RGB value under certain lighting conditions – a phenomena known as metamerism (Wyszecki and Stiles 2000)– RGB-based calculations can, and occasionally do, yield incorrect color or illuminance values for certain scenes. Further, the CIE RGB color model and the associated photopic spectral sensitivity function are known to distort the complex contribution of blue light to color and illuminance perception for the sake of developing a linear, additive model for photometric units (Rea and Figuerio 2010).

Melanopic Lighting Simulation and Rendering Systems

Further, the CIE RGB color space and associated models do not correspond precisely to our current knowledge of the non-visual, circadian impact of light. Over the past decade, however, much attention has been placed on analyzing the role of ipRGCs, which have the greatest photosensitivity to light with wavelengths in the range of 447-484 nm (roughly the 'blue-cyan' portion of the visible electromagnetic spectrum for a monochromatic light source; included in Figure 1) (Lucas et al. 2014). Since ipRGCs gain their photosensitivity from the presence of a photopigment known as melanopsin, various curves that have been proposed in scientific literature for characterizing the spectral sensitivity of ipRGCs have often been referred to as 'melanopic' functions. In contrast, the CIE photopic spectral sensitivity function, which describes visual perception of brightness, has a peak at 555 nm (corresponding to 'tennis ball yellow' in appearance), and groups together the response of all of the associated retinal bio-circuitry into a single metric of photopic illuminance.

A number of researchers have developed methods for simulating the melanopic component of circadian illuminance in the context of building design. Rea et al. (2012) incorporated biological research in their Circadian Stimulus (CS) calculator, which includes the effects of sub-additivity and color opponency processes in its version of a melanopic spectral sensitivity function, and facilitates the calculation of circadian efficiency for a given light source. Inanici et al. (2015) implemented a full-spectral rendering technique developed by Ruppersberg and Bloj (2006, 2008) as the basis from which the authors calculated melanopic illuminance for given 3D scenes. This technique is further developed in their Lark Spectral Lighting Tool for lighting simulation and rendering (Inanici and ZGF Architects 2015). Based upon this increasing body of research, melanopic illuminance analyses are now informing the building design profession. For example, the International WELL Building Standard (International WELL Building Institute 2016), recently provided a computational method to calculate equivalent melanopic lux (EML), and have recommended minimum EML exposure durations and illuminance guidelines for projects seeking WELL certification.

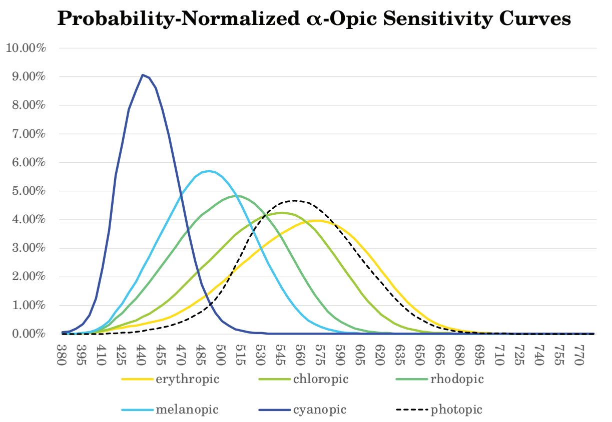


Figure 1: The five α-opic spectral sensitivity curves recommended by Lucas et al. (2014), along with the photopic function for reference. As further recommended by the authors, each curve has been 'probability-normalized' or scaled for equal area underneath each curve. The color of each curve (excluding the photopic function) roughly corresponds to the apparent color of the peak wavelength.

Pentachromic Lighting Simulation

By focusing on melanopic illuminance alone, however, these systems do not consider the complex, nuanced contribution of other circadian functions. More recent findings demonstrate that multiple retinal and physiologic factors, including the rods, cones and ipRGCs, contribute to non-visual as well as visual mechanisms. Ho Mien et al. (2014) demonstrated that alternating red light – light with wavelengths beyond currently-proposed peak spectral sensitivity ranges for melanopsin – can mediate circadian phase resetting of physiologic rhythms in some individuals. Their results also show that sensitivity thresholds differ across non-visual light responses, suggesting that cones may contribute differentially to circadian phase resetting, melatonin suppression, and the pupillary light reflex during exposure to continuous light. Gooley et al. (2012) further demonstrate that rods, cones, and ipRGCs play different roles in mediating pupillary light responses during exposure to continuous light, and suggest that it might be possible to enhance non-visual light responses to low-irradiance exposures by using intermittent light to activate cone photoreceptors repeatedly in humans. Lucas et al. (2012) reviewed electrophysiological and behavioral data to provide a model in which each photoreceptor class plays a distinct role in encoding the light from the environment. As the intact retina is a composite of extrinsic (rod/cone) and intrinsic (ipRGC) mechanisms, the authors propose that all three photoreceptor classes, including the ipRGCs, contribute light information to the brain's circadian clock.

A seminal paper published by leading experts in circadian research noted that currently, “the most appropriate use of that capacity [referencing the ability to record or simulate the spectral power distribution of light sources] would be to calculate the effective irradiance experienced by each of the rod, cone and melanopsin photoreceptors capable of driving non-visual responses” (Lucas et al. 2014, p. 6). They devised a new light measurement strategy that takes into account these complex non-visual mechanisms, and categorized illuminance stimuli into five individual photoreceptor components: cyanopic (short-wavelength cones), chloropic (medium-wavelength cones), erythropic (long-wavelength cones), rhodopic (rods), and melanopic (ipRGCs) illuminance quantities. Each of these photoreceptor components (collectively referred to as ‘α-opic’ components) have different spectral sensitivity curves (see Figure 1). In addition, the authors provided a spreadsheet for calculating these illuminance quantities for a given light source of a specified spectral power distribution and photopic illuminance value.

A Novel Pentachromic Lighting Simulation and Rendering System

While the spreadsheet developed by Lucas et al. (2014) allows for calculation of multiple circadian illuminances given a single light source of known spectral power distribution, the building professions must also begin to consider how light reflection, absorption and transmission through building materials may alter lights’ spectral characteristics and impact circadian exposure calculations. In addition, designers must consider each occupant’s field of view and exposure to light as it interacts with the geometry and spatial arrangement of materials. The calculation methodology to be presented in this paper addresses these considerations; further, it is applicable to all building types, as the circadian impact on human function is relevant to any place that humans occupy (Edelstein et al. 2008).

In order to simulate circadian light in ways that incorporate the varying photoreceptor functions mentioned above, we developed a raytracing-based computational method to render the spectral reflectance and transmission of daylight entering and interacting with a 3D model, from a user’s singular point of view and location, at a particular date and time. These analyses are carried out across an arbitrary number of spectral channels or bins (nine, in the case of this paper), as opposed to conventional three-channel raytracing and simulations.

Methodology

Setting

Sprout Space,™ (Figure 2) a high-performance, modular, single-room classroom system, was used as a vehicle for exploring the impact of conceptual design and material choices on metrics describing circadian exposure. A digital model was developed at geographic coordinates and EPW weather conditions for Los Angeles, CA (34.0522°N, 118.2437°W). June 21, 9:00AM PDT was the chosen date and time for all analyses performed. The sky dome color correlated temperature (CCT) was set to 12,000K; this is consistent with typical blue sky CCT measurements occurring in the range of 9,000-25,000K (Lechner 2014). No artificial light sources were included in the model. The chosen viewpoint for the analyses is in the center of the classroom, standing height (chosen as 1.829 m above finished floor), looking straight north, with a view angle towards two windows facing northeast and northwest, respectively. A 0.6 m roof overhang extended around the entire building. Matte-finish Munsell color chip reflectance spectra, measured in 1 nm increments and compiled by Spectral Color Research Group at the University of Eastern Finland (n.d.), are used as proxy data for simulating opaque material choices. Spectral properties for glazing choices, measured in 5 nm increments, were retrieved from the International Glazing Database 14-5 (Lawrence Berkeley National Laboratory 2011). Material data included in the analysis are provided in Tables 1 and 2.

Figure 2: Sprout Space,™ a modular, single-room classroom system, as-built. This design concept was used as a starting point for material design exploration.

Calculation Methodology

We extend the calculation methods proposed by Inanici et al. (2015) to include coefficients for circadian illuminance in rhodopic-, cyanopic-, chloropic-, and erythropic-lux for nine-channel spectral lighting simulations to be performed using the Radiance Lighting Simulation and Rendering System (Ward 1994). In Radiance, three-channel (RGB) lighting calculations and how they relate to photopic luminance or illuminance quantities can be described as shown in Equation 1:

$$L = 179(0.2651R + 0.670G + 0.065B) \qquad (1)$$

where the coefficients for Radiance are defined as R (586-780 nm), G (498-586 nm), and B (380-498 nm) to correspond to each channels’ relative contribution to photopic luminance. The luminous efficacy factor for equal-energy white light in Radiance is 179 (lm/W). Some readers may note that the peak spectral efficiency of the photopic luminosity function is 683.002 lm/W at 555 nm, approximately corresponding to ‘tennis ball yellow’ in apparent color. Lighting in Radiance, however, is considered spectrally-neutral and not ‘tennis ball yellow’, and the factor 179 corresponds to average luminous efficacy for all visible wavelengths of light (380-780 nm).

The nine spectral bin intervals proposed by Inanici et al. (2015) are also retained for the purposes of this analysis.

Table 1: Munsell color chip reflectance spectra to be included in α-opic illuminance analyses.

Specification	Description
5R 9/2	Pale Red
5R 4/12	Medium Red
5YR 6/12	Medium Red-Yellow
5YR 2.5/1	Dark Red-Yellow
5Y 7/10	Medium Yellow
5GY 8/10	Medium Green-Yellow
5BG 5/8	Medium Blue-Green
5PB 6/10	Medium Purple-Blue

'Specification' denotes the official Munsell name for the material, whereas 'Description' denotes the name to be used in this paper.

Table 2: Munsell color chip reflectance spectra to be included in α-opic illuminance analyses.

Specification	Description
Pilkington North America Optiwhite	Clear Glazing, $\mathrm{T_{Vis}} = 0.91$
Hankuk Glass Industries Inc. HanGlas Hanlite Green 8mm	Green-Tinted Glazing, $\mathrm{T_{Vis}} = 0.68$
Pilkington North America Graphite Blue	Blue-Tinted Glazing, $\mathrm{T_{Vis}} = 0.61$

'Specification' denotes the IGDB manufacturer and product name for the selection, whereas 'Description' denotes the name to be used in this paper.

This allows for increased spectral resolution over typical three-band increments, in order to more accurately capture inflections in lighting and material spectral data, as well as each of the various α-opic spectral irradiance or functions. The 24 illuminance analyses and raytracings of the example model included in this paper can be completed within the course of an 8-hour working day. Finer spectral resolution may be achieved by designating more bins, at the cost of performing additional renderings and incurring additional analysis time.

Spectral photosensitivity functions $\mathrm{N}_\alpha(\lambda)$ (also referred to as 'filters' for shorter reference) for the five human photopigments included by Lucas et al. (2014) in the Irradiance Toolbox spreadsheet, normalized to unity in surface ($\int_{380}^{780} N_\alpha(\lambda)d\lambda = 1$), are integrated over each of the nine spectral bins as follows (Equation 2):

$$c_{\alpha,n} = \int_{\lambda_{n,0}}^{\lambda_{n,1}} N_\alpha(\lambda)d\lambda \tag{2}$$

where $c_{\alpha,n}$ is the spectral band coefficient to be calculated, $\lambda_{n,0}$ and $\lambda_{n,0}$ are the corresponding boundaries in nm for the given spectral bin, and $\int_{380}^{780} N_\alpha(\lambda)d\lambda = 1$. This yields the following coefficients shown in Table 3. For melanopic illuminance, we use the Lucas et al. (2014) spectral sensitivity function. As bin coefficients were summed from data interpolated (Catmull spline) to 1 nm resolution from the original 5 nm data in Lucas et al.'s (2014) supplementary Irradiance Toolbox spreadsheet, bin intervals were also start-offset by 1 nm from the values defined by Inanici et al. to avoid overlapping values at bin boundaries.

It should be noted that Inanici et al.'s (2015) approach uses photopic and melanopic spectral sensitivity functions of equal peak amplitude (683 lm/W), whereas Lucas et al. (2014) and the methodology presented here begin with spectral photosensitivity functions of differing amplitude, but with equal areas under each curve (refer to Figure 1). Both methods aim to offer mathematical convenience in the sense that α-opic illuminance quantities have similar orders of magnitude, and can be more readily compared to each other in a given set of analysis results. It should not be construed, however, that the magnitude of each quantity implies any 'functional' weighting with respect to photoreceptors' contribution to circadian responses, as further scientific research is needed to accurately describe the relative contribution of each photoreceptor to circadian responses, as well as under what scenarios.

Next, raytracing analyses for each of nine spectral bins are performed in Radiance. For materials, the reflectance or transmittance quantities for each run are derived by taking the average reflectance or transmittance over each spectral bin. These material spectral reflectance or transmittance quantities are then assigned, three at a time, to sub-analyses in order to perform illuminance calculations and renderings in Radiance.

To calculate α-opic illuminance (or per-pixel α-opic luminance for renderings) each spectral bin result p_n in radiometric units (watts, W) is weighted by a corresponding $c_{\alpha,n}$, summed, and scaled by the 179 lm/W Radiance luminous efficacy constant (Equation 3):

$$L_\alpha = 179 \sum_{i=1}^{n} c_{\alpha,n} p_{\alpha,n} \tag{3}$$

In the specific case of the analyses performed in this paper, this calculation may be simplified to a notation similar to the equations given in Inanici et al. (2015), as shown in Equation 4:

$$\begin{aligned} L_\alpha = 179(&c_{\alpha,1}p_1 + c_{\alpha,2}p_2 + c_{\alpha,3}p_3 \\ &+ c_{\alpha,4}p_4 + c_{\alpha,5}p_5 + c_{\alpha,6}p_6 \\ &+ c_{\alpha,7}p_7 + c_{\alpha,8}p_8 + c_{\alpha,9}p_9) \end{aligned} \tag{4}$$

An important note is that that here, the Radiance luminous efficacy constant 179 lm/W is held constant for all of the α-opic illuminance calculations, and is not scaled as in Inanici et al. (2015). This is to conform with the recommendation by Lucas et al. (2014) in their Irradiance Toolbox spreadsheet documentation that the various α-opic illuminance values are always equal to photopic illuminance (and each other) for a theoretical equal-energy radiator. Inanici et al. (2014) recommend a melanopic luminous efficacy constant of 148 lm/W for the Lucas et al. (2014) melanopsin photosensitivity curve and 130 lm/W for the Rea (2005) version. Melanopic illuminance results

Table 3: Nine spectral analysis bins and corresponding weighting coefficients for calculating α-opic illuminances.

Coeff.	Wavelength	Erythropic	Chloropic	Rhodopic	Melanopic	Cyanopic	Photopic
B1	380-422	0.005353	0.006532	0.012830	0.017681	0.141026	0.000421
B2	423-460	0.027821	0.050377	0.124047	0.184631	0.618178	0.009797
B3	461-498	0.083861	0.157113	0.290932	0.398948	0.230136	0.053295
G1	499-524	0.119148	0.181933	0.246991	0.244785	0.009820	0.131072
G2	525-550	0.169969	0.216596	0.199600	0.118204	0.000748	0.224349
G3	551-586	0.279473	0.260651	0.111940	0.033460	0.000074	0.316548
R1	587-650	0.292456	0.124616	0.013745	0.002134	3.91E-06	0.248866
R2	651-714	0.021719	0.002299	0.000087	0.000013	4.22E-08	0.015700
R3	715-780	0.000249	0.000022	1.02E-06	1.73E-07	1.02E-09	0.000201

calculated via Inanici et al.'s (2015) method may be scaled by 179/148 for the Lucas curve, or 179/130 for the Rea curve, to convert to the method delineated in this paper.

We analyzed twenty-three (23) material design alternatives for the Sprout Space, grouped into seven sets of runs, for comparison to an asserted baseline design: Munsell colors of yellow-green walls, a dark red ceiling, a pale red floor, and clear glazing (Figure 3a).

A breakdown of these seven experiments are as follows:

- Wall material: 5 alternatives
- Ceiling material: 5 alternatives
- Floor material: 5 alternatives
- Wall specularity ('shininess'): 2 alternatives
- Ceiling specularity ('shininess'): 2 alternatives
- Floor specularity ('shininess'): 2 alternatives
- Glazing material: 2 alternatives

The purpose of this limited exploration is to begin to explore the relative impacts of design choices on circadian exposure, and to test the efficacy of the calculations. Future work will include more systematic exploration of the design space.

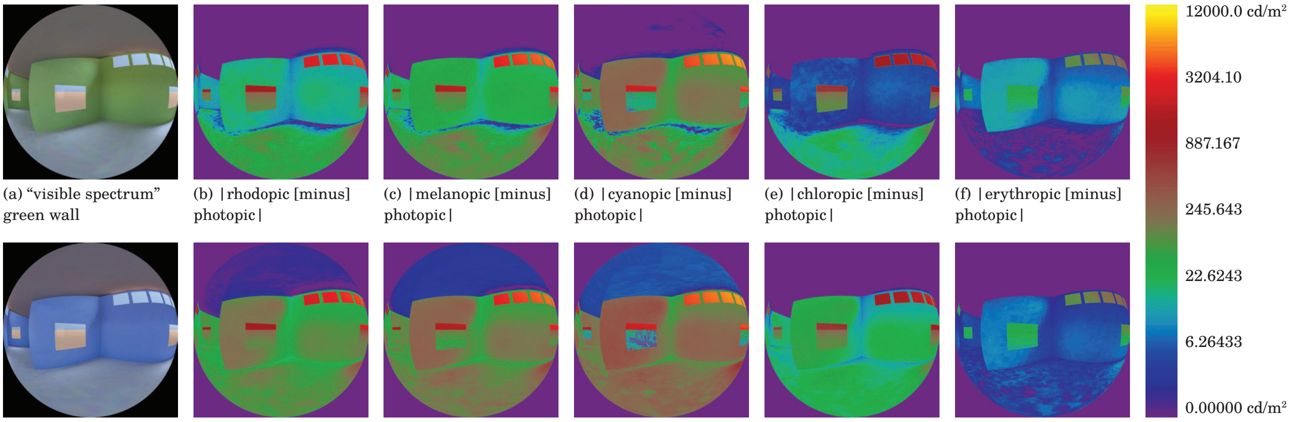
Results and Evaluation

Design Decision-Making

Although the precise impact of different and combined dosages of the various circadian illuminance levels are not yet well-defined in the scientific literature, it is possible to compare the impact of design choices to each other based on their impact on the various components of circadian illuminance. This paper limits its scope of decision-making to visualization and analysis of design choices on maximizing or minimizing each α-opic illuminance value.

Results

In Figure 3, the false-color scale (y-axis) shows the difference from the photopic visible spectrum, with the greatest difference in yellow (12,000 cd/m^2) and no difference in purple (0.00 cd/m^2). In the baseline condition with the yellow-green wall (Figure 3a-3f), the greatest absolute difference from photopic luminance is observed with the cyanopic filter (3d), and a moderate difference is seen with the rhodopic (3b) and then melanopic (3c) filters. The least difference is observed with the erythropic (3f) and then chloropic filters (3e). In the test condition with a purple-blue wall (Figure 3g-3l), the false-color scale also shows the greatest difference from the photopic filter (3g) with the



(a) "visible spectrum" green wall
(b) | rhodopic [minus] photopic |
(c) | melanopic [minus] photopic |
(d) | cyanopic [minus] photopic |
(e) | chloropic [minus] photopic |
(f) | erythropic [minus] photopic |

(g) "visible spectrum" blue wall
(h) | rhodopic [minus] photopic |
(i) | melanopic [minus] photopic |
(j) | cyanopic [minus] photopic |
(k) | chloropic [minus] photopic |
(l) | erythropic [minus] photopic |

Absolute difference (α-opic [minus] photopic)

Figure 3: Baseline α-opic luminance and illuminance analysis run for a Sprout Space design scenario.

Legend: The fisheye renderings show the absolute difference in luminance of each of the a-opic filters minus the photopic filter. The false color scale shows the greatest difference ranging from yellow (12,000 cd/m^2) to purple (0.00 cd/m^2).

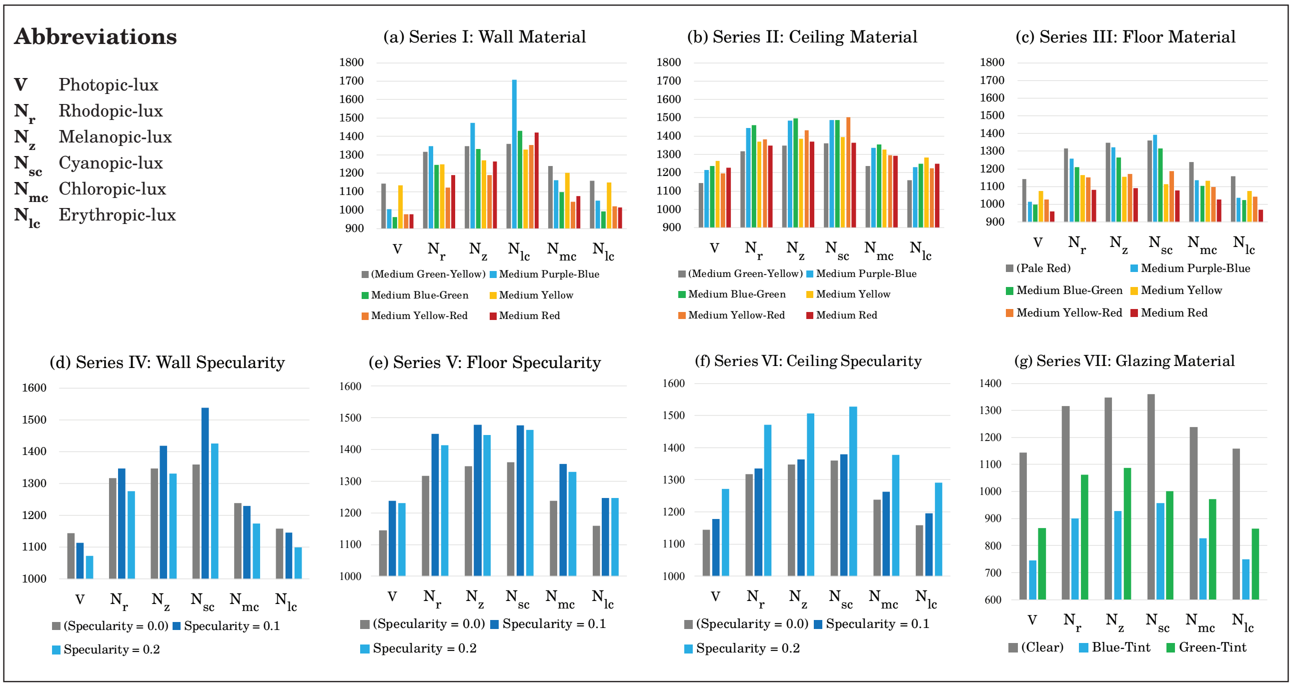


Figure 4: Results for the 24 illuminance analysis runs, grouped into seven series (I-VII, a-g).

Legend: Series I (a) compares the impact of wall material changes on various -opic circadian illuminances while holding all other design choices constant with respect to the baseline analysis run; Series II (b) explores changes in ceiling material; Series III (c) explores floor material; Series IV (d) explores wall specularity; Series V (e) explores floor specularity; Series VI (f) explores ceiling specularity; Series VII (g) explores glazing material.

cyanopic filter (3j). However, the compared to the baseline room condition in the row above, there is greater change in the melanopic (3i) than in the the rhodopic (3h) filter. The least change is observed in the erythropic (3l) rather than in the chloropic filter (3k).

We observe almost no difference for α-opic quantities on the ceiling in the baseline scenario. Aside from the dark color of the ceiling limiting reflected light in general, another observation would be that if any differences in α-opic luminances were to occur due to reflected light from the yellow-green walls, we might expect the yellow-green-sensitive chloropic filter to most strongly illustrate such differences (3e). Since the photopic filter is already heavily weighted towards the chloropic filter, little difference occurs in this scenario. In contrast, when the purple-blue wall is introduced (Figure 3g-3l), we see some absolute difference in the ceiling luminances in the rhodopic (3h), melanopic (3i) and cyanopic (3j) filters, which are all in the blue range of the spectrum.

The α-opic illuminance values in Figure 4 show changes for each decision variable of wall, ceiling, floor or glazing materials. Across all of the trials, we notice that cyanopic illuminances are typically the highest among the various α-opic illuminance quantities. This makes sense, given the short-wavelength ('blue') light from the clear blue sky is the dominant light source in the scene.

It is also noticeable that the photopic illuminance quantities for each run are often more similar to the chloropic and erythropic illuminance quantities than to other α-opic illuminance quantities. This is consistent with Rea and Figuerio's (2010) discussion of how photopic spectral sensitivity weightings (defined by the luminosity function $V(\lambda)$) are primarily derived from the photosensitivities of medium-wavelength cones (chloropic-lux) and long-wavelength cones (erythropic-lux). Further, in our wall analysis trials (Figure 4a), the 'spike' in photopic illuminance for a medium yellow wall material is mirrored in the chloropic and erythropic illuminance quantities, but not the rhodopic, melanopic or cyanopic illuminance quantities.

In the ceiling material trial (Figure 4b), α-opic illuminance values typically increased for all changes from the baseline analysis run. Given the dark material chosen for the ceiling (a dark-red Munsell color sample), it makes sense that lighter materials would generally reflect more light and increase illuminance almost across all α-opic quantities. The peak values for each α-opic illuminance quantity, however, correspond with the peak reflected wavelength of each material. For chloropic illuminance, which reflects the spectral photosensitivity of medium-wavelength or 'green' cone cells, medium blue-green ceiling material results in the highest chloropic-lux value.

Conversely, α-opic illuminance quantities typically decreased for almost every alternative floor material choice (Figure 4c), compared to the baseline analysis run. Since the baseline floor material reflectivity was relatively high to start, it makes sense that the series of darker material alternatives generally absorbed more light and decreased α-opic illuminances.

In the glazing material trial (Figure 4g), clear glass ($T_{Vis} = 0.91$), unsurprisingly, yields the greatest α-opic illuminance values. The green-tinted glass ($T_{Vis} = 0.68$) yielded greater α-opic illuminance values than the blue-tinted glass

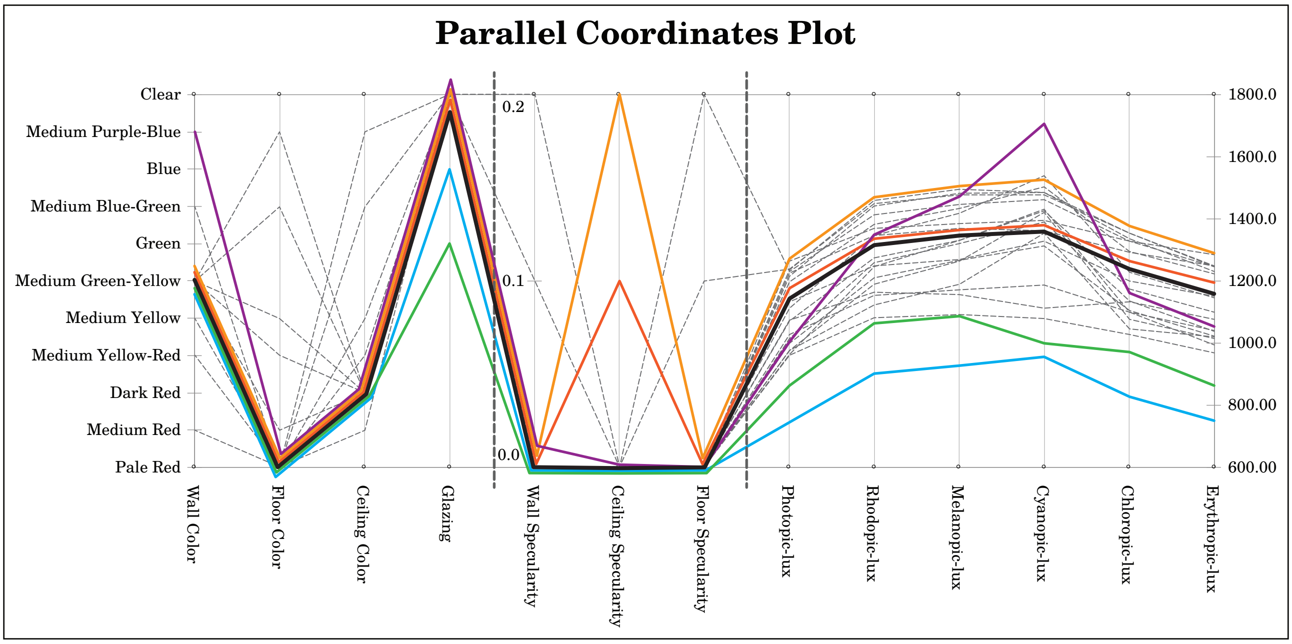


Figure 5: Parallel coordinates plot of different material inputs and illuminance levels.

Legend: Each y axis denotes a particular design parameter or feature; input parameters for each run are denoted in the left half, and results are denoted on the right half. The black line denotes the baseline configuration; the purple line denotes the impact of changing the walls to a purple-blue material; the light orange line denotes the impact of increasing ceiling specularity ($S = 0.2$) while holding all other variables constant; the dark orange line denotes the same, for an intermediate specularity ($S = 0.1$); the green line denotes the impact of green-tinted glazing ($T_{Vis} = 0.68$); the blue line denotes the impact of blue-tinted glazing ($T_{Vis} = 0.61$).

($T_{Vis} = 0.61$), which yielded the lowest α-opic illuminance values among all of the 24 analysis runs. This result may demonstrate the effect of reduced visual transmittance for the green- and blue-tinted glazing selections on visual transmittance compared to the clear glazing. Continued exploration of the design decision space would be a way of further evaluating this finding.

The parallel coordinate plot in Figure 5 explores the interaction of multiple architectural variables on the α-opic illuminance values for the Sprout Space design alternatives. This method allows visualization of interactions that can be a useful design tool to evaluate a series of decisions. The physical input variables are plotted on the left side of the graph, and the resultant α-opic illuminance values are plotted on the right. The black line represents the initial baseline run using Munsell colors of yellow-green walls, a dark red ceiling, a pale red floor, and clear glazing.

Relative to this baseline, increasing the ‘shininess’ or specularity S of the dark red ceiling surfaces (up to $S = 0.2$) was associated with the largest values across photopic, rhodopic, melanopic, chloropic and erythropic illuminance quantities (Figure 5, light orange line), as well as a relatively high value for cyanopic illuminance. The intermediate setting for ceiling specularity ($S = 0.1$), however, shows a decrease in the various α-opic illuminances compared to the ‘shiniest’ ceiling (Figure 5, dark orange line).

However, a change to purple-blue walls (Figure 5, purple line), even with the lowest specularity settings for ceiling, walls and floor ($S = 0.0$), yields a clear cyanopic peak (with ceiling, floor, and glazing colors maintained at the baseline design configuration).

In comparison to clear glazing used in the baseline condition, the introduction of a green-tinted glazing with a lower transmittance ($T_{Vis} = 0.68$), demonstrates a drop in all α-opic illuminance values (Figure 5, green line). Here, we again see that the blue glazing material (Figure 5, blue line) tested had the lowest transmittance ($T_{Vis} = 0.61$), and yielded the lowest α-opic illuminance values.

A more systematic exploration of the design space and continued evaluation of such interactions are needed to validate these findings, and to understand more precisely how changes to material properties, geometries and proximities may impact α-opic illuminance quantities.

Conclusion

Current physiologic research demonstrates that a pentachromic visual system influences human circadian responses, and yet few simulation and rendering techniques have attempted to calculate more than a single melanopic function. The methods reported in this paper demonstrate the computation and rendering of light in terms of five retinal irradiance functions, which may then be applied to architectural design scenarios and design decision processes. In addition, the system described shows the disparate impact that material choices may have on the interactions between the various α-opic spectral irradiance functions, simulated in both visual and false-color renderings.

With this tool, we can use visual pattern and color recognition to rapidly assess where maximal circadian exposure would occur. With this tool, the differential impact of each filter can be computed, simulated and predicted in isolation and in combination with changes to material parameters. The literature to date shows us that these different opic filter impact human outcomes. By using this tool in combination with on-site, real-world and empirical studies, we can advance our understanding of the relative impact of each retinal irradiance function in human terms.

Although it is not yet possible to predict the relative impact of each retinal irradiance function, the value of continued research is clear. Clinical studies confirm the deleterious effects of both over and under exposure to light on the brain, mind, body and behavior. Yet, lighting trends and preferences often result in exposure to unnatural wavelengths and intensities, and the pervasive use of computer monitors, smart screens, and street lighting systems add further risk to human health.

However, the development of programmable LED lighting systems may provide the dynamic control necessary for each individual to tune their lighting exposure to their visual acuity, circadian status, and non-visual sensitives. The output of such lighting systems would take into account the effects of circadian exposure that vary as a function of time, duration, and wavelength of light.

With the advancement of research that defines the specific influences of different wavelengths, rendered simulations may assist in guiding architectural programming, planning and design. The design of the material properties, spatial geometries, and architectural fenestration will offer a more nuanced means to optimize light for human visual and circadian health.

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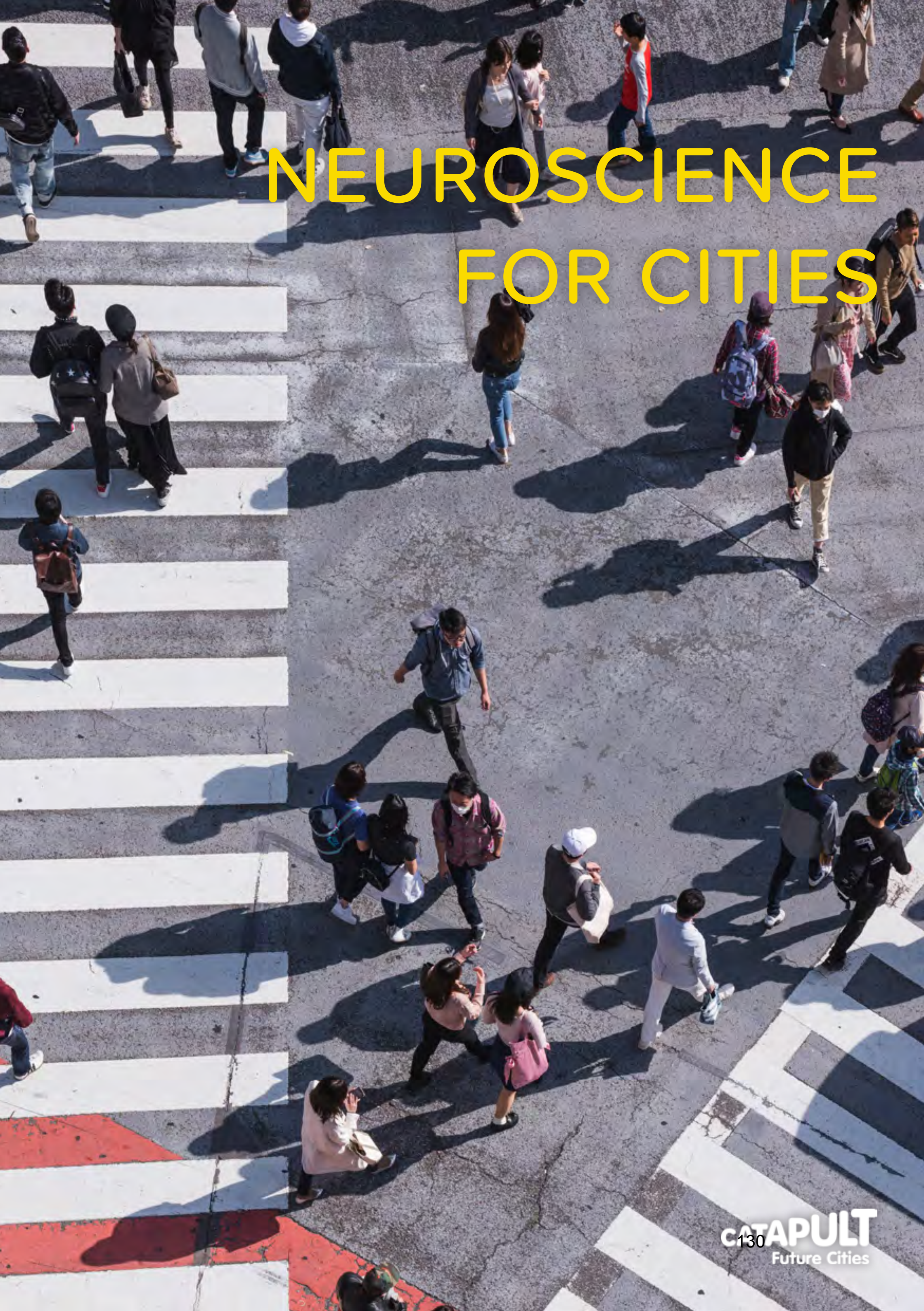


NEUROSCIENCE FOR CITIES

FOREWORD

Nicola Yates OBE
Chief Executive, Future Cities
Catapult

At Future Cities Catapult our mission is to help firms develop innovative products and services that meet the needs of cities – and help them sell those products and services to the world. A key component in delivering that mission is connecting businesses to the latest and emerging academic research so that they can harness that knowledge to develop innovative propositions. This new report, developed in close collaboration with the Centric Lab and University College London, is a prime example of that work to translate and communicate cutting edge academic thinking for commercial and public sector audiences. This report takes shape as a playbook, packed with new tools, methodologies and strategies for businesses and organisations, big and small, to adopt scientific knowledge into daily routine.

In a globalised economy, highly mobile talent demands attractive places to live and work that enable high quality of life, maximise productivity and promote innovative problem-solving. City managers and corporates seeking to attract and retain such talent must pay close consideration to the quality of the spaces they provide.

Developments in neuroscience are showing us new ways to understand how people experience the built environment, revealing new opportunities for innovation and improved experiences, leading in turn to greater productivity, wellbeing and attraction. Neuroscientists are also discovering important insights about outcomes for the less advantaged in our cities, providing compelling evidence in support of interventions to tackle the negative health impacts of city living, and ways to reduce barriers to access and opportunity.

Whether you are reading this playbook from the perspective of business or the public sector, I hope that you will find it a helpful resource to explore the potential applications of this important area of research.

WELCOME

Nick Tyler CBE FREng
Chadwick Professor of Civil Engineering
Faculty of Engineering Science
University College London - UK

Often when we think about a city we think about it on a grand scale and mainly in terms of buildings and tall structures. However, I don't see it that way: a city is people. We should think about the city not at the scale of buildings, but at the scale of people. For me, a person can never walk on the same street twice. People recreate their city every time they experience it; the urban environment is not made up of a combination of static structures and memories, but is instead an ephemeral place where people constantly experience their surroundings afresh. Furthermore, we should think about how to make cities for everyone, this means employing the full range of cognitive, physical and perceptual variety so that everyone can create the city they want, every time they experience it.

This is where neuroscience can help with the making of cities: understanding how people from a wide variety of perspectives can create their individual-yet-collective life in cities. Cities are intricate sensorial ecosystems connecting people for the survival of culture and society. With neuroscience we can discover how to help people respond to their sensorial perceptions so that this ecosystem can really work for them. We can then use this knowledge to orchestrate ever-renewing perceptions and create a responsive 'symphony of the city' that will enable, even inspire, people to meet their constantly changing desires, needs and challenges.

EXECUTIVE SUMMARY

Cities have a long-standing reputation of being epicentres of culture, politics and industry owing to cohesive social networks facilitated by their concentrated infrastructure. From a societal perspective, cities catalyse movements and inventions, making them highly important to human society. While we often think of cities in terms of great buildings or iconic streets, at their core cities are people. It is people who guide the visions of cities across all parameters of influence. Economic growth and culture are driven by human effort. City design and infrastructure are constructs of human imagination. Lives led in cities are based on human aspirations. Therefore it makes sense for cities to be seen as the scaffolding that supports and holds human activity.

This perspective is not new, there has been a strong and historical catalogue of work that supports the theory of 'human centricity'. Many architects, engineers, and urban planners have launched city plans to make cities prosperous, industrious, and exciting places to live. In fact, there is already substantial data on what makes a 'good' city. In her book, The Death and Life of the Great American City, urban theorist, Jane Jacobs highlights four qualities that cornerstone a great city: mixed land use, small blocks, high density, and diverse architecture. Given then inordinate amount of knowledge and theory on cities, it would be redundant for neuroscience to comment from this perspective. Instead it should be seen as a tool that allows those who work in the cities to understand the consequences of their work on human biology.

In a globalised economy, mobile individuals want attractive places to live, work and play, and that provide a high quality of life. City representatives and corporates seeking to attract and retain talent must pay close consideration to the quality of the spaces they provide, and their relationships to key economic attributes of high productivity and complex problem-solving. With neuroscience, we now have the opportunity to think about concepts such as productivity and quality of life from a human biological perspective. Allowing us to go one step further into theories of 'human-centric' city planning. For the use of this playbook, we are defining neuroscience as a multidisciplinary branch of biology and is the scientific study of the brain and nervous system, including its interaction with the other parts of the body.

This playbook illustrates the potential neuroscience can bring to the built environment: ranging discussion of how it works with emerging technology, how it utilises and qualifies urban planning theory, and how it can contribute insight to increase the user experience of cities, which in turn, leads to greater productivity, wellbeing and desirability.

For the full scope of opportunities that neuroscience provides, please see the infographic in the adjacent pages.

City analysts predict the rise of 'mega-cities', much to the excitement of economists, civic leaders, and builders; the construction rate alone will create substantial economic growth. Numbers indicate more job prospects, more goods and services to consume, and boundless opportunities for high-level innovation

However, growth without purpose or measure could potentially lead to a high human cost, which could turn living in cities undesirable. Especially as cities are already facing a mental health crisis, which, without immediate intervention, could get worse. Providing solutions to mental and physical health challenges in cities is crucial for economic development. In New York City alone, 4% of the adult population have a serious mental health issue. This equates to roughly 230,000 adults who are not at their productive best and who cannot fully engage with the city's services and products.

Through the merging of technology and neuroscience, urban planners, government, and city experts have the opportunity to turn around the adverse effects of environmental stressors and catapult cities into a new era. Why shouldn't a city be a place of convergence, culture, and knowledge mobility, as well as healthy places to live?

Neuroscience will undoubtedly be a catalyst for new era of built environment innovation. With time and technological advancement, neuroscience will be able to help us understand the nuances of human biology, as it is affected by the built environment. This will lead to the sophisticated orchestration of different physical environmental elements such as light, sound, or street typography.

To reach this level of adaptiveness, we need the support of multi-disciplinary programmes and laboratories. For example, the Ecological Brain Project at University College London (UCL) aims to harness and develop 'new methods and techniques to measure behaviour and brain activity in the wild' . With the objective of understanding how the brain solves real world problems in real time.

One of the most exciting aspects about these types of programmes is their extensive collaboration between different areas of science and industry. The future of cities looks to be in great hands as they continue to sprout all over the world.

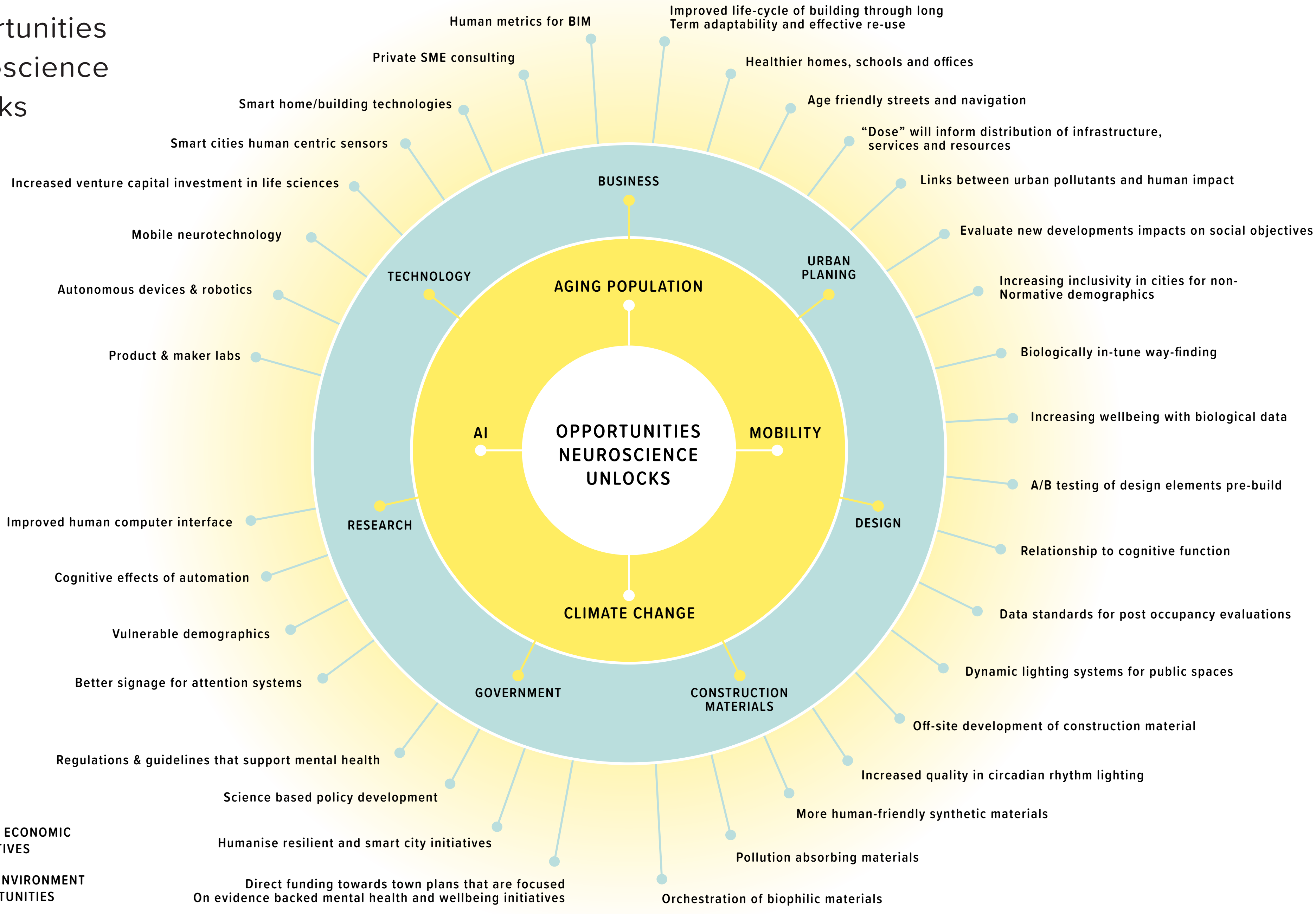
As new neuroscience technologies emerge, such as the recently reported portable Magnetoencephalography system created by UCL and the Wellcome Trust, they will allow for an increased depth of study into humans in 'the wild'. This device will not only help with clinical applications, but could feasibly be used to study brain activity as people navigate in natural environments.

This technology can also be used in tandem with other technology, such as Augmented Reality (AR) or Virtual Reality (VR), to compare the brain activity of different environments. This is especially useful when studying variant demographics which show differences in spatial cognition, such as those with visual challenges, people on the autism spectrum disorder, dementia, or those with depression.

Twenty years ago, to tell a property developer they could virtually walk through their future development using their smart telephone would have seemed impossible. Twenty years from now we may look back and wonder how we ever planned cities without the use of cognitive and biological data.

It is exciting to present a new tool for the advancement of city life and potentially catalyse a new industry.

Opportunities Neuroscience Unlocks



OPPORTUNITIES NEUROSCIENCE UNLOCKS

AGING POPULATION

MOBILITY

CLIMATE CHANGE

AI

BUSINESS

URBAN PLANING

DESIGN

CONSTRUCTION MATERIALS

GOVERNMENT

RESEARCH

TECHNOLOGY

Human metrics for BIM

Improved life-cycle of building through long Term adaptability and effective re-use

Healthier homes, schools and offices

Age friendly streets and navigation

“Dose” will inform distribution of infrastructure, services and resources

Links between urban pollutants and human impact

Evaluate new developments impacts on social objectives

Increasing inclusivity in cities for non-Normative demographics

Biologically in-tune way-finding

Increasing wellbeing with biological data

A/B testing of design elements pre-build

Relationship to cognitive function

Data standards for post occupancy evaluations

Dynamic lighting systems for public spaces

Off-site development of construction material

Increased quality in circadian rhythm lighting

More human-friendly synthetic materials

Pollution absorbing materials

Orchestration of biophilic materials

Direct funding towards town plans that are focused On evidence backed mental health and wellbeing initiatives

Humanise resilient and smart city initiatives

Science based policy development

Regulations & guidelines that support mental health

Better signage for attention systems

Vulnerable demographics

Cognitive effects of automation

Improved human computer interface

Product & maker labs

Autonomous devices & robotics

Mobile neurotechnology

Increased venture capital investment in life sciences

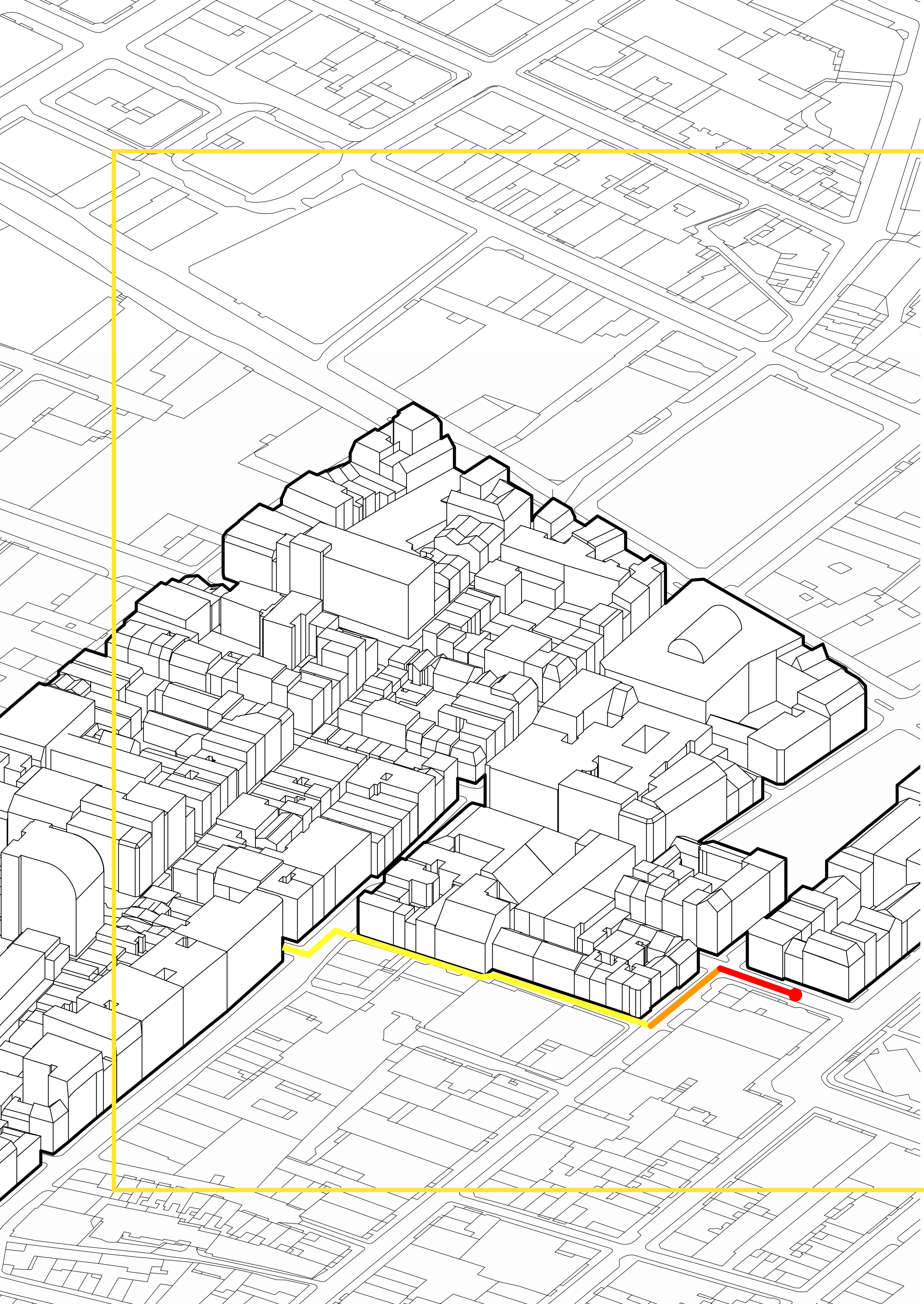
Smart cities human centric sensors

Smart home/building technologies

Private SME consulting

🟨 MACRO ECONOMIC OBJECTIVES

🟦 BUILT ENVIRONMENT OPPORTUNITIES



1. INTRODUCTION

As this playbook will cover a wide range of concepts and scientific research, it is important to start with the definitions and establish context for this work. We would like this playbook to be seen as a framework for applying neuroscience into the built environment and be used as a platform to catalyse new research, business opportunities, and theories for future application.

We expect this document to also instigate debate and further conversation across all industries. This means that whilst this is bringing together a cohesive and detailed instruction for application, it is still within the confinements of exploration.

WHAT IS NEUROSCIENCE

Neuroscience is a multidisciplinary branch of biology and is the scientific study of the brain and nervous system, including its interaction with the other parts of the body[1]. A broad definition, as is used here, includes the study of human thought, emotions and behaviour since each of these functions arise from the brain and nervous system. The study of the mind, without reference to brain function, has a long tradition in the field of experimental psychology. More recently experimental psychological methods and neuroscience methods have been integrated in the field of cognitive neuroscience, which seeks to provide a neural basis for behaviour and cognition. Such an approach has been important for areas such as mental health disorders where cognitive models needs to be integrated with neural data.

To explore the full impact of neuroscience on how humans interact with the built environment, we integrate findings from experimental psychology, mental health research and cognitive neuroscience, with the study of individual brain cells (neurons) and specific brain circuits. We also examine brain-body-environment interactions such as the stress response[2] of certain environmental factors such as light, which can have a potential effect on circadian rhythms, thus affecting our sleep[3].

In this playbook we draw on the field of neuroscience and its related disciplines of psychology and physiology; research across these fields works to inform us about how the human brain reacts and interacts with the built environment.

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1. Neuroscience. (n.d.) In: *Oxford Living Dictionaries* [online] Available at: https://en.oxforddictionaries.com/definition/neuroscience [Accessed 19 Apr. 2018]
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3. Jung, C.M et al. (2010). Acute Effects of Bright Light Exposure on Cortisol Levels. *Journal of Biological Rhythms*, 25(3), pp. 208-216.

WHAT IS THE BUILT ENVIRONMENT

In regards to the built environment, it can be defined through macro elements such as urban design, public areas, land use, and transportation systems. As well as through micro elements such as streets, neighbourhoods, and buildings. However, it is of no use to only define the built environment without its main purpose, which is to support "patterns of human activity"[1].

For the businesses in the built environment industries of transport, planning, and development this playbook covers how incorporating neuroscience into brief development and programming stages might help to improve adoption rates and long-term usage. Early-stage risk assessments will help ensure that the allocation of finite resources will lead to an effective and enhanced human-task-space relationship. As the science progresses and refines knowledge, these findings will inform standards and new modelling programmes. Neuroscience will add a sophisticated layer of intelligence onto understanding how urban environments can become resilient from a human perspective.

This will lead to the sophisticated orchestration of different physical environmental elements such as light, sound, or street typography. Imagine planning a neighbourhood that anticipates how a person with visual differences might respond to shadows, heights or grey-scales, or how city sounds might play a role in their spatial navigation.

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WHY IT MAKES SENSE TO USE NEUROSCIENCE IN THE BUILT ENVIRONMENT

All animals adapt their environments to fit their needs and ensure survival. Humans have done the same, except at a far greater scale, allowing us to build cities and societies[1]. The changes and adaptations we impose on our environments have been to ensure survival, both from an immediate point of safety and culturally. For example, the invention of aqueducts provided us access to water more effectively and readily. This adaptation not only ensured our immediate survival as water is an essential element to all living life, it also catalysed an opportunity to create more complex habitats such as cities as we were no longer tied to a specific water source or dependent on weather fluctuations[2].

The level of sophistication of our adaptations is driven by the type of technology and science available to us at any given time. Now that we have entered a new era of rapid advances in technology and insight into the workings of the human brain, it makes sense for us to explore these new tools and insights for even greater adaptation.

To some academics and industry professionals neuroscience may seem like an unlikely ally for the built environment. Afterall one is intrinsically biological whilst the other is intrinsically non-biological, however, the built environment provides the backdrop or the “set” for much human activity. Cities are places where people are birthed, where they create and where they grow old. In informal terms neuroscience is the science of humans; it teaches us about how we perceive the world, how our brain develops, how we think, why we think, how we problem-solve, and how we interact with the world. Therefore it makes sense to use neuroscience to better understand the relationship between people and the physical world. This could provide us insights to address questions such as; how are people’s mental health and sense of place impacted by city expansion? Is air pollution having an effect on the neurodevelopment of children? How do variable demographics such as those with visual impairments use sensorial information differently to navigate cities?

As already stated, humans have learned to adapt and manipulate their environments to ensure survival. Now we have a new knowledge pool and tools to exploit, to help us create more sophisticated adaptations for our evolving needs, ones that ensure our prosperity and good for the greater ecosystem.

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[1] Poon, L. (2017) Cities are one big evolutionary experiment. Citylab. Available at: https://www.citylab.com/environment/2017/11/urbanization-is-one-big-evolutionary-experiment/544562/ [Accessed 12 Feb. 2018]

[2] Encyclopaedia Britannica (2018) Aqueduct. [online]. Available at: https://www.britannica.com/technology/aqueduct-engineering [Accessed 07 Mar. 2018]

ETHICS AND SCIENCE SCRUTINY

As we are breaking new ground with our proposed framework it is important to discuss ethics. In writing this playbook we have carefully selected studies based on their scientific merit and ethical approval. In the media, books and some academic articles, neuroscience is misused to explain phenomena, and interpreted far beyond the data can warrant, for example, the endogenous molecule dopamine is often credited as the ‘feel good’ chemical in the brain[1]. Whereas its role is much more complex and relates to predictions about possible outcomes[2]. Neuroscience and neuroimaging (brain scanning) research in particular, has been prone to misguided interpretations of reverse inference[3].

To take an example argument:
1. We know that a brain area called the anterior cingulate is involved in reward.
2. We observe the anterior cingulate more activated by red objects than other objects in our neuroimaging task.
3. Therefore red objects are more rewarding to humans than other objects.

This interpretation relies on the assumption that the anterior cingulate is only activated by reward. This, however, is not the case, and the interpretation in our example is an overreach and simplification of the science. This type of interpretation is often taken even further when it is translated to ‘industry speak’; one potential impact of this would be to say, ‘studies show that the brain is hard-wired to be attracted to the colour red, so we have included the colour in our entrances to attract customers.’ In short, for this playbook we have worked to avoid this type of mistranslation.

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[2] Schultz, W., Dayan, P. and Montague, P.R. (1997) A neural substrate of prediction and reward. Science, 275(5306), pp. 1593-1599.

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A CALL TO ACTION

Despite the incredible human ability to adapt, currently we are facing a human crisis in cities. This is not to sound alarmist, but to point out the urgency behind this playbook. Scientists all over the world are looking at the adverse effects of city life. Research shows that the prevalence of mental health problems is greater in cities than in rural areas[1], however the full scope of determining factors is not yet known. Both urban and rural environments are complex ecosystems with many variables, so it would be an oversight to assume that 'city life' is a central driver of mental health related illness. Nonetheless, certain toxins (produced by traffic, industrial parks), environmental stressors (noise and light pollution), climate conditions (urban heat islands) and social conditions (isolation), all of which are interlinked with cities, have been found to contribute to mental health problems[1-4]. The research on mental health in cities goes far beyond 'self-reported' questionnaires, and explores the links between the incidence of mental health disorders and the environment. There is direct link between the above factors and the biological aspects of mental health, which we discuss in detail throughout the playbook.

These statistics are to highlight what we are facing rather than give cities a bad reputation. Cities can be places of health and human prosperity, however we must start taking action sooner rather than later.

£26 billion	in mental health cost to London[1]
1 in 4	people experience a diagnosable mental health condition in London[1]
1 in 10	children in London experience a diagnosable mental health condition[1]
38.5%	in the UK experience high levels of anxiety[1]
42.1%	in inner London experience high levels of anxiety[1]
1 in 5	people in New York City suffer from mental health problems[2]
1 in 5	people in Australia suffer from mental health problems[3]
20%	of all cases of illness in China are mental health related[4]

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2. Kearney, L. (2015) New York City finds one in five adults has mental health problems. Reuters, [online]. Available at: https://www.reuters.com/article/us-new-york-mentalhealth/new-york-city-finds-one-in-five-adults-has-mental-health-problems-idUSKCN0T12O020151112 [Accessed 19 Apr. 2018]
3. Black Dog Institute (n.d.) Facts & figures about mental health. [online] Available at: https://www.blackdoginstitute.org.au/docs/default-source/factsheets/facts_figures.pdf?sfvrsn=8 [Accessed 19 Apr. 2018]
4. China Daily, (2016) 100 million people suffer depression in China. [online] Available at: http://www.chinadaily.com.cn/china/2016-11/28/content_27501518.htm [Accessed 19 Apr. 2018]

2. USING THE PLAYBOOK

In this playbook we use neuroscience research for three types of outcomes. The first is to increase knowledge of well-known environmental stressors, to understand their effects both on our physiological and cognitive development. Secondly, we discuss the potential of new tools to measure the brain activity in relation to the built environment. Finally, neuroscience is used as a biological lens to examine well-known metrics and guide recommendations in relation to physical comforts.

3 PILLARS

PEOPLE

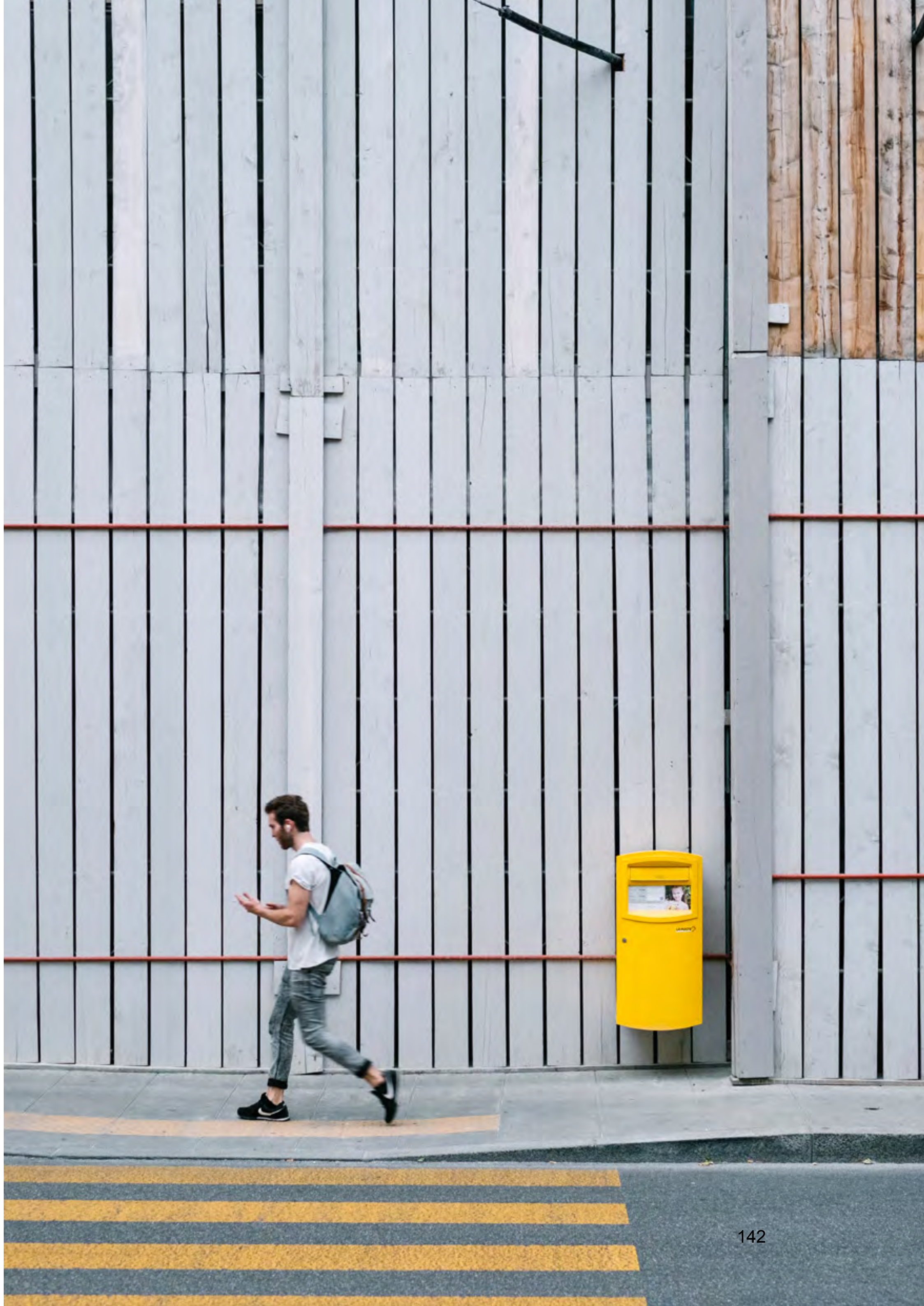
- Enhance social cohesion
- Increase user experience of cities across demographics
- Create places that support human productivity
- Increase engagement of the city at a lower human cost

BUSINESS

- Validate the use and investment support of emerging technology
- Catalyse the beginning of new industry

INFRASTRUCTURE

- Equitable distribution of infrastructure
- Increased mobility across all demographics including the neurologically diverse
- Highlight the effects of environmental stressors



HOW INDUSTRY SHOULD USE THE PLAYBOOK

This outline is a quick glance as to which industries this playbook might be of interest to and suggestions of usage. We hope that this playbook is a springboard for new ideas and opportunities.

CITY REPS & GOVERNMENT AUTHORITIES

- Recommendations for enhancing quality of life
- Insights to help attract talent to cities
- Have a new human lens and toolkit for setting city strategies such as the New London Plan and Local Enterprise Partnership manifestos

URBAN PLANNING

- Scientific evidence to support new city growth strategies
- Understand the physiological and cognitive effect of poor transport infrastructure
- Wayfinding ideas for enhanced inclusive mobility for all demographics

PRIVATE DEVELOPMENT INDUSTRY

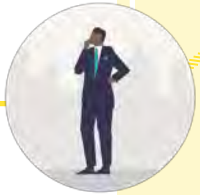
- Understand how macro-city trends will affect what people will need and expect from developments
- Learn how environmental and urban stressors impact quality of life
- Develop methodologies to avoid low adoption rates through user experience insights and testing
- Scientific insights to deliver the next wave of housing, offices, and leisure spaces fit for multi-generational, differently abled, and neurodiverse use

ARCHITECTS & URBAN DESIGNERS

- A deeper understanding of how physical comforts and elements effect people on a physiological and cognitive perspective
- A human-based risk assessment process to avoid unintended consequences of physical elements on experience

ACADEMICS & RESEARCHERS

- Gather information from other disciplines to understand how neuroscience can influence the built environment on a global scale, catalysing opportunities for future research
- Provide evidence for future grant applications, specifically in support of impact statements for research councils



BUSINESS

- Evidence for supporting tech products that help enhance user experience of cities and buildings
- New business and start-up opportunities from the evaluations highlighted in this document

LIMITATIONS AND CAVEATS

This section is to ensure there is clarity about the limitations and caveats regarding the use of the playbook.

Architectural Design Determinism

There is a risk of using this playbook to support a line of thought that could be seen as deterministic. The term architectural design determinism is the term applied to the “concept that building environments directly affect behaviour and attitudes[1].” Although neuroscience provides a deeper lens from which to understand people, this is still quite far from thinking it is possible to control with certainty the final output of behaviour by making adjustments to the built environment. It is difficult to define the line, however we shall endeavour to do so by providing a very simple example.

Research into the non visual effects of natural light indicate changes in cortisol levels, cognitive performance, and circadian rhythm[2]. Additionally, natural light has been linked to better scholastic performance in children and higher productivity in the workplace. However, using natural light in a workspace design may not necessarily have a favourable effect on everyone in the space. Nor should it be expected that this factor alone will determine higher levels of the general productivity of a worker. In a real world context we should consider the many factors at play, for instance, if the people are conducting a task (e.g. software coding) that requires a lot of screen time, natural light might have a different effect than for those conducting a task with little screen time (e.g. a face to face meeting)[3]. Most of the literature links productivity with natural light through its effects on the circadian system. Studies have shown the prolonged amount of time in blue light may have an effect on circadian function and thus present a change in sleep patterns[3]. These changes to sleep patterns in turn may affect aspects of productivity, such as focus, due to sleep deprivation[3]. However, one recent study has provided another view, it proposes that the effects of blue light might be related to the circadian phase of light exposure[9]. This means that the effects are related to where in the circadian phase a person is when exposed to blue light rather than it being a universal effect. This is important, as it showcases the nuances in our biology and the need to understand them. In short, when it comes to neuroscience, 'x' does not always equal 'y'.

As we said, the line is fine and a great example of where physical elements have had a perceived positive effect are within varied demographics such as those within the Autism Spectrum Disorder (ASD). Schools designed with considerations for ASD symptomatology such as anxiety and noise sensitivity indicate to be better choices than mainstream schools[7]. These instances should be held up as example of best practice and supported with further neuroscience research.

Relationship doesn’t mean causality

A limitation of correlating human behaviour to the built environment is that these relationships are often viewed as causal. This is especially true when creating a through-line between a built environment element (cause) and tying it to a socially complex behaviour (effect). For example, a recent study investigating the correlates between air pollution and crime, pointed to some compelling evidence[10]. However it would be remiss to interpret its results as “air pollution causes crime”. Crime or antisocial behaviour[11] is a highly complex social, biological, genetic, and physiological phenomena, therefore interpreting corollary findings as causal can be misguided and oversimplified.

Context

The final part to consider for this section is context. For example, there have been many studies on the effects of high rise buildings. Some studies suggest that high-rise living promotes unhealthy social and health habits, whilst others indicate that they allow for social cohesion[1]. There is even evidence that those living in the upper floors breathe cleaner air[1]. However, there is a risk and limitation in studying a particular physical element in isolation. In a review of high-rise studies, it argued that new studies need to look at other non-building factors, including “characteristics and qualities of the residents themselves, and the surrounding physical and resource context. These factors moderate the relation between living in high-rise and outcomes of living in one”[12]. In Chapter 5 the playbook will detail what tools and methods can be used to establish further context.

Autism Spectrum Disorder - “Is one of the most common neurodevelopmental disorders. According to the Diagnostic and Statistical Manual of Mental Disorders, fifth edition (DSM5), the core symptoms of ASD comprise deficits in social communication and interaction, repetitive and restricted behaviours, and sensory abnormalities.”[8]

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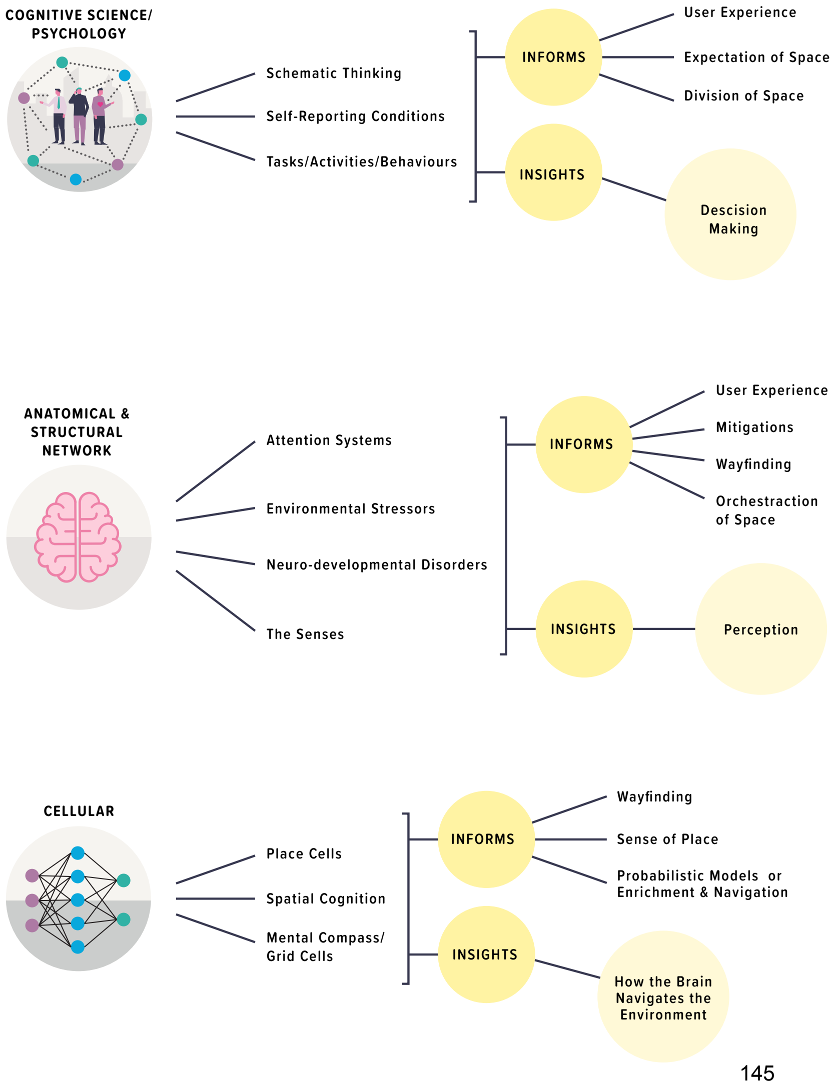
10. Bondy, M., Roth, S. and Sager, L. (2018) Crime is in the air: The contemporaneous relationship between air pollution and crime. [online] London: Institute of Labor Economics. Available at: http://ftp.iza.org/dp11492.pdf [Accessed 17 Apr. 2018].
11. Rowe, D.C. (1986) Genetic and environmental component of antisocial behaviour: a study of 265 twin pairs. Criminology, 24(3), pp. 513-532.
12. Gifford, R. (2007) The consequences of living in high-rise buildings. Architectural Science Review, 50(1), pp. 2-17.

FURTHER POINTS OF CONSIDERATION

1. Recommendations have to work in tandem with other integral elements such as social services and community led initiatives.
2. We must understand the limitations of the built environment effect. In other words we cannot see ourselves as just input/output predictable machines.
3. We should understand the margin of error and the standard deviation of every intervention made to the built environment.
4. We should understand that the physical elements give affordances to certain tasks and actions, but will not necessarily guide behaviour.
5. Finally, there is a difference between enhancing the user experience of an area and thinking that design will be fix-all-solution to complex societal problems.

THE SCALE OF NEUROSCIENCE

One of the foundational elements that ensures neuroscience is translated and applied appropriately, is through understanding which scale (ranging individual neurons to psychology) is best for different methods of the study of the built environment and application of neuroscience.



NEUROSCIENCE IMPACTING THE BUILT ENVIRONMENT

This table is an index of the various ways neuroscience has the potential to influence and transform the built environment.

LENS	• Understand unintended human consequences (e.g. examine whether well-lit streets cause sleep disturbances for local residents). • A sophisticated lens to understand the biological and cognitive effects of city infrastructure. • Identify methods and mitigation techniques for buildings and cities to increase usability, wellbeing, and productivity for users. (see chapter 6 and 7 for more details) • With the use of VR, AR, mobile biosensing devices (e.g. mobile electroencephalography), and A/B (controlled experiment with two variables) testing of different environments can be used to assess how people navigate different environments. This provides urban planners and architects with a new tool and process to analyse the effectiveness of design options.
QUALITY	• Help streamline a coherent universal strategy for measuring and defining, wellbeing, productivity and the quality of place, based on biological/cognitive baselines. Opening up the opportunity for universal codes and less ambiguity for planners. • Offering a high level of user experience is becoming a primary driver of commercial real estate companies in attracting occupiers, customers and users. Through identifying how people perform tasks from a cognitive perspective it will be possible to orchestrate environments to support them. Removing stressors from this investigatory process will elevate user experience. • Neuroscience compliments the built environment industry's (inc. transport, city planning, services and infrastructure) drive for efficiency and functionality by ensuring a high level of user experience through every stage of their journey.
ADAPTABILITY	• A living lab is a research methodology for sensing, prototyping, validating and refining complex solutions in multiple and evolving real life contexts. Deploying co-created and user-centred programs in neighbourhoods would allow scientists and built environment practitioners to observe changes in residents through the use of smart sensors. Any changes can then be studied to assess and mitigate root causes of human problems within the built environment. • Neuroscience, together with living labs and smart city technology, could change cities from passive to dynamic systems that are responsive to human needs by making iterative changes to the built environment using biological and city data.

4. Going Further With Neuroscience

The previous chapters covered how to use this playbook, the scale of neuroscience it will use, and the challenges of applying neuroscience into the built environment. This new chapter will focus on how human biology can provide those within the built environment with a more sophisticated lens for understanding people in the context of cities.

This chapter has four sections; starting with an explanation of how neuroscience methods advance us beyond psychological methods, then it will look at the historical link to the physical environment from a physiological and social perspective, and the third section will provide an understanding of the senses and perception.

BEYOND PSYCHOLOGY

Linking neuroscience to cities and buildings is both timely and relevant. This is due to increasingly applicable discoveries in a range of neuroscience research areas (such as in attention and with spatial cognition), and also due to new tools that have emerged in recent years. These tools include new mobile brain imaging and biosensors with GPS tracking, meaning that our capacity to understand the link between the human brain and the environment is becoming increasingly sophisticated[1]. The processing capacity of computers now makes it possible to process data from millions of people to make impressive predictions concerning mass scale human behaviour and experiences. The prospects of which are increasingly attractive to both academia and industry, insofar as the application of science to real-world built environment scenarios.

A key point of contention however is the question of what neuroscience can tell us that psychology does not; specifically, why do we need neuroscience if psychology has proven quite useful to industry in the past. Below are four examples of why neuroscience is relevant now and how it works beyond an experimental psychology approach. Neuroscience specifies 'where' and 'how' the brain underpins behaviour. The nuance to this additional depth of human biology is especially important when looking at the built environment:

1. Technologies used by neuroscientists help reveal what demands the environment is placing on us that purely psychological measurements cannot achieve. For example, recent research shows that when we navigate a city, certain parts of our brain process future possible paths at particular times during navigation and only when we rely on our memory, not a Sat Nav[2]. Testing behaviour alone fails to appreciate the specific demands the environment places on us.

2. Neuroscience provides a level of precision that is important when considering people in the population who live with dementia or mental health conditions. Understanding the differences in brain function in these conditions is important towards considering how to build cities that are more inclusive.

3. Whilst self-reporting and questionnaires are a legitimate source of research within neuroscience, it is now possible to become more technical in approach. For example, research into green spaces mainly focuses on self-reported data, concerning how these spaces make people feel, or the perceived benefits to local communities[3]. With the use of neuroscience, we can understand this at a biological level. There is an emerging field that attends to restoration theory, which in part proposes that access to greenery helps to restore the brain[4]. Restorativeness can be a factor in positive reported feelings while being in a green spaces[4]. Understanding this from a biological perspective establishes further insights into the reasons behind the benefits of green spaces[5].

4. We now have the opportunity to look at the mechanisms behind psychological and social theories, such as 'cognitive maps' or 'sense of place'. For a long time psychologists only imagined that the brain had a cognitive process that allowed people to map their physical environment. However, it is the work of neuroscience that has proven this theory to be true, exemplified by the work of Dr. John O'Keefe[6]. Using electrodes in the hippocampus of mice, he determines how the brain maps environments through the identification and locating of 'place-cells'[6].

We are not dismissing psychology as it is still an important area of study, especially when it comes to analysing human to human interaction and the self-reporting of certain experiences. This section was to highlight new methods that are now available for understanding the complexities of human behaviour.

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THE PHYSIOLOGICAL AND SOCIAL TIES TO OUR ENVIRONMENT

We now have the opportunity to take this new knowledge and start to think about cities in much more expansive timelines. We shouldn't be thinking of cities in terms of 15 or 30 years, we would be thinking about 50 to 200 years. How does what we do right now shape our evolution as a species, furthermore, what kind of role do we want to play. A passive role or a proactive role?

There is a core understanding that cities shape us from a societal and cultural perspective. However in the next two sections we evidence how cities can also shape us in a physiological manner.

Physiological

Humans have always had a symbiotic and evolutionary relationship with the physical environment. Physiologically and cognitively human development is dependent on our relationship with external environments; our brain and the cognitive systems it supports, develop in tandem with our interactions with the physical world, including interactions with other people[1]. The structure of the urban environment and its properties, e.g. buildings, streets, noises, light, etc., all have an impact on the brain and cognitive systems, and these impacts vary in scale with the length of exposure[1].

This relationship is highly complex, which makes it very difficult to study in a laboratory setting. Therefore finding real-world studies, which provide data and an insight of how deeply the physical world impacts people are fundamental to the work presented in this playbook.

As an example, the Romanian orphan studies[2] provided strong evidence for the link between an individual's ecosystem (physical and social elements) and biological makeup (physiological and brain development) in a real world context, going deeper than short-term physiological or self-reporting studies. In the case of the Romanian orphan children, deprivation was caused by the lack of varied stimulation in the physical environment; no views outdoors, no toys, little wall decoration[2]. From a social perspective, the children were not picked up, and lacked integration and interaction with other children and the attendants[2]. Using Positron Emission Tomography (PET), it has been reported that, compared to healthy matched control children, these children had significantly decreased metabolic function in various brain regions that are crucial for cognitive, behavioural and physiological functions. This dysfunction may have been as a result of the stress from early environmental and social deprivation[2]. The neurodevelopmental and physical impairments of about 10% of the adoptees have shown to be long-term, even after adoption[3]. While this is an extreme case, it highlights that the environment can have long-lasting impacts on brain function, and that its role in nurturing us is vital.

From an industry perspective, this highlights the importance of understanding how the physical elements in the built environment have an effect the biological aspect of human development. We now have the means to define the physical elements or stimuli that have the greatest impact on our quality of life. For example, there is strong evidence that air pollution affects people with asthma and other cardiovascular problems. However, neuroscience research is now concluding that air pollution toxicity is creating problems in the womb, which can later have a significant effect on neurodevelopment. Having this information can build a strong case for moving residential areas away from high-traffic areas, to help reduce the longer-term consequences of toxicity, such as behaviour problems including ADHD[4], or childhood obesity[5].

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The Social Brain

At the core of human interaction is communication, verbal and non-verbal. We can set off a relay of emotions, intentions, and meanings with a flick of an eyebrow or a simple “Hello”. These initial and superficial moments of communication can add up to more profound moments of conversation, which we use to disseminate ideas, negotiate, and collaborate. With time, and more importantly consistency, these conversations can turn into long term bonds. Paving the way for higher types of human activity and outputs, such as knowledge mobility, culture and the creation of societies.

The density of cities makes them ideal ecosystems for sustaining long-term social interactions. The infrastructure of cities brings people in close proximity, which provides the opportunity for dynamic and varied social interaction. This aspect is one of the main reasons people are attracted to cities. Interaction with people means information and information can be used to create new ideas and solve problems. Furthermore, people interacting means bonding, which is essential for our survival as it builds families and friendships. Given how significant human-to-human communication is to cities, it is important to define it in neuroscientific terms.

Communication has biological underpinnings as the task of communication itself requires physiological and brain anatomy for its execution. In the diagram below we explain the different components of human-to-human communication. As we consider the future of cities, we should take into consideration what people need in order to communicate at higher quality levels. We are defining quality as the opportunity to understand context and extract meaning from an interaction, increasing the probability for longer term bonding and building trust.

Additionally, the social aspects of communication also draw on certain circuits of the brain. For instance, social cohesion, defined as the willingness of groups to come together and cooperate for survival and prosperity[1], is a precursor to good health, mental wellbeing, physical and psychological safety, and an overall improvement of life quality. When people do not have strong social cohesion in their communities, feelings of isolation can occur, which have adverse consequences for mental and physical health[2]. A report on old age living concluded that illness was exasperated by feelings of loneliness and lack of social contact[3]. Loneliness can even expedite cognitive decline in older adults[4] and according to some studies it increases the likelihood of mortality by 26%[5]. Robert Weiss in 1973 went as far as to describe it as a ‘gnawing chronic disease’[4]. This is an important insight for city planners, as tackling incidents of isolation through social cohesion can help elevate wellbeing and health in neighbourhoods and cities.

In terms of built environment industry, we should begin to consider how well neighbourhoods afford the opportunity for human interaction and to what level of quality. For example, do the public areas such as parks genuinely offer an opportunity to engage in casual interactions or conversations? Even very basic considerations such as seating that provides closeness to allow for people to hear each other or interact without disruption helps catalyse social collisions. Also consider how the greenery can help mitigate noise levels[8] for more auditory comfort as noise can cause high levels of distraction[6] which can in turn lower the quality of comprehension from a specific mode of communication. A point of inspiration are Italian piazza’s[6], which are centred around human interaction, from conversations to simple people watching. It is also where Jan Gehl based most of his studies on human interaction[7]. Understanding what physical affordances support human to human interaction can help mitigate against isolation, increase wellbeing, and create more opportunities of idea dissemination. All attributes that will make cities attractive places to live.

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Human to Human Communication

This is an overview of what a communication process looks like between two people. It is important to note that in order for the communication to be considered successful there should not be interruption or degradation to any part of the process.

Auditory level: two people (A and B) sharing information have to be at a physical proximity to be able hear each other.

- Comprehension: person B has to be able to understand the auditory stimuli from person A to extract context and meaning. In addition to the audible detection of tone, speed, pitch and the words themselves, this is done through reading facial expressions to detect emotion[1].
- Acknowledgment: once the information is transferred, person B should acknowledge the information as being received and understood. This can be done through facial cues[2] such as nods and words that confirm comprehension.
- Retention: finally, person B will have learned the piece of information and retain it for retrieval and use at a later time[3].

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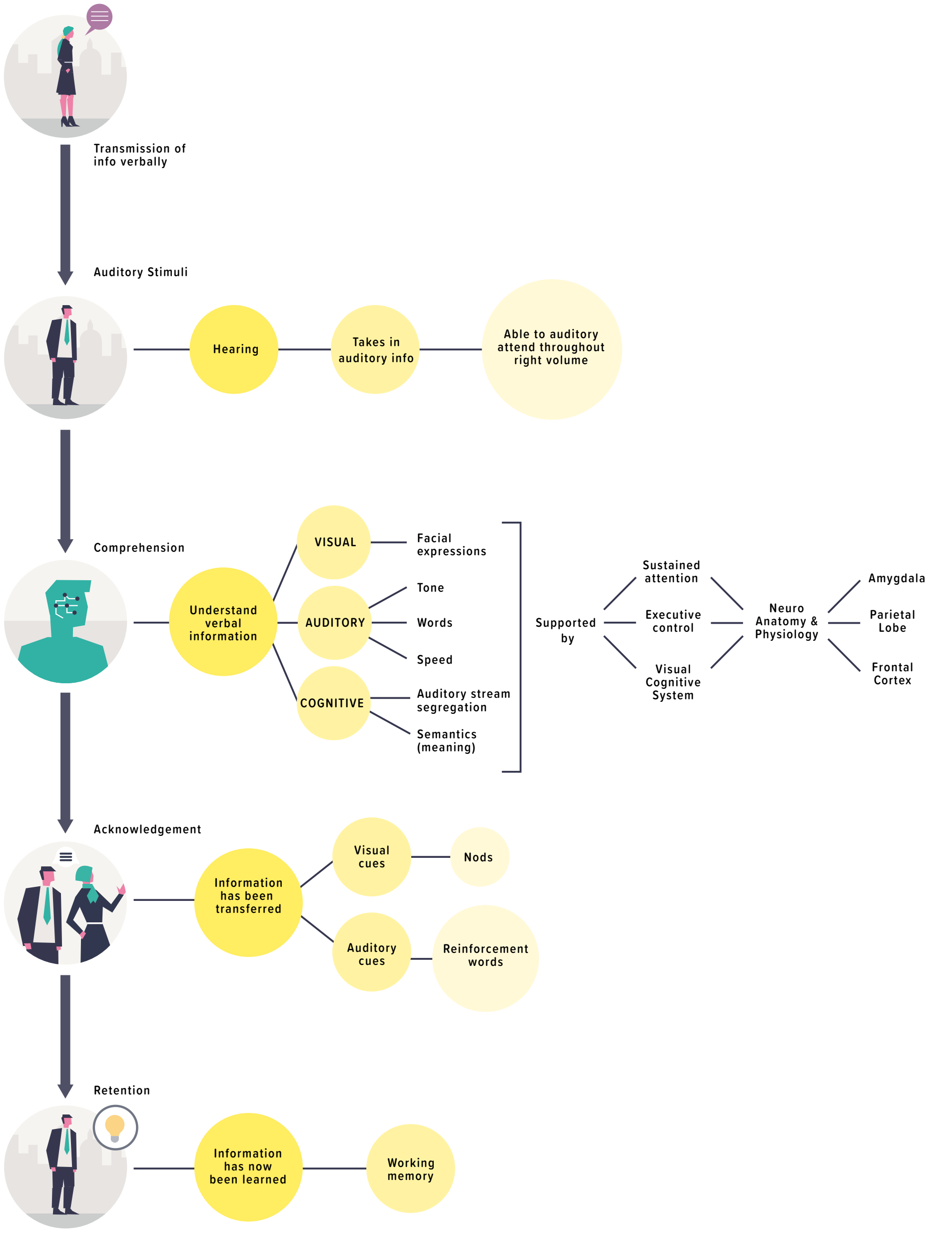

PERCEIVING CITIES

Before going further, it is important that we establish some working principles of human perception.

This section will include 3 parts; perception and senses, visual spatial attention, and orchestration.

Perception and Senses

Perception is one of the most fundamental and significant topics in relation to the built environment, it traverses across psychology and neuroscience. It is a complex and vast subject matter with many working definitions and different elements that underpin its identification. At its most basic level perception can be defined as having an awareness of the external and internal environment generated by the neural processing of the human sensory system[6]. Even though we experience the world as a unified whole, sensory systems do not input to the brain in this way[8]. For instance, different brain areas are specialised for encoding different features of the visual modality such as colour, shape, size, and motion[8].

It would be sensical to assume that what we see, hear, touch, or smell is a literal representation of sensory inputs. In other words, it would be sensible to think that what we experience through our senses (sounds, light, smells, touch) is what we become aware of (shades of colours, loudness, softness, hardness, bitterness, sweetness, forms)[6]. However, this is not the case. The information generated by the first phases of sensory processing is refined, modulated, and integrated with the influence of other factors. These factors may include the recent activity of the sensory system, prior experience with that specific stimuli, the context in which a stimulus occurs, influence from other sensory systems, mood, mental states, and physiological state of the perceiver[6]. There are also other more complex “top down factors”, which also play a role in influence perception such as emotional modulation, culture, past experiences, and social context[6].

Therefore what we perceive goes beyond just sensory input[6].

For built environment practitioners it means considering how physical elements may be interpreted and experienced differently than intended by those who created them. This goes to further support against deterministic design which is discussed in the section "Limitations and Caveats". How we modulate sensorial stimuli is so complex and driven by different variables therefore it would be difficult to assume a literal or linear line from design to adoption.

For example, a local park could have high aesthetic value and be in the right location from a planning perspective. However, if it is perceived as too far (psychological distance), spatially confusing, or even socially intimidating, it can run the probability of not being used by intended demographics. An interesting example of this phenomenon is the New York City High-line. It has been reported that whilst it has been a great achievement for the city on economic metrics, it has not done well on human or society metrics[7]. The author of a recent report concluded that the High Line is failing as a democratic public space[7]. The data gathered indicated that the use of the space was predominantly white, which is out of sync with the racial/ethnic demographics of Manhattan and New York City as a whole. The “level of racial homogeneity significantly exceeds that of other comparable parks[7]. This difference in use is quite surprising as the space is open to the public, has no fee and it is in the middle of the neighbourhood with various access points. However, there might be cognitive factors or cultural top down factors that are responsible for the difference in use. This example presents two opportunities; the first it is an opportunity to understand more about how culture or social factors influence perception and adoption rates. Secondly, it offers an opportunity to study the extent of variation between what is intended by the design and how it is interpreted by the user.

Key protagonists in the built environment are real estate developers who have access to global capital resources. They are often seen as the necessary leaders in urban change, however they are risk averse as often trade in investors capital. This often leads to low levels of innovation and new ideas being implemented. By adding guidelines, underpinned by biological and cognitive data, a more innovative development can be done with greater confidence.

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Visual Spatial Attention

Visual spatial attention is one of the most relevant cognitive processes behind the perception of city scenes, such as an intersection, a street, or a cluster of buildings. "Visual images and scenes are typically comprised of a rich, detailed mosaic of features, surfaces, objects, and events"[1] and which areas or aspects we isolate and decide to focus our attention is called visual spatial attention.

One significant purpose of attentional systems is to rapidly prioritise aspects of a complex scene that are of significant or relevant to a specific goal[3]. Where we decide to look is rooted in complex neurological processing with various cognitive outputs[1]. For example, crossing a busy intersection, we would focus on a selected area of the street to help us cross without causing an accident.

We would select the area where the cars are coming from, light signals or pedestrian crossings. From a neurological perspective, this requires eye movement (frontal lobe, saccades, superior frontal gyrus)[4] head orientation (motor cortex)[3], and ability to switch attention from one place of focus to another (parietal cortex)[5]. On the cognitive side, there are decisions about what speed to drive in, what direction to take, and the distance needed to keep in relation to other cars.

A random selection process would not be very useful as it would impede our ability to successfully interact with our environment. Taking the example from above, if our attention randomly switches to the trees in the nearby park that would not help in decision making processes involved to crossing the intersection safely.

Knowing more about how visual spatial attention works in tandem with decision making can help improve wayfinding techniques related to street and building navigation. It is also important to note that understanding how different cognitive demographics such as those with ASD or visual impairment differ in the in the context of visual spatial attention, this would be a great step forward for inclusive city design.

A wayfinding study conducted by Roger Ulrich and colleagues, found that hospital staff lost 4,500 hours per year giving directions to disoriented patients and hospital visitors, resulting in $220,000 in lost revenue.

Ulrich, R. et al. (2004) The role of the physical environment in the hospital of the 21st century: A once-in-a-lifetime opportunity. [online] Concord: The Centre for Health Design. Available at: https://www.healthdesign.org/system/files/Ulrich_Role%20of%20Physical_2004.pdf [Accessed 23 Mar. 2018].

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Orchestration

The final piece to this section is what we have identified as orchestration. The senses do not work in isolation and the perception of one sense is highly influenced by other senses. For example in the case of olfaction (smell) basic aspects of olfactory processing, such as detection thresholds, adaptation rates, and intensity are all strongly modulated by visual information[1]. This suggests that the interactions between olfaction and other sensory modalities may play a role in effective odour perception[1].

An event-related fMRI study, using a low level odour detection task, demonstrated that olfactory detection was faster and more accurate when odours appeared in context of semantically congruent visual cues[1]. In other words detection improved when the smell of an orange was experienced simultaneously as an image of an orange was shown[1]. The full extent of how the modality happens in the brain still needs more study, however the hippocampus is indicated to be partly involved in the modulation[1].

"Event-related fMRI involves separating the elements of an experiment into discrete points in time, so that the cognitive processes (and associated brain responses) associated with each element can be analyzed independently"

Huettel, S.A. (2012) Event-related fMRI in cognition. Neuroimage, 62(2), pp. 1152-1156.

Hippocampus . "It is crucially involved in cognition, particularly in episodic, semantic, and spatial memory processes. It also plays a role in novelty processing"

Konrad et al 2009. Defining the human hippocampus in cerebral magnetic resonance images—an overview of current segmentation protocols. Neuroimage, 47(4), pp.1185-1195.

From the perspective of the built environment orchestration means two things. Firstly, we need to fund more research to further investigate the effects of diverse sensorial information specifically in the context of offices, schools, and hospitals. These are environments where this type of information will be most useful. Secondly, we must start to think in terms of sensorial orchestration rather than saturation. Small environments such as offices, schools, and hospitals are especially vulnerable to incoherent sensorial input that can yield significant impacts. For example, absenteeism and poor performance has been linked to noise in hospitals[2] and in offices[3]. Another challenge is when we focus on one sensorial input, we do not understand it the bigger context. For example, does an office space filled with warm lighting have an effect on thermal perception[4]? Finally, we should also consider those who are neurologically different, to make these spaces more inclusive, for example do noise level affect how a blind person navigates a space? Or does a person with ASD have different sensorial requirements than those who are not on the spectrum?

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FACTORS AFFECTING PEOPLE IN CITIES

As it has been specified in the first section of this chapter, perception is highly influenced by "top down factors". These can range from micro factors such as an immediate goal ('I need to find my keys') to more macro factors such as societal trends. In this section, we will point out the factors that will have the most influence on city dwellers in the next 20-50 years.

There are two parts to this section the first is "technology" and the second is "urban sprawl". Each part will also include sub-parts titled "The unintended human consequence" and "Relevance to the built environment".

Technology

The first major factor that will influence how people perceive and interact with cities is technology. Within this subject there are two further distinctions; digital devices and automation. These have been chosen due to their impact on our attention systems and human to human interaction.

I) Device use and information access:

Digital devices are a technology that accesses media and information; laptops, smartphones, tablets, televisions and computer screens[4]. The devices are catalysing and affording a new culture of high information consumption.

A key trait amongst most mammalian species is curiosity, it is a drive to seek new information[1]. It is curiosity that led to access new types of food resources, explore new territories, and it landed us on the moon. Formally curiosity can be defined in terms of emotion, behaviour, and task[1]. We feel a need to be curious, we behave in a curious manner, and we do things based on curiosity.

In the context of today's culture we are satiating our curiosity through digital devices as they are a portal for which to access an ordinate amount of information. Digital devices are fully integrated into nearly every aspect of our lives[2]. Imagine the change in productivity if we couldn't answer emails on a train, or how our social connections would change if we couldn't access loved ones around the clock, or how our perception of autonomy and safety would change if we didn't have our phones to call for help? Ofcom has presented statistics which indicate that people are spending nearly 9 hours per day on various devices[2]. Young people (16-24) are doing 14 hours per day and children are also spending more time on screens than they do on other activities[2].

These stats should be taken with caution as this is not representative to all sections of society. For low income families, their situations is quite opposite. Their lack of access to digital technology is having an effect on their ability to excel at school and work at the same rate as their digitally connected counterparts[3]. This is referred to as digital inequality, which is focusing on how access to, and the use of digital technologies varies among people with or without access to the internet[3].

There are two things to take away from this part; the first is that digital devices are a portal of access to information and the second is the amount and rate of information is the important factor rather than the device. In the next part we will look at what this consumption is doing to our attention systems.

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A) The Unintended Human Consequences

Despite all the great advancements automation will catalyse, there are two possible unintended human consequences to highlight. This is not to say automation has to be halted, it means that cities should be aware of the human effect of automation. This will lead to a smoother and smarter integration.

Firstly, we should consider the possible development of situational depression. This type of condition refers to experiencing depressive symptoms resulting from psychosocial stressors, such as sudden death in the family, a divorce, or a sudden job loss[1]. Some cities in the UK are predicting to see between 13-25% jobs losses due to automation by 2030[2]. If there are no plans or provisions to disperse these workers into other industries, we hypothesise a rise in situational depression amongst this segment of the population. This could potentially lead to a lower quality of life as well as increase mental health costs. This theory requires further research as not all people who lose their job will develop situational depression, we must understand all other contributing factors. In doing so we could help mitigate the effects.

The full extent of the consequences to cities and people from fast and widespread unemployment loss can be seen in the history of “ex-factory” towns such as Flint or Detroit, both in the state of Michigan, United States of America. The former is in the depths of a crisis[3] whilst the latter has taken many decades to rise up[4]. We have the opportunity to prevent history from repeating itself and make this transition smoothly.

Highly automated cities are still in the far future. However we should consider how a reduction in face-to-face interaction due to automation could have an effect on cognitive elements, such as empathy.

“Depression is a mental disorder of the representation and regulation of mood and emotion”[1]. Depression is linked to abnormalities in the frontal cortex, anterior cingulate cortex, amygdala, and hippocampus[1]. This can lead to an array of cognitive differences such as recognising emotions on faces, difference in attention patterns, and differences in regulating emotion[10]. It can also have physiological symptoms such as “chronic joint pain, limb pain, back pain, gastrointestinal problems, tiredness, sleep disturbances, psychomotor activity changes, and appetite changes[2].”

Davidson, R.J., Pizzagalli, D., Nitschke, J.B. and Putnam, K., 2002. Depression: perspectives from affective neuroscience. Annual review of psychology, 53(1), pp.545-574.

Trivedi, M.H., 2004. The link between depression and physical symptoms. Primary care companion to the Journal of clinical psychiatry, 6(suppl 1), p.12.

Human empathy is a psychological construct which has both cognitive and emotive components providing us with a highly sophisticated ability for emotional understanding[5]. From the emotive perspective it is the ability to experience someone else’s emotions, an emotional contagion if you will (‘I feel what you feel’)[5]. When we perceive through visual and other sensorial cues another person’s behaviour it instantly elicits one’s own experiences for the behaviour. Output from this shared experience automatically activates the “motor areas of the brain where the responses are prepared and executed”[5]. This means that we experience another person’s sadness on a mental and neurological level. This is extraordinary detail into another person’s mental state that allows us to make highly intelligent decisions about social interactions. The second component is cognitive empathy, which includes more complex cognitive functions such as empathy perspective-taking and mentalising. This translates to ‘I understand what you feel’[5]. Cognitive empathy allows us to extend our minds far away from our mental state, giving way for complex problem solving.

Empathy is necessary for various different tasks from providing the correct emotional support to a conversation or social interaction to understanding the plight of another human being. It can also be involved in more complex outputs, such as a the fast and strategic thinking in negotiations or a doctor developing new diagnostic techniques through constant observation and mind extension to the world of her patients. It is the ability to ask questions such as ‘how would a person react or feel if this happened’ or ‘is there a better way to communicate an idea’, or ‘how what is a service that people really need?’

This understanding of empathy illustrates how empathy is tied to human to human interaction. We have learned to develop our empathy capacity due to our highly socialised existence. Therefore, if automation begins to strip away the opportunities for human-to-human interaction, there could be a change in how we exhibit empathy as well as our capacity for it.

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B) Relevance To The Built Environment

- Creating opportunities in cities where people can spend time together such as parks, public squares and other third spaces. This will be increasingly important to counterbalance the places where people will have a depletion of human-to-human interaction.

- Automation can have huge implications for the real estate and built environment industries. There is both risk and opportunity. Occupiers of office real estate will likely see their business practices change as a result of technology and automation. A report from McKinsey & Co states that 60% of businesses will see ⅓ of their processes automated, this changes the dynamic of employment and from whom office is rented[1]. There is already a shift occurring in large companies using serviced office centres such as WeWork over traditional office settings due to the cultural and physical offerings[2]. However, these serviced offices are still catering to the 20th century worker. Companies are urgently searching for the best possible talent. Some, like the BBC, HP, and Microsoft are going as far as attracting talent that is on the autism spectrum disorder to fulfil niche jobs. As automation helps with repetitive tasks or analyse large data sets, people will be expected to problem solve more complex problems. This means two opportunities, the opportunity is two fold; offices can evolve to places where people gather to think, meet, and research. Like a modern library or thought salons for those needing to solve complex problems. There is also an opportunity to transition workspaces to labs and makerspaces for future invention and growth. There is no evidence to point towards no longer needing to generate ideas due to automation. Therefore, whilst ideas are still needed, spaces for face to face interaction will still be needed.

- Creating cities only for efficiency should not be the aim of automation, it should be to humanise the city. Autonomous vehicles could result in the reduction of traffic, which in turn allows transporting someone quicker to their family, work, or social activity. We need to think of automation as a tool to enhance and increase the time for human-to-human interaction.

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Urban Sprawl

The second macro category of factors to consider is urban sprawl, especially in the context of transport and climate change. In the next parts we will discuss the cognitive and physiological implications of ever-sprawling cities.

Urban sprawl is defined as the uncoordinated growth of a community, usually away from an urban centre into outlying areas. This is usually without concern or consequence to environment or societal impact[1]. Interestingly, it is not always due to population density, but a mixture of socio-economic factors. Such as means of transportation, price of land, house prices, cultural constraints, preference for rural living, demographic trends, pollution, and changes in city culture[1]. It is one of the most studied phenomena of the last ten years due to rapid rate of expansion and the severe consequences it could have on city dwellers, environment, and infrastructure[1].

I) Transport and Distance

Transportation is one of the most important infrastructure elements for cities. It is the connector of people to resources, opportunities, and social interactions. The transport modes we are referencing are bus, car, trains, and taxis. We are excluding active transport from this section, which is the ability to walk, run or cycle to a destination. Currently, as cities expand the more commuting time increases[2]. However, it does not have to be this way, plenty of studies have shown that density and mix use development helps reduce commuting times as it reduces the distance between places[3].

In this section we will look at the consequences of distance and transport modes on human cognition and physiology.

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A) The Unintended Human Consequences

This section will focus on four consequences of transport; poverty, social exclusion, stress, and toxicity. All of these areas have cognitive and physiological consequences.

A recent report produced by UCL[3], discusses how poor access to transport contributes to poverty and social exclusion. These two factors separately and together have correlates to longer term cognitive and physiological consequences such as obesity, depression, and anxiety[7,8,6]. Furthermore there are also links between obesity, depression, and anxiety, often found as comorbidities of each other[9,10]. In other words people with obesity may also to also be anxious or depressed and visa versa. This is important as it shows the high human cost and significance of the issue.

Stress can be caused by an array of environmental elements or stimuli, long commutes in both automobile and trains are well documented and researched environmental stressors[1]. More research needs to be done to understand the long term cognitive effects of transport, specifically in the context of productivity. For example, do stressful commutes affect our ability to focus at work? Or do they have an effect on brain systems such as memory and attention? Two systems that are linked to learning new skills and information.

We should also consider the elderly and those with physical variances as they have statistically less opportunity to access transportation due to having personal mobility challenges[4, 3]. Improving access to transport for these groups will have an impact on their feelings of isolation and social exclusion[11, 12]. Which have links to anxiety and depression[7,6]. Additionally in the case of the elderly there is a correlation between feelings of loneliness and cognitive decline[13].

The final consideration is the exposure to toxins in public transport systems as they may have long term has long term effects on our mental and physical health. A Canadian study looked at the level of daily exposure to $PM_{2.5}$ in the underground metro network of three major cities[14]. It identified that a typical 70min commute, which constitutes 4.9% of the day, was estimated to contribute to over 50% of the estimated daily exposure to several $PM_{2.5}$ metals. In turn this has an effect on rates of asthma, developing respiratory inflammation, and lung function[14]. Furthermore, there is now evidence that long term exposure of $PM_{2.5}$ can influence the onset of severe depression, with symptomatology so acute, it is leading some people to request the help of emergency services[15].

The problem is not cities growing, the problem is how they grow. With the right infrastructure we can mitigate many of the challenges mentioned in this section.

$PM_{2.5}$ is the most common term used to describe an array of particle pollutants, they can be solid or liquid [14]

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B) Relevance to Built Environment

- One of the challenges in creating solutions within cities is knowing where to start or what solution will have the most impact. With neuroscience pointing out the infrastructure elements that have the most acute biological consequences, industry can use this data to create guidelines, which can aide with decision making on mix use developments or in understanding what planning initiatives to prioritise.

- Those living on city peripheries can feel excluded and find it hard to take up available jobs unless there is transportation linking them to the centre. The Brazilian city of São Paulo is experiencing commutes of up to 4 hours where almost 70% of journeys are made by bus. In some municipalities like Itaquaquecetuba in the extreme east of the city, bus transportation is the only link to work[1]. This translates to forcing poor people to endure, not only the mental stress of extremely long commutes, but also long exposure times to pollutants as they sit in traffic, which can have severe mental and physical health implications[4].

- There is also a nutritional factor, that many ghettoised places outside of city centres have higher incidences of malnutrition due to poverty and lack of access to fresh food[5]. Malnutrition is not only a physical experience, it also has vast neurodevelopment problems, which can lead to lifelong disorders, such as schizophrenia and antisocial personality disorders[6]. Therefore urban planning concepts like density where there are various options to access food and work can help mitigate against long term debilitating mental disorders.

- How to transport people from A to B is a long studied concept and the role of neuroscience is from two perspectives. The first is research to support the longer term biological effects to validate city planning strategies. The other is wayfinding, especially in public transport. Part of the access problem with the elderly and the physically variant is that it is not intelligible to them. For example, someone with visual impairment may find it difficult to navigate complex tunnels and multiple access points, which can act as deterrent, decreasing their desire to access their local transport link. In the case of the elderly, legible and clear signposting, auditory instructions, and better safety measures would increase use as it would make transport less confusing and daunting[3].

In schizophrenia “the symptoms segregated into three syndromes: psychomotor poverty (poverty of speech, lack of spontaneous movement and various aspects of blunting of affect); disorganisation (inappropriate affect, poverty of content of speech, and disturbances of the form of thought); and reality distortion (particular types of delusions and hallucinations). Both the psychomotor poverty and disorganisation syndromes were associated with social and occupational impairment; in particular, the psychomotor poverty syndrome was associated with impairment of personal relationships, and the disorganisation syndrome with poor self-care and impersistence at work.”

Liddle, P.F., 1987. The symptoms of chronic schizophrenia. A re-examination of the positive-negative dichotomy. The British Journal of Psychiatry, 151(2), pp.145-151.

Antisocial personality disorder is an overt pattern for anti-social acts alongside traits such as impulsivity and irritability.

De Brito, S.A. and Hodgins, S.H.E.I.L.A.G.H., 2009. Antisocial personality disorder. Personality, personality disorder and violence, 42, pp.133-153.

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II) Climate

In this final part, we will be looking at the effects of climate change with a particular focus on heat and displacement. As we mentioned in the introduction of the this section, the playbook should point to long term trends that will affect human dynamics in cities and climate change will continue to be an important factor. We will also like to note that this is not a section on how to solve climate change, rather an understanding of how it affects people on a cognitive and physiological level.

Motor vehicle traffic is a major contributor to climate change due to the release of greenhouse gases. In the US cars account for 26% of greenhouse emissions[9]. Expansion also means deforestation which increases impervious surfaces, making city more vulnerable to flooding. Flooding in turn erodes storm water into water streams, increasing the risk of disease contagion[3]. The third climate change phenomena is urban heat island (UHI) effect, which makes cities several degrees warmer than surrounding areas[2]. The fourth element related to climate change is the rise in extreme weather[10]. This means more frequent floods, hotter summers, colder winters, and hurricane systems[10].

A) The Unintended Human Consequences

The demand for new infrastructure in cities as a result of urbanisation is pushing a city's resilience to breaking points. The replacing of nature with built environments destabilise an ecosystems natural ability to mitigate extreme environmental activities, such as flooding[3]. A recent example of this was the devastation caused by hurricane Harvey in Houston, Texas[2]. One of the major contributors to the high levels of flooding was the ratio of concrete pavement to natural green areas[11]. This caused the city of Houston to become water repellent increasing the expansion and levels of flooding[11].

There is an argument that flooding in cities is a zoning problem, the allocation of land for development (sidewalks, buildings, roads) rather than for green spaces (parks, natural reserves) is causing cities to flood uncontrollably[1]. Hurricane Harvey damaged over 200,000 homes and nearly 40,000 people were displaced to shelters, other cities, and hotels[3]. This is a significant amount of human disruption. Relating this back to neuroscience, we propose that the displacement of people via these natural disasters has mental health implications. The first is post traumatic stress disorder (PTSD) from the initial shock of experiencing extreme trauma[4]. PTSD has devastating long term effects, such as depression and anxiety[5]. As more extreme weather conditions arise and force people to leave well established lives for new and possibly alien environments, industry should think about how this contributes to isolation and alienation[6].

Alienation is feelings of meaninglessness, powerlessness (lack of control) belonging lessness, social and self-isolation.

Clark, J.P., 1959. Measuring alienation within a social system. American Sociological Review, 24(6), pp.849-852.

The second consideration is the UHI effect occurring in urban areas,which is generated from urban structures, such as buildings or large areas of concrete re-radiating the heat coming from vehicles, power plants, air conditioners, and other heat sources[8]. A lack of natural heat-mitigating elements such as trees providing shade and ventilation can result in people increasingly living in “hot ovens”, with no respite[8]. The UHI effect causes demand for more energy as people struggle to keep buildings cool, which in turn adds more pollutants into the air[8]. It increases ground level ozone layer, which can be very harmful to children and infants[8]. Most of the current literature concentrates on UHI's effect on general health and mortality, which are very important factors to consider[7]. However, it is also important to consider what effects UHI has on cognitive performance and in turn productivity due to stress caused by elevated temperatures. Heat stress affects cognitive performance differently, depending on the type of cognitive task and exposure levels[12]. However, one core correlation is that heat contributes to lower cognitive performance as it competes for attentional resources[12]. In other words, as attention is being allocated to respond to the stress of heat it distracts focus from the task at hand. Additional research should be considered to investigate if UHI has an effect on brain development and structure, which could have further effects on productivity.

B) Relevance To The Built Environment

- We need to understand more about the cognitive and psychological effects of displacement. This will help urban designers and engineers understand what type of design interventions and social systems are needed for cities taking in displaced people. Research should especially focus on the effects of social cohesion and social capital.

- Industry should start to consider how extreme weather might change people's interaction with the built environment. Do colder winters or hotter summers cause children and adults to choose shelter over outside activities? What will be the health implications of these new behaviours? What will staying indoors mean for human-to-human interaction? Will it change how we socialise? Social cohesion? Could it increase isolation in varied demographics such as the elderly?

- What will extreme weather do for economically challenged demographics in terms of quality of life, if they cannot afford to mitigate the effects of weather?

- UHI deteriorates the experience of the city as it thermal comfort decreases, this could have an effect on dwell and general engagement with city activities and resources.

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On Slowness
Tod Williams & Billie Tsien
***2G*, 1999**

In an earlier edition of *2G* devoted to Arne Jacobsen, Knud Aerbo, one of his former associates, spoke of Jacobsen's office:

"What we had when we worked with Arne Jacobsen: A drawing table—a 90 x 160 cm uneven table top—a side chair with a straw bottom. Our own T-square and a pencil which had to be sharpened with a knife… Drawing pins to hold the paper; tape was not invented yet... If you look at it today, you will have to say: it could not be done. But luckily we did not know then."
Recently, one of the architects in our studio put down the telephone and said incredulously, "No more leads!" Calling to place an order for new "F" leads, he was told that Faber-Castell was no longer making them. People apparently do not draw enough anymore to make it worth their while. This is just the latest disappearance. And it seems to be happening more and more often to more and more tools that we use. Lettering and shape templates are disappearing. In 1993 we were told that there were only 144 more Dietzgen lettering templates in all the warehouses in the United States. So, we bought twenty. The "S"s and "4"s on these templates are wearing out, breaking, and there are no more templates to be had. Because we hear that they too are being phased out, we are hoarding ink pens. It is isolating and disorienting; a very strange feeling, rather like waking up to find that that the tide has come in, and familiar landmarks are submerged. Slowly, the tools of the hand disappear.

In the United States, the practice of architecture has come to rely on the computer. In offices the word "efficiency" is always mentioned, and in design schools the capability to create and rotate complex forms in space is lauded. So, with surprising speed, the tools of the hand are becoming extinct.

clutch pencil, lead, and lead pointer*
bunny bag*
pounce*
erasing shield*
lettering template*
**soon to disappear*

This is a lamentation for lost tools and a quiet manifesto describing our desire for slowness. We write not in opposition to computers—in fact we are in the midst of bringing them into our studio—but rather it is a discussion about the importance of slowness. We write in support of slowness.

"There is a secret bond between slowness and memory, between speed and forgetting. Consider this utterly commonplace situation: A man is walking down the street. At a certain moment, he

tries to recall something, but the recollection escapes him. Automatically, he slows down. Meanwhile, a person who wants to forget a disagreeable incident he has just lived through starts unconsciously to speed up his pace, as if he were trying to distance himself from a thing still too close to him in time.

In existential mathematics, that experience takes the form of two basic equations: the degree of slowness is directly proportional to the intensity of memory; the degree of speed is directly proportional to the intensity of forgetting."
—Milan Kundera, **Slowness**


Photo by Peter Arnold, 1998

Slowness of Method
Our desire to continue to use the tools of the hand, even as we may begin to use the computer, has to do with their connection to our bodies. Buildings are still constructed with hands, and it seems that the hand still knows best what the hand is capable of doing. As our hands move, we have the time to think and to observe our actions. We draw using pencil and ink, on mylar and on vellum. When we make changes, they occur with effort and a fair amount of tedious scrubbing with erasers, erasing shields, and spit. We have to sift back through previous drawings and bring them to agreement. So, decisions are made slowly, after thoughtful investigation, because they are a commitment that has consequence. It is better to be slow.

We like to keep the stack of finished and unfinished drawings nearby so that the whole project can be reviewed easily. Their physical presence is evidence of work done, and a reminder of what there is to do. The grime that builds up from being worked over is poignant and satisfying. We see the history of the presence of our hand. To have the actual drawings in reach allows us to understand the project in a more complete and comprehensive way. In the buildings we design, we struggle to achieve a unity and sense of wholeness that can come from a balance of individual gestures within a larger and more singular container. The focus of a computer screen feels too compartmentalized and tight to see and understand the whole. And if every time a change is made, a new printout is made, there is the problem that the printouts are too clean. They don't show the scrubbed and messy sections of erasure, so there is no evidence to indicate the history of the development of an idea. Crucial to creating wholeness is the understanding of the development of the idea.

We work together, twelve people in one room without divisions. Much like a family, we expect that others will help whenever we need them, and however we need them. So there is no division of labor into design, production, model-making, or interiors. Each architect is involved in the making of contracts, billing, and writing of letters. Since we have no secretary, the phone is answered by whomever has the least patience with the ringing. Because each person must be a generalist, a certain amount of efficiency is lost, as each person must learn all the tasks of the office. We ask that people constantly shift their attention between their particular task and one which helps the office as a whole. What this rather casual approach to office management accomplishes is that everyone knows what is going on around them. If there is a problem, it is shared, and of course we try to share the joys as well. The sense of well-being in the studio must be supported and nurtured by each member.

So our way of working allows us to have the experience of slowness. Tools are connected to the slower capacity of the hand; the presence of hand-drawn pages documents both the path of thought and the destination. The generalization of tasks means our office works not as an efficient machine, but as a loose and independent and somewhat inefficient family. The slowness of method allows us breath and breadth.

We have written a Mission Statement for the office: Whatever we design must be of use, but at the same time transcend its use. It must be rooted in time and site and client needs, but it must transcend time and site and client needs. We do not want to develop a style or specialize in any project type. It is our hope to continue to work on only a few projects at a time, with intense personal involvement in all parts of its design and construction. We want the studio to be a good place to work, learn, and grow, both for the people who work in the office and for ourselves. The metaphor for the office is a family. Each person must take responsibility for their own work, but as well must be responsible for the good of the whole. We do not believe in the separation or specialization of skills. Each architect in the office will work through all aspects of a project. We would like to be financially stable, but this will not outweigh artistic or ethical beliefs, which will always come first. The work should reflect optimism and love. The spiritual aspect of the work will emerge if the work is done well.

Slowness of Design

In a public forum we were asked, “What is your design strategy?” We were at a loss for words. There is no strategy for either an ascendant career, or more importantly, the way that we design. It is so easy to use the cushion of past thoughts to soften the terrifying free fall of starting a new project. It is inevitable that, as we accumulate a longer design history, we repeat things unconsciously. Still, perhaps naively, but in earnest, we try to start each project with a blank slate. The design is incremental—small steps that are made in response to the site, the client, the builder, and our own intuition. We try to fight through what we have learned, toward the freedom found in innocence. The design is a slow and often uneven accumulation of stitches, that are often ripped out part way through while we struggle to make clear, or to understand, what the pattern and organization might be, even as we avoid as much as possible knowing what the final image might be.

So, the first intuitive drawings are usually very rough plan forms which might demonstrate the gesture of the body’s movement and how that is expressed by a mass in relationship to the land. We always show these drawings to the client because we want them to understand the intuition or gesture that is the genesis of the design. It is also a way of saying, “I don’t know what I am doing yet, but I do have a feeling about it.”

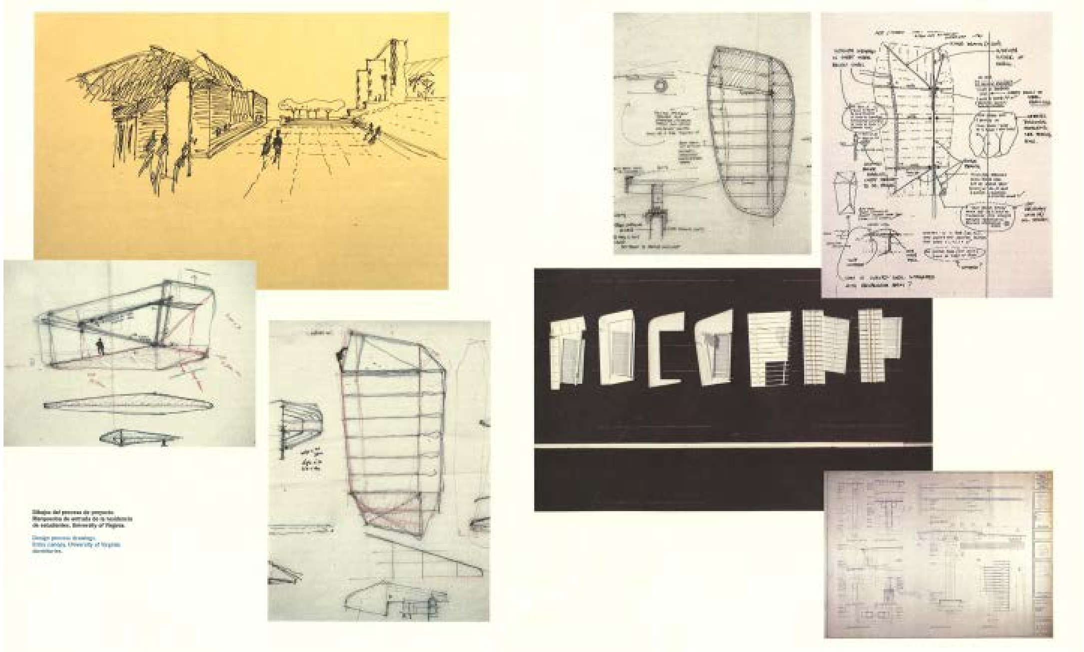
Often, as the plans are worked through, an idea about a section or a detail or a piece of cabinet work will come to mind. And for a while the plans are put aside and the stray thought is pursued. Progress is a stutter step, not a forward march: three steps forward, two to the side, and one step back. It is a choreography that somehow pulls itself together. With each project, it feels as though we are infants learning how to walk. We pull ourselves up, wobble, take a few steps, and fall down.

This way of developing the design mirrors the working method of the office: moving back and forth between advancing the particular task and attending to the myriad details that are the sidetrack. One generally thinks that to be “sidetracked” is a bad condition, but we think that it is enriching. The sidetrack is simply a parallel route. It has been said that architecture is the mother of all the arts; meaning, one supposes, that it is the generative root. We prefer to think that architecture is like a mother caring for a toddler: she must keep hold of the larger vision of the adult whom the child will become, while stopping to clean up fingerprints and wipe noses.

For us, elevations are always the last part of a building to be developed. Often we are at the end of design development before we even begin to rough out the elevations. This is because elevation drawings close down the process of questioning by making the image of the building too clear, too “graspable,” and therefore too final. Clients, magazines—in fact, we as architects and human beings—all want an easy and clear answer. But it is better not to provide one before the interior habitation and the structure of the building has been given enough time to develop as the logic for the facade.

In our current practice, the construction drawings are produced on 30” x 42” mylar sheets using pencil and ink. Notes are typed up on the computer and Xeroxed onto what we call “stickyback,” which is an acetate with an adhesive surface. This is glued to each page. The working drawings consist of the typical site plan, plans, reflected ceiling plans, wall sections, and general details. At the same time, and continuing through almost the entire construction process, is a sketchbook. The page size is 11”x17,” which is the largest sheet size that our Xerox machine can duplicate. Divided into sections of cabinetwork, miscellaneous metals, window details, roofing details, and miscellaneous building details, the sketchbook can often run up to two hundred pages. Based on previous experience we try to have the contractor set an allowance for certain trades like cabinetwork or metal fabrication. There are several reasons why the sketchbook is useful. It allows several people to work on parts of a specific section at the same time. It means that questions can be answered quickly by issuing a sketch sheet rather than by going back to the large drawing set. Most importantly though, it means that we don’t have to stop designing at the issuance of construction documents. It allows us to continue to develop drawings and details even as the project is being built and constructed.

Finally, during the construction period, the project architect—who has been involved since the beginning intuitive drawings—supervises the construction. Often on larger projects, the project architect has moved to the site for as long as a year and half. In this way as questions come up during the course of the project, the choices that are made are made with a sense of the history of the idea and they are true design decisions that accrue to wholeness. They are not simply the result of expediency in the field. This position of “not knowing a priori” is antithetical to the general model of the architect as hero. This is a damaging model because it discourages the slowness of process that comes from the patient search. Certainty is a prison.



Scan of excerpt from 2G

Slowness of Perception

As our work matures, the perception of it is less and less understandable through photographs. One can only understand it by being there and moving and staying still. One reason is that we have been trying to integrate our buildings into the landscape. Thus, often the most important space is the empty space that is contained by the built forms. This empty space is the heart of the project at the Neurosciences Institute in La Jolla. It is the invisible magnet that holds together the separate buildings, and provides the coherence that makes the project feel whole. So what is not there is equally important, perhaps more important, than what is there. How does one photograph nothing? One experiences it.

And because we develop our facades as late as we can, we are not relying on a flat plane to carry the strength of the building or to transmit a sense of the place. So it is difficult to shoot the facade of a building because it is only seen by itself, and not, as your eyes see it, in relation to the buildings next to it, in relation to the empty space next to it.

So there is no quick take on our work; no singular powerful image that is able to sum it all up. We are not sure how to present our work. We know that the answer is not a computer-generated “fly-through,” or even a video of the real thing. The pacing and the viewpoint of these methods are still too consistent. They are cold, machine-like lenses that follow a too-logical sequence of movement. A human eye scans panoramically, and then suddenly focuses down on a tiny point. You see the ocean, and then you see a grain of oddly colored sand. The boundaries of what one chooses to perceive are constantly expanding and contracting.

And of course there are the myriad of stray thoughts, memories, and images that are called up by what you see in the color and shade of an actual space. There are the distractions (and perhaps one can also see them as positive additions) of sound, smell, shifting light, and the conversations of passers-by. This can only happen when you are there. So, we suppose we can only offer this monograph of our work as a suggestion of what we do, or perhaps even as a pack of lies, which must be proven or disproven by your own feet and eyes.

Slowly (improving) Vision

Tod Williams & Billie Tsien

***2G,* 1999**

We wrote this essay as a continuation to *Slowness* in 1999 for the publication *2G*.

During a recent telephone interview, a student asked me to describe “our architectural vision.” The question, asked by a person still in high school was so naïve as to be easily dismissed, yet so profound that I realized it was deserved a thoughtful and considered response.

As architects committed to resolving problems of human habitation through built form, most of our thoughts of peering into the future are restricted to such questions as, “How will potential users need their space to function when they move in, or, several years hence, what issues of growth and change might there be? What kind of expansion and use might be expected? Will there be more children? Guests? How much storage in the future? What kind of maintenance will be required? How long will the roof last?”

These concerns for a project’s future are similar for practicing colleagues all over the world. They are issues that carry such important implications that they occupy much of our creative thought. We believe that creative resolutions to such questions are often precisely the ingredients of our creative search. The sporadic moments when the answers manage to transcend the questions are the foundation of what we imagine to be our vision. The constructed result of answering these questions is Architecture.

Giovanni Battista Piranesi, 1761

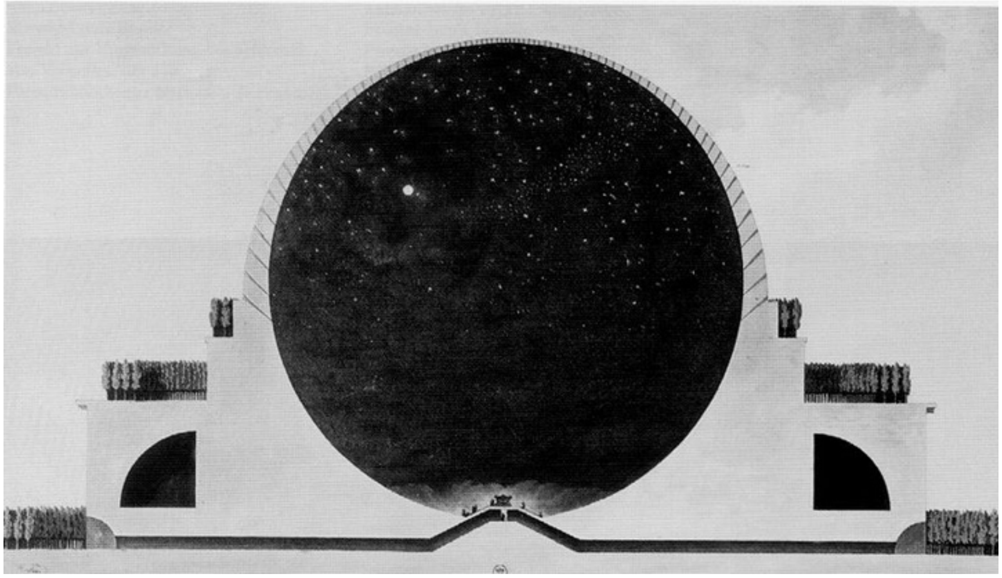
Giovanni Battista Piranesi, 1761

But this answer, as understandable as it might be for most practicing professionals, provides little inspiration for a thoughtful and concerned high school student.

So I thought about the work of the visionary architects—Boullée, Ledoux, Sant'Elia—and came across *Twelve Lines*, a poem by Louis Kahn:

Spirit in will to express
can make the great sun seem small.
The sun is
Thus the Universe.
Did we need Bach
Bach is
Thus Music is.
Did we need Boullée
Did we need Ledoux
Boullée is
Ledoux is
Thus Architecture is.

The power of the drawn idea can be almost as irresistible as the sun, and as Bach. Piranesi's dark, layered, mysterious drawings, Sant'Elia's bold studies for the Citta Nuova, the Mile-High tower of Frank Lloyd Wright, have all reverberated in our collective architectural imaginations. Today, cyber-architecture occupies many students' imaginations.



Étienne-Louis Boullée, 1784

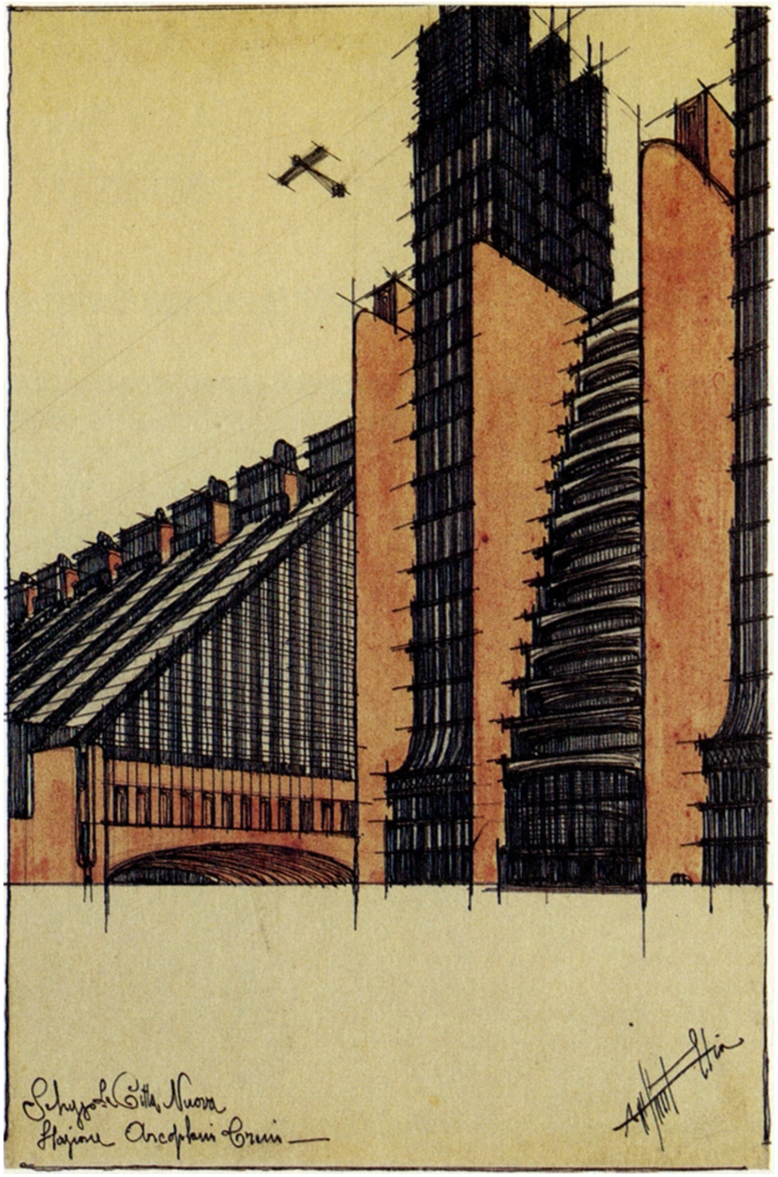
Visionary architecture achieves its greatest power as unbuilt work.
What is lost in the actual realization of the work? Is the thought more powerful when it is expressed without dilution than the ambiguity that results from responding to a complex series of factors so common and necessary as client, cost, code, and use?

Antoni Gaudí is one architect whose work has retained its vision in built form. He is one of the most extraordinary, elusive, and intriguing of the visionary architects. Yet upon examining the Colònia Güell models, one is struck by the absolute logic that informed the fantastic. A series of strings with small, weighted sandbags were used to determine the curves created by gravity. Gaudí's work is so based on the physical observation that it seems very much in the spirit of observations made centuries earlier by Leonardo da Vinci. Da Vinci is a prime example of an artist, an architect, an inventor, whose visionary ideas may be best appreciated in hindsight. As much as he was appreciated during his lifetime, he was also very much criticized. Today, however, virtually all of his work is regarded as 'visionary,' even though it was originally generated by very practical applications, and was part of a larger society. It is the product of practicality and devotion to problem-solving. The techniques he and Gaudí used were very much a product of their time and place. Gaudí's work, principally executed in the '20s, when most of the great architectural minds were looking to the machine for inspiration, hardly foreshadowed the future. Rather, it was an observation and rumination on the present. He, as Leonardo, was trying to solve a problem set before him at that moment.

So how does one address the question of 'vision' in built work?
Perhaps we are looking for a clear vision rather than looking to be visionary.
Vision can be attained after a long period of building. To be visionary is exclusive of building.

We believe clear vision is slow in evolving, as is 'good work.'

We are not visionary architects, but we are beginning to see more clearly.
We have chosen to work in a particular way; it is a way at once ordinary and connected to the world around us. But it is precisely in the ways it is ordinary and connective that it produces extraordinary results. In this way, it may (eventually) be considered to have vision.

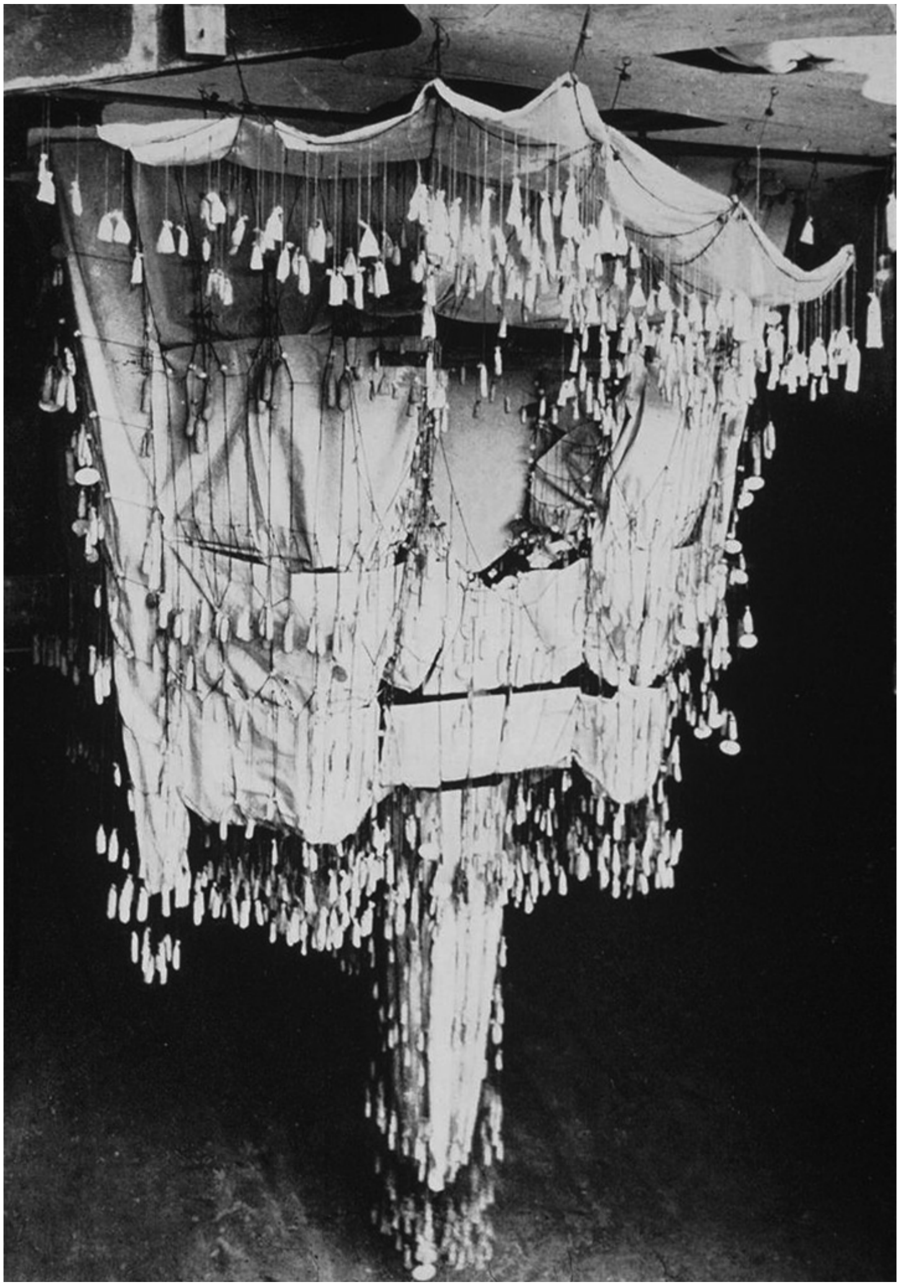


Antonio Sant'Elia, 1914

Relationship to the Earth

Architecture is connected to the Earth. Too many buildings have an ambiguous relationship to the land. As long as we live on Earth, we will be dealing with principles of gravity, atmosphere, and the very richness of Earth's surface.

Virtually all adults, standing, are connected to the ground with their feet, their line of vision a mere four to six feet above it. This is the point of origin of our waking perception. Architecture must first be concerns with this zone: our feet in contact with the ground. The surface of the Earth is the canvas of the architect. The precise detail of this zone is ours to affect. If we give away responsibility for these crucial areas of concern (to the landscape architect, to the interior designer), we then reduce and weaken our ability to be effective within our most intimate environment.



Antoni Guadí, 1898-1915

Location on the Earth

We need shelter from the brilliant sun in a desert site in Phoenix, but within an infill house condition in New York, we need as much light as possible. The construction methodology in Phoenix will necessarily be different from that of New York, because of codes, labor, material availability, site accessibility, and a host of other reasons, all of which could be conquered, if one wished. And people do wish! Whether by purchasing a Big Mac or hiring an important ‘signature’ architect or artist, there are people who choose to ignore or erase the differences of locale. The exploration of ideas (which are universal) and locations (which are singular) should give rise to an unlimited series of connective responses. It is easy to step up and order the known; more difficult, risky and slower to search for the original.

"Le notti di Cabiria," Federico Fellini, 1957

Care for Our Vision

As we become older, it is a little discouraging to discover our eyesight is less clear, particularly when near- and far-sightedness occur at the same time. Fortunately, this is a problem which is easily solved. A more difficult one is realizing that in this section of our lives we have more demands than ever, and with so much on our minds we find ourselves walking without seeing. But early this summer we attended a screening of Federico Fellini's film, "The Nights of Cabiria." Twenty-five years had passed since we had seen it first, and here we were astonished. A story was revealed to us in ways we never could have appreciated when we were young. Was it that the film's vintage had come into its own, or had our ability to see the work improved over the years? Our understanding and compassion for the human condition does improve with time. We have more to bring to our work as we grow older. Even as we may lose our ability to see distance, the accumulation of life as experience enables us to see depth. Over time our vision is (slowly) improving.

10

NEUROSCIENCE FOR ARCHITECTURE

Thomas D. Albright

Buildings serve many purposes. One might argue that their primary function is to provide shelter for the inhabitants and their possessions—a place to stay warm and dry, and to sleep without fear of predators or pathogens. Buildings also provide spaces to safely contain and facilitate social groups focused on learning, work, or play. And they provide for privacy, a space for solace and retreat from the social demands of human existence.

These primary physical requirements, and their many subsidiaries, simply reflect the fact that we are biological creatures. In addition to building constraints dictated by site, materials, and budget, an architect must respond to the nonnegotiable facts of human biology. Indeed, architecture has always bowed to biology: the countertop heights in kitchens, the rise:run ratio of stairs, lighting, water sources, heat and airflow through a building, are all patent solutions to salient biological needs and constraints. There are creative technology-based extensions of these solutions afoot in the form of smart homes. But there are subtler instances in which a deeper understanding of human biology affords a qualitatively superior solution. Consider, for example, the ascendance of the door lever as a design imperative imposed by biology. Seen from a strictly biomechanical perspective, a door lever is a far better tool than a traditional round doorknob for opening the latch. Pressure to adopt this superior solution came largely from recognition that it could benefit people with certain biological limitations ("physical disabilities"). Not surprisingly, the U.S. Americans with Disabilities Act (1990) has mandated the use of door levers because their design is easy to grasp with one hand and does not require "tight grasping or pinching or twisting of the wrist to operate."[1] Here is a case in which design centered explicitly on the details of a biological problem allows for greater accessibility and enhanced use.

At the same time that our buildings provide physical solutions to problems dictated by human biology, we also expect them to satisfy our psychological needs. We expect them to inspire and excite us, to promote mental states that lead us to discover, understand and create, to heal and find our way, to summon the better angels of our nature. We expect them to be beautiful. Not surprisingly, psychological considerations have been a part of the design process since humans began constructing lasting communal environments. The ancient tradition of Vaastu Veda, which dictated the design of temples and dwellings in early Hindu society, focused on ways in which a building directs "spiritual energies" that influence the souls of the inhabitants[2]—or, in today's parlance, the ways in which design influences the many facets of mental well-being. Feng shui, the ancient Chinese philosophy of building design, emerged for similar reasons.[3]

VAASTU VEDA IN THE AGE OF NEUROSCIENCE

While the basic psychological needs of a building's inhabitants today remain largely the same as they were in ancient times, we have one notable tool that promises a new perspective on how buildings influence our mental states: the modern field of neuroscience. Considered broadly, neuroscience is the umbrella for a collection of empirical disciplines—among them biology, experimental psychology, cognitive science, chemistry, anatomy, physiology, computer science—that investigate the relationship between the brain and behavior.[4] There are multiple internal processes that underlie that relationship, including sensation, perception, cognition, memory, and emotion.

There are also multiple levels at which we can investigate and characterize the relationship between brain and behavior. We can, for example, describe behavior in terms of the interactions between large brain systems for sensory processing and memory. Or we can drill down and explore how cellular interactions within circuits of brain cells (neurons) give rise to larger system properties, such as visual perception. Deeper still, we can explore the molecular components and events that underlie the behaviors of individual neurons, or the genetic codes and patterns of gene expression that produce the cellular substrates and organized circuits for brain function.

Most importantly, modern neuroscience affords the tools and concepts that enable us to identify the causal biological chains extending from genes to human behavior. This powerful approach, and the rich understanding of brain function that it affords, naturally has broad implications for and applications to many problems in human society, particularly in the field of medicine. But one might reasonably ask—and many do—whether there is any practical value for architecture and design that comes from knowing, for example, how neurons are wired up in the brain. I argue that there is value: knowing how the machine works can offer insights into its performance and limitations, insights into what it does best and how we might be able to tune it up for the task at hand. In the same way that understanding of an amplifier circuit in your car radio can lead to principled hypotheses regarding the types of sound it plays best, knowledge of how the human visual system is wired up may, for example, lead to unexpected predictions about the visual aesthetics or navigability of a building. At the same time, of course, the level of analysis of brain function should be appropriate for the question. In the same sense that knowledge of electron flow in a transistor offers few practical insights into what your radio is capable of, it seems unlikely that today's knowledge of patterns of gene expression that underlie brain circuits will yield much grist for the mill of design. That said, our understanding of brain development, function, and plasticity is still evolving, and we may find that the larger multilevel picture eventually leads to new ways of thinking.

THE BRAIN AS AN INFORMATION-PROCESSOR

In trying to understand more concretely how neuroscience might be relevant to design, it is useful to think of the brain as an information-processing device, which of course it is. Indeed, it is the most powerful information-processing device known to man. The brain acquires information about the world through the senses and then organizes, interprets, and integrates that information. The brain assigns value, affect, and potential utility to the acquired information, and stores that information by means of memory in order to access it at a later time. These memories of information received form the basis for future actions.

Thinking further along these lines, we can make the argument that architecture is a multifaceted source of information. The sensory appearance tells us how space is organized, and thus its utility and navigability. Similarly, the appearance and its relationship to intended function may be profoundly symbolic, conjuring up a broader view of the responsibility to the users of the space and their relationship to society. Prior experiences with the world will of course come into play in understanding the meaning of the space and how it might most effectively serve its intended purpose, or inspire other unintended uses. And, of course, information conveyed by our senses, considered in a symbolic and functional context, may be the source of strong aesthetic and emotional responses, including our perception of beauty.

Building on this information-processing perspective, we can begin to articulate a few basic principles about how knowledge of the brain may bear upon architectural design. These principles conveniently fall into categories of information *acquisition*, *organization*, and *use*. In terms of acquisition, the built environment should be optimized to neuronal constraints on sensory performance and information-seeking behavior, and optimized with respect to the adaptability of those constraints. At the simplest level, for example, knowing something about human visual sensitivity—what we see best and what we have difficulty seeing—may define rules for efficient design of environments for labor, learning, healing, and recreation. I will elaborate on some examples of optimizing sensory performance later in this chapter.

In terms of organization, the built environment should facilitate perceptual organization and engender the formation of cognitive schema/neuronal maps for the task at hand. An example of the relevance of neuronal maps can be found in research on wayfinding behavior.[5] A rich vein of neuroscience research has revealed much about how space, and the location of an observer in space, is represented by populations of neurons—neuronal maps of space—in a brain structure known as the hippocampus.[6] This knowledge, in conjunction with an understanding of how landmarks and other sensory cues in the built environment facilitate wayfinding, may lead to new ideas about how to facilitate navigability by design. These ideas, in turn, may help those who suffer from memory disorders associated with dementia, and help to improve design of transportation hubs and public areas in general.[7]

In terms of use, the built environment should elicit internal states that benefit sensory, perceptual, and cognitive performance and behavioral outcomes. "Internal states" here refers to those associated with focal attention, motivation, emotion, and stress. A number of recent studies support the plausible conjecture that certain environments elicit attentional states,[8] or states of anxiety and stress,[9] which can either facilitate or interfere with the ability of observers to respond to information embedded in the environment or to carry out actions for which the environment was intended. In work with Alzheimer's patients, for example, John Zeisel[10] has shown that architectural design elicits certain outcomes that have clinical value: anxiety and aggression are reduced in settings with greater privacy and personalization; social withdrawal is reduced in settings with limited numbers of common spaces that each have a distinctive identity; agitation is reduced in settings that are more residential than institutional in character. This type of knowledge could similarly inform the design of classrooms, lecture halls, health care facilities, workspaces, and more.

VISUAL FUNCTION, PERCEPTION, AND ARCHITECTURE

One area of neuroscience research that is particularly amenable to this kind of information-processing approach—and its relevance to architecture—is that associated with study of the visual system. This is true in part because vision plays a primary role in architectural experience, but also because we now have a wealth of information about how the visual system works.[11] In the following sections, I will highlight some examples drawn from our current understanding of vision, in order to illustrate the merits of this way of thinking. To set the stage, I will first briefly summarize the basic organization of the human visual system, as well as the neuroscience research methods used to study it.

Visual experience depends, of course, on information conveyed by patterns of light. Most of the patterned light that you see originates by reflectance from surfaces in your environment—sunlight returned from the façade of a building, for example. This reflected light is optically refracted by the crystalline lens in the front of your eye, yielding a focused image that is projected onto the back surface of the eye. This back surface is lined with a crucial neuronal tissue known as the retina, which is where phototransduction takes place: energy in the form of light is transduced into energy in the form of electrical signals, which are communicated by neurons. Retinal neurons carrying information in the form of such signals exit the eye via the optic nerve and terminate in a region near the center of the brain, known as the thalamus. Information reaching this stage is conveyed across chemical synapses and relayed on by thalamic fibers to reach the visual cortex. The visual cortex comprises the most posterior regions of the cerebral cortex, which is the large wrinkled sheet of neuronal tissue that forms the exterior surface of the human brain. The visual cortex is where high-level processing of visual images takes place, and it is the substrate that underlies our conscious visual experiences of the world. Our objective here is to understand how the organization of the visual cortex might have implications for the design of human environments.

EMPIRICAL APPROACHES TO UNDERSTANDING VISION

There is a variety of powerful experimental tools for studying the organization and function of the brain, which are summarized here as they apply to an understanding of the visual system.[12] Perhaps the simplest approach involves analysis of behavioral responses to sensory stimuli. This method, known as psychophysics, dates to the nineteenth century and involves asking people under very rigorous conditions to tell us what they observe when presented with visual stimuli that vary along simple dimensions, such as wavelength of light or direction of motion. From this we are able to precisely quantify what stimulus information observers are able to perceive, remember, and use to guide their actions. This approach is particularly valuable when used in conjunction with other experimental techniques, such as those that follow.

One important complement to psychophysics is neuroanatomy, which reveals the cellular units of brain function and their patterns of interconnections. With this approach we can, for example, trace the neuronal connections from the retina up through multiple stages of visual processing in the cerebral cortex, thereby yielding a wiring diagram of neuronal circuits.[13] Such wiring patterns reveal, in turn, computational principles by which visual information is combined and abstracted to yield perceptual experience.

Another powerful experimental technique is electrophysiology, the main goal of which is to understand how information flows through the system. To measure this flow, we use microelectrodes—fine wires that are insulated along their lengths and exposed at the very tips—that are inserted into the brain to monitor electrical signals (known as action potentials) from individual neurons. From such experiments we know that the frequency of electrical signals carried by a visual neuron is often correlated with a specific property of a visual stimulus. A neuron might thus “respond” selectively to a particular color of light, or to a specific shape.[14] These patterns of selective signaling reflect the visual information encoded by neuronal circuits. Moreover, by monitoring the ways in which signals are transformed from one processing stage to the next, we can infer the “goals” of each stage and gain insights into the underlying computation.

Fine-scale electrophysiology of the sort described above is largely restricted to use in experimental animals, but there are larger-scale approaches that involve assessment of patterns of brain activity recorded from the surface of the scalp. Despite the relative coarseness of the latter approach, electroencephalographic (EEG) methods are advantageous for our interest in architecture because they can be used to assess broad patterns of neuronal activity noninvasively in humans who are actively exploring an environment.[15]

Electrophysiological approaches are often complemented by a newer experimental technique known as functional magnetic resonance imaging (fMRI). This noninvasive method exploits the fact that: (1) oxygenated blood has a distinct signature in a magnetic resonance image, (2) oxygenated blood is dynamically redirected to regions of the brain that are metabolically active, and (3) neurons that are electrically active have a higher metabolic load. Thus the fMRI blood flow signal serves as a proxy for measurements of neuronal activity and can be used to identify brain regions that are active under different sensory, perceptual, cognitive and/or behavioral conditions.[16]

The various experimental techniques of modern neuroscience, summarized above, are most powerfully used in concert with one another, where they can collectively yield a rich and coherent picture of the ways in which information is acquired and organized by the brain, and used to make decisions and guide actions.

ON THE STATISTICAL PROPERTIES OF VISUAL INFORMATION

With this brief introduction to the organization of the visual system and the methods by which it can be studied, we can consider how current knowledge of information processing by the brain might suggest principles for design of human environments. I will begin with the premise that the brain has evolved to maximize acquisition of behaviorally relevant information about the environment, but must do so in the face of biological constraints. These constraints include various sources of noise and bottlenecks inherent to the neuronal machinery of the brain itself, the consequence of which is that our sensory systems are less than perfect transducers. Or, to put it more concretely, there are some things that we see better than others.

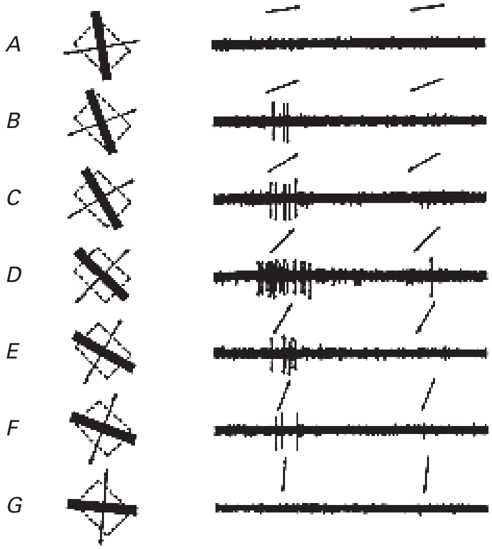
To illustrate how this limitation applies to architecture and design, we can start by measuring the physical properties of visual scenes from which the brain extracts information. There are many ways to do this—both natural and built environments have measurable statistics and we can quantify simple things like the frequency distributions of primary features, such as the different colors in a scene, or the orientations of contours (for example, those forming the frame of a window, or the branches of a tree). These simple statistics can be compared with the empirically determined sensitivity of the visual system for the same features, which provides a measure of the extent to which people can actually acquire (and thus use) certain classes of information present in the environment.

Employing the same approach, we can also quantify the statistics of higher-order image features—which are arguably more directly relevant to human behavior in natural and built environments—such as particular shapes and the joint probabilities of certain features (e.g., how often a specific color coincides in space with a certain shape). One specific example that has been looked at in some detail is the relationship between different line orientations as a function of their proximity in visual space.[17] As intuition suggests, there is a strong tendency for image contours that are nearby to have similar orientations, but as distance between them increases there is a progressive increase in the variance between pairs of contour orientations. One need only look at the contours of common man-made or natural objects—a teapot, for example, or a rose—to see that this distance-dependent contour orientation relationship simply reflects the physical properties of things in our visual world. The functional importance of this relationship can be seen by contrasting it with man-made objects that violate the principle: the image statistics of a Jackson Pollock painting,[18] for example, reflect a riot of angles and colors whose relationships yield no real perceptual synthesis.

FUNCTIONAL ORGANIZATION OF THE VISUAL BRAIN

Some unexpected insights and predictions come from consideration of image statistics in conjunction with knowledge of the organizational features of the visual cortex. Over the past few decades we have learned that there are a number different regions of the visual cortex that are specialized for the processing of unique types of visual information; one region processes contour orientation, another motion, another area processes color, and so on.[19] This knowledge has come, in part, from electrophysiological studies of the sort described above, in which the response (measured as frequency of action potentials) of a given visual neuron varies with the value of a simple stimulus along a specific feature dimension: for example, the particular angle of an oriented contour, or the particular direction of a moving pattern.

Figure 10.1 illustrates this type of cellular “tuning” as originally discovered for neurons in primary visual cortex.[20] The data represent action potentials recorded as a function of the orientation and direction of motion of a simple visual stimulus (an oriented contour). In this case, the recorded neuron responded best to a slightly off-vertical orientation moving up to the right, and the neuronal response waned as a function of the angular deviation of the contour relative to this preferred orientation. The vast majority of neurons in the primary visual cortex exhibit this property of "orientation selectivity." Their discovery in the 1960s by David Hubel and Torsten Wiesel transformed the way we understand the visual system, and fostered the development of a whole new set of techniques to study it. The existence of this specialized population of neurons in the cerebral cortex, and other populations that represent stimulus direction[21] and color,[22] accounts for the primacy of such simple features in our visual experience of the world.



10.1 Orientation selectivity in the primary visual cortex. D. H. Hubel and T. N. Weisel, 1968.

Each of these functionally specific areas is further arranged according to certain organizational principles. One of these is columnar organization, which means that similar values of a given feature dimension (such as contour orientation or direction of motion) are represented in adjacent cortical tissues.[23] These functional columns extend through the thickness of the cerebral cortex and are mediated by neuronal microcircuits that correspond anatomically to the functional columns.[24] The neuronal architecture is such that the preferred value of the relevant feature (e.g., the preferred contour orientation) remains constant as one moves from the surface through the depth of the cortex, but changes gradually as one moves in the orthogonal plane, i.e., parallel to the cortical surface.[25] The scale of this system is fine, with a complete cycle of preferred orientations contained within less than a millimeter of cortex. A highly similar columnar system exists in a region of visual cortex specialized for encoding direction of motion.[26] In this case, the individual neurons represent specific directions, rather than contour orientations, and a complete cycle of direction columns similarly spans a region of cortex less than a millimeter across.

Another organizational principle of the visual system is built around the concept of association fields.[27] Association fields reflect patterns of local anatomical connections that link neurons representing specific values of a visual feature dimension. In the primary visual cortex, the specificity of these connections is made possible by the existence of an organized columnar system for representing contour orientations (see above). The connections are manifested as anatomical links between columns representing specific contour orientations. In particular, within cortical regions representing close-by locations in visual space, there exist strong connections between columns that represent similar orientations and only weak connections between columns that represent widely different orientations (perpendicular being the extreme).[28] As the spatial distance grows, the pattern of anatomical connections becomes more isotropic.

ASPECTS OF PERCEPTION FACILITATED BY NEURONAL ARCHITECTURE

These highly specific organizational properties for representing information about the visual environment raise interesting questions and conjectures about their relationship to visual perception. For one, we note that there is an apparent symmetry between the association fields for contour orientation and the statistics (summarized above) of contour orientations in the visual world. As we have seen, contours that are nearby in visual space are more commonly similar in orientation, relative to those that are distant in visual space. Analogously, in the visual cortex, cells representing similar orientations are preferentially interconnected provided that they also represent nearby locations in visual space. There are evolutionary arguments one can make: it seems highly likely that this cortical system for organizing visual information conferred a selective advantage for detecting statistical regularities in the world in which we evolved. At any rate, we hypothesize that the existence of the system helps to facilitate the processing of commonly occurring relationships between visual features.

A key part of this conjecture, which has implications for architecture and design, is the word *facilitate*. Human psychophysical experiments have shown, for example, that when people view random patterns of line segments, any colinear, or nearly colinear, relationships within those patterns tend to stand out perceptually from a background of

10.2 Field of wheat.

10.3 Green bodhi leaves.

10.4 Alaskan tundra.

10.5 Feathers of an ostrich.

noise[29]—according to our hypothesis, perceptual sensitivity to these arrangements is *facilitated* by the organizational properties of the visual cortex.

As implied by the foregoing arguments, visual patterns in which there is a statistical regularity between adjacent contour orientations—repeating lines in colinear, curvilinear, parallel and radial patterns, for example—are ubiquitous in the natural world. Fields of grass, waves in the ocean, the veins of a leaf, the branches of a tree, the leaflets of a palm frond, or the barbs of a feather are all commonly encountered examples that embody this principle.

We hypothesize that man-made designs that adopt this same principle "benefit" in some way—detection of them is "facilitated"—by tapping into the highly organized neuronal

10.6 Fay Jones, Thorncrown Chapel, Fayetteville, Arkansas.

system for representing contour orientations. One need not look hard to find prized exemplars in the built environment that feature colinear, curvilinear, parallel and radial patterns: Fay Jones's Thorncrown Chapel in Fayetteville, Arkansas, the colonnades in Romanesque churches and monasteries such as the abbey at Assisi, or the rose window in the cathedral of Notre Dame. The cable-stayed bridge, which is commonly constructed using radial fans of cables to cantilever the road bed, is a particularly notable example. This is the most commonly built highway bridge today. There are many reasons for this that stem from advances in materials science and engineering, as well as economy of construction. But I speculate that the popularity of the cable-stayed bridge is also due, in part, to the fact that the gradually changing contours tap into something fundamental in the native organization of our visual system. There is, I will argue, an attractiveness to

10.7 Cloisters, Monreale, Sicily.

these designs that originates from the ease with which they are processed and perceived by our visual systems.

THE SENSE OF ORDER

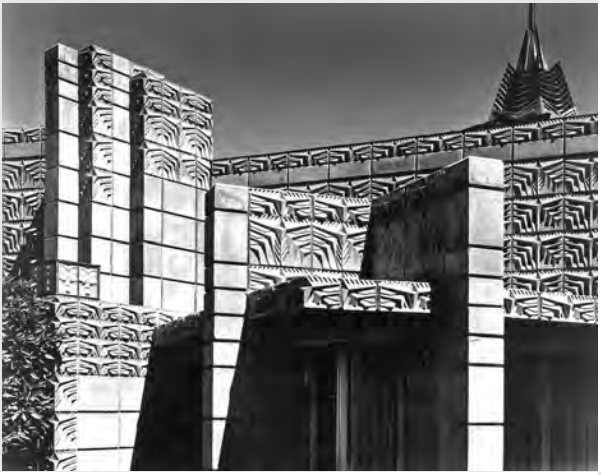
Neuroscientists were not the first to make this connection. Ernst Gombrich, one of the great geniuses of twentieth-century arts and humanities, wrote and reflected deeply on the relationship between art and visual perception.[30] His text *The Sense of Order: A Study in the Psychology of Decorative Art* addresses the use of certain timeless design features in art and architecture. Summarizing his thesis elsewhere, Gombrich wrote: “I claim that the formal characteristics of most human products, from tools to buildings and from clothing to ornament, can be seen as manifestations of that sense of order which is deeply rooted in man's biological heritage. These ordered events in our environment which exhibit rhythmical or other regular features (the waves of the sea or the uniform texture of a cornfield) easily 'lock in' with our tentative projections of order and thereby sink below the threshold of our attention while any change in these regularities leads to an arousal of attention. Hence the artificial environment man has created for himself satisfies the dual demand for easy adjustment and easy arousal."[31]

Gombrich was not a neuroscientist, of course, but his concept of "manifestations of that sense of order which is deeply rooted in man's biological heritage" and his suggestion that "these ordered events in our environment … easily 'lock in' with our tentative projections of order" resonate deeply with the view that our perception of the world depends heavily upon highly ordered neurobiological characteristics of the human visual system. Again without knowledge of the neuroscience of vision, Gombrich expanded along similar lines: "There is an observable bias in our perception for simple configurations, straight lines, circles and other simple orders and we will tend to see such regularities rather than random shapes and our encounter with the chaotic world outside. Just as scattered iron filings in a magnetic field order themselves into a pattern, so the nervous impulses reaching the visual cortex are subject to the forces of attraction and repulsion."[32] Gombrich's iron filings metaphor is striking in the present context, as it poetically captures the notion that the organizational properties of the visual system serve to efficiently encode statistical regularities in the visual world.

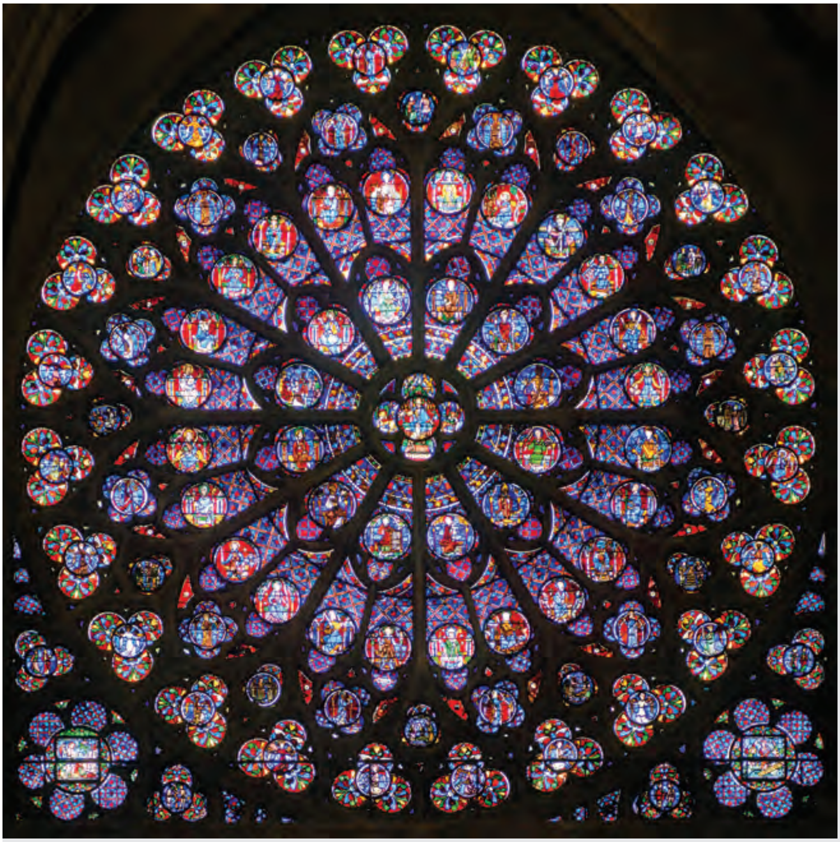
Gombrich spoke at length about designs that impart this sense of order. Some examples include the mosaics at the Alhambra, and the paper and textile patterns of William Morris. To these I would add the decorative designs of Frank Lloyd Wright from a similar period to those of Morris. For each of these examples, it is not necessary to sit and examine how it is put together; you see one part and a perceptual understanding of the whole follows without visual scrutiny—they are repetitive designs that capitalize on the ordered nature of the visual cortex.

Similar arguments apply to mandalas, which have been used as meditation aids for centuries in the spiritual practices of Hinduism and Tibetan Buddhism. As for the decorative patterns cited above, mandalas have image statistics that are complementary to the organization of the visual cortex. Our conjecture is that they have an ordering effect owing to the ease of visual processing—they are calming, regular structures.

10.8 Frank Lloyd Wright, textile block pattern.



10.9 Frank Lloyd Wright, textile block house, Los Angeles.



10.10 Rose window at Notre Dame, Paris.

By the same logic, of course, we should expect that images possessing irregular statistics, or properties that do not tap into to the organizational features of the visual cortex, should require greater effort to process and may lead to confusion, disturbance, and distraction.

FAMILIARITY VERSUS NOVELTY

I interpret Gombrich's statement that the built environment "satisfies the dual demand for easy adjustment and easy arousal" to mean that the optimal environment has varying degrees of familiarity and novelty. That is, we create features in our environment with a sense of order; of things that are familiar. Without visual scrutiny, such features are

10.11 Tibetan sand mandala. Minneapolis Institute of Arts.

easily processed because they tap into the inherent organization of our brain systems for visual perception. This order provides a suitable background—and liberates neuronal resources—for detection of novelty (a predator or an intruder, perhaps, or a new piece of furniture), which is nearly always of behavioral significance and demanding of attention. To put it simply, the built environment tends to reflect the way visual perception works.

Gombrich was not the only person who noticed this phenomenon. Oscar Wilde also observed: “The art that is frankly decorative is the art to live with. The harmony that resides in the delicate proportions of lines and masses becomes mirrored in the mind. The repetitions of pattern give us rest. Decorative art prepares the soul for the reception of imaginative work.”[33] Again, Wilde is using literary language to describe how the visual system functions between the poles of familiarity and novelty. Repetition gives us rest, because we are not required to scrutinize every part of it. Comfort derives from ease of visual processing. Wilde suggests that the regularity of background sets the stage for truly imaginative work, for something new to emerge.

BRAIN AND BEAUTY

It should not go unnoticed that these ideas have implications for the neurobiology and evolution of aesthetics. There are surely many different reasons for the aesthetic judgments that we make about features of the natural and built environment, many reasons why we find beauty in one form and ugliness in another. Much of this is cultural and learned. Doubtless many people will tell you that Leonardo's *Mona Lisa* is beautiful, simply because that is what we have taught them. Oftentimes judgments of beauty will reflect frequent exposure to certain stimuli in the presence of reward (money, information, social power, or sex), or a cultural "consensus" defined by commercial interests and displayed through magazines, billboards, and television. But the foregoing discussion suggests a definition of beauty based on ease of visual processing—beauty defined by the extent to which features of the visual environment engage organized processing structures in the visual brain, and are thus readily acquired, organized, and "understood." Evolution is invoked in this definition of beauty, since we hypothesize that the relevant brain structures exist because they conferred a selective advantage for survival and reproduction in an environment replete with the image statistics described herein.

GENERALITY OF PRINCIPLES

The latter part of this chapter has focused on a specific set of organizational features in the visual cortex—those involved in the detection and representation of oriented contours—primarily because this is the visual submodality that we know the most about. The principles exemplified by this submodality are likely to be very general, however. Indeed, there are good reasons to believe that a detailed understanding of the architecture and function of brain systems for other visual submodalities (e.g., color or visual motion processing), or for other sensory modalities (e.g., audition and touch), will have similar implications for understanding the built environment.

PLASTICITY AND VISUAL ATTUNEMENT

Finally, it is important to note that the information-processing features of our brains are not rigid over time. On the contrary, they are plastic and tunable by experience. Recent evidence indicates that the sensitivities of our sensory systems are adapted to the statistics of our environment, but those sensitivities may change—they may be recalibrated—when the properties of the world change.[34] This adaptability has profound implications for design. Suppose, for example, that I adapt you to the baroque opulence of Marie Antoinette's bedroom in Versailles, and then move you to a minimalist home designed by Mies van der Rohe. The transition will elicit recalibration and will, we hypothesize, necessarily involve windows of time in which sensitivity is nonoptimal for the new environment. These considerations have particularly important implications for the design of spaces for work and learning, as frequent changes of environmental statistics may interfere with the ability of observers to acquire, organize, and use information from the environment.

CONCLUSIONS: TOWARD A NEUROSCIENCE FOR ARCHITECTURE

Neuroscience is a new research discipline in the armament of longstanding efforts to understand the influence of built environments over human mental function and behavior. Using a variety of powerful experimental approaches, and focusing efforts on the information-processing capacities of the brain, we have begun to develop an empirical understanding of how design features influence the acquisition, organization, and use of information present in the built environment. On the basis of this understanding, we argue that selective pressures over the course of human evolution have yielded a visual brain that has highly specific and tunable organizational properties for representing key statistics of the environment, such as commonly occurring features and conjunctions of features. Simple visual pattern types, which are commonly used in architectural and decorative design, mirror these environmental statistics. These patterns are readily "seen" without scrutiny, yielding a "sense of order" because they tap into existing neuronal substrates. A fuller understanding of these relationships between organizational properties of the brain and visual environmental statistics may lead to novel design principles.

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14. Mind, Mood and Architectural Meaning

Alberto Pérez-Gómez

Mind: From Romanticism to Neurophenomenology

In my book *Architecture and the Crisis of Modern Science* (MIT Press, 1984), I described how Western architecture was profoundly affected by the Scientific Revolution of the seventeenth century, revealing a set of intentions that are wholly modern long before the material changes brought about by Industrial Revolution.[1] In relation to perception and cognition, an initial consequence of that momentous transformation in European thinking was the incorporation of René Descartes' dualistic epistemology/psychology into the dominant conception of how architecture communicates. This assumption had far-reaching consequences, opening the door for a subsequent understanding of architecture as a "sign"-- whose meaning was articulated as the intellectual "judgment" of exclusively visual qualities. This became the primary assumption of many twentieth century poststructuralist and deconstructive philosophers and architects, and one still present, often tacitly, among contemporary theoreticians.

The Cartesian understanding of cognition first appeared in architectural theory toward the end of the seventeenth century in the writings of Claude Perrault, the famous architect, medical doctor, biologist and theoretician.[2] He believed that architecture communicates its meanings to a disembodied soul (today often still identified with a brain, understood as the exclusive seat of consciousness), thoroughly bypassing the body with its complex feelings and emotions.[3] Perrault assumed perception to be passive and cognition to be merely the result of the association of concepts and images in the brain. Like Descartes, Perrault believed that human consciousness (enabled by the pineal gland at the back of the head, conceived as a geometric and monocular point of contact between the measurable, intelligible world -- *res extensa* -- and the disembodied, rational soul -- *res cogitans* -- was capable of perspectival visual perception, and that this assured the human capacity to grasp the immutable geometric and mathematical truth of the external world.[4] He could question, for the first time ever in the history of architectural theory, the bodily experience of "harmony" as synesthetic, applicable to both hearing and sight embedded in kinesthesia: a phenomenon that had always been taken for granted since Classical antiquity and that constituted the primary quality of architectural design. For Perrault, sight and hearing were autonomous and segregated receptors, and therefore the inveterate experience of harmony in architecture was a fallacy -- or at best the result of misguided associations between self-evident visual qualities and cultural assumptions.

While mainstream, technologically-driven planning and architectural practice has remained caught in this framework of understanding until our very own times, around 150 years after Descartes' influential writings another, often unacknowledged revolution in the human sciences took place. Even though it was originally qualified as a mere reaction to positive reason, associated with the arts as they lost their claim to truth, and sometimes taken as a plea for "irrationality," over the last two centuries this transformation has proven to be as important for Western thought as the Galilean revolution.[5] This momentous shift happened at the end of the eighteenth century with the rise of Romantic philosophy. Writers associated with this position questioned the dualism of Cartesian philosophy and argued for the reciprocity and co-emergence of inner and outer realms of human experience.[6] This initial insight allowed thinkers to establish a distance from materialism, establishing a critical position with regards to the technological dogma of their own times, while affirming the importance of imagination and the truth-value of fiction. In his *Essais* (1795) Friedrich Schelling declares that it is our prerogative to question the times we live in and to contemplate within ourselves eternity with its immutable form. This is the only way to access our most precious certainties, to know “that anything is in the true sense of being, while the rest is only appearance.” This intuition appears to us whenever we stop being an object for ourselves… we are not “in” linear time. Rather “time, or pure eternity, is in us.” This insight anticipates Maurice Merleau-Ponty's phenomenological understanding of time as thick present,[7] an experience which I will argue below, is now corroborated by recent neurobiology. It is important to emphasize that Schelling added an important observation that qualifies his introspective critical understanding: “Even the most abstract notions retrieve an experience of life and existence… *all our knowledge has as a point of departure direct experiences*” (my emphasis).

Recovering an insight that had been put forward initially by Aristotle in *De Anima*, these Romantic philosophers posited a concept of self which first feels and then thinks; the *I* who wakes up every morning is not equivalent to the Cartesian ego (an *I* that can only believe itself existing because he/she thinks).[8] The first person in Romantic philosophy is always the same throughout her life, yet never fully "coincidental" with her thoughts. Her words point towards meanings but never exhaust them. This embodied, non-dualistic understanding of reality includes our emotions and feelings; its primary seat of awareness is *Gemüt*, and its most significant experience is *Stimmung*: attunement, understood as a search for lost integrity, health, wholeness and holiness. This concept has been shown to have its roots in traditional ideas about harmony (proportion), concert and temperance in the context of Ancient Classical and Renaissance cosmology, philosophy, music and architectural theories,[9] eventually becoming cast as "atmosphere" or "mood;" a concept that is now understood as of great consequence for art and architecture. The self is endowed with a consciousness that cannot be reduced to transparent reason, and since the elements of consciousness (subject, object and action) are inevitably codependent, it starts to appear "ungrounded." Not surprisingly, Romantic thinkers were fascinated by Eastern philosophy and started to incorporate some insights of Buddhism into their own positions, an approach welcomed eventually by Heidegger and more recently by enactive cognitive science.[10] They also could imagine a holistic biology that included the mind in the living body as opposed to the mechanistic medicine at the origins of contemporary physiology.

Romantic philosophy questioned positivistic thinking through narrative, giving rise to the modern novel as the privileged "place" for both the expression of *Stimmung* and meditation on philosophical and ethical topics.[11] It also gave rise to the new discipline of history as interpretation (hermeneutics), distinct from the models and methodologies of the hard sciences, postulating this discipline as the proper mode of discourse to understand human problems. This argument was expressed with clarity by Friedrich Nietzsche in his crucial essay on "The Advantages and Disadvantages of History for Life," a text which is as relevant today as when it was first published.[12] I would argue that these positions were the precursors of late-nineteenth century American pragmatism (William James and John Dewey) and of the early and mid-twentieth century phenomenology of Edmund Husserl and Maurice Merleau-Ponty; they thus lay at the root of later developments in American philosophy, like the contemporary work of Mark Johnson, of contemporary existential phenomenology, and also of the recent revolution in the cognitive sciences that has approximated this discipline with the previously mentioned philosophical positions, notably in the works of Evan Thompson and Alva Noë.

Given this lineage, I would like to suggest that from the point of view of Western architecture (whose assumptions, both instrumental and critical, are often universalized in our global village), the crucial moment when neuroscience starts to become useful for architects is after the now-famous "invention" of neurophenomenology in *The Embodied Mind* (1991), by Francisco Varela, Evan Thompson and Eleanor Rauch. In a later work, Evan Thompson explains how cognitive science came into being in the 1950's as a revolution against behaviorist psychology:[13] the same concern that motivated Maurice Merleau-Ponty to continue the work of his teacher Edmund Husserl in *The Phenomenology of Perception* (first published in 1945). Early cognitivism, however, had as its central hypothesis the computer model of the mind. While cognitivism made meaning -- in the sense of representational semantics -- scientifically acceptable, it fundamentally banished consciousness from the science of the mind.[14] It soon became evident that abstract computation was not well suited to model the thought processes within the individual, leading in the 1980's to what has been labeled as the "connectionist criticism," which focused on the neurological implausibility of the previous model.[15] While cognitivism still presumed the mind to be firmly bounded by the skull (cf. Descartes' psychology), connectionism started to offer a more dynamic understanding of the relationships between cognitive processes and the environment, creating models of such processes that took the form of artificial neural networks run as virtual systems on a digital computer.[16] These systems, however, did not involve any sensory and motor coupling with the environment; their inputs and outputs were artificial. Only "embodied dynamicism," the most recent approach of cognitive science that arose only in the 1990's, involved a truly critical stance towards computationalism of any form.

Indeed, this latest approach in cognitive science stopped depending on analytic philosophy and computer brain models and started acknowledging the relations between cognitive processes and the real world. Embodied dynamicism called into question the conception of cognition as disembodied and abstract mental representation.[17] The mind and the world are simply *not* separate and independent of each other; the mind is an embodied dynamic system *in* the world, rather than merely a neural network in the head. For Varela, Thompson and Rauch (1991) cognition is the exercise of skillful know-how in embodied and situated action, and cannot be reduced to pre-specified problem solving. In other words, the perceiver (subject), the perception, and the thing perceived (object) could never be said to exist independently, they are always codependent and co-emergent, and therefore *ultimately* groundless or "empty" (a term taken by the authors from Mahayana Buddhism, to emphasize that this awareness is as opposed to absolutism as it is to a despairing nihilism, for out of the experience of emptiness in Buddhist meditation -- letting go of grasping and anxiety -- arises "sense" and mindful compassion). In that same seminal book they introduced the concept of cognition as "enaction," linking biological autopoiesis (living beings are autonomous agents that actively generate and maintain themselves) with the emergence of cognitive domains. The nervous system of all living beings in this view does not process information like a computer but rather creates meaning, *i.e., the perception of purpose in life,* whose articulation becomes more sophisticated with the acquisition of language in higher animals.

The world in this model is not a pre-specified external realm represented externally by the brain, but a relational domain enacted by a being's particular mode of coupling with the environment. Experience in this approach is not a secondary issue (as it was since Descartes), but becomes central to the understanding of the mind, and requires careful examination in the manner of phenomenology. In this connection, I would like to cite as well the work of distinguished neuroscientist Antonio Damasio, who has argued for the importance of emotions and feelings as essential building blocks of cognition, supporting human survival and enabling the spirit's greatest creations.[18] Recovering Baruch Spinoza's (and later phenomenology's) refusal to separate the mind and body, Damasio has shown the continuity between emotions and appetites, feelings and concepts. He points out that every emotion is a variation of pleasure and pain, a condition of consciousness at the cellular level, always seeking for homeostatic equilibrium.

In a later work, Thompson (2007) relies upon the findings of Husserl and Merleau-Ponty to explicate selfhood and subjectivity from the ground up, accounting for the autonomy proper to living and cognitive beings. There is a deep convergence between phenomenology and the enactive approach that concerns the actual experience of time prefigured by Romantic philosophy and discussed by Merleau-Ponty in relation to his concept of *écart* as a "thick present." Thompson summarizes (my emphasis): *"The present moment manifests as a zone or span of actuality, instead of as an instantaneous flash*, thanks to the way our consciousness is structured. [It] manifests this way because of the nonlinear dynamics of brain activity. Weaving together these two types of analysis, the phenomenological and the neurobiological, in order to bridge the gap between subjective experience and biology, defines the aim of neurophenomenology..."[19]

The consequences of this revolution in cognitive science are far-reaching, and the first two decades of the twenty-first century have witnessed the publication of important works exploring different aspects of them.[20] Alva Noë popularized the enactive understanding of perception and cognition in *Out of our Heads: Why you are not your Brain and other Lessons from the biology of consciousness* (2010), emphasizing particularly that in order to understand consciousness in humans and animals we must look not inward, but rather to the ways in which a whole animal goes on living in and responds to their world. Noë's work allows us to understand how the traditional view of perception (recovered in phenomenology and present in pre-modern psychology) as primarily synesthetic, is vindicated by the recent understanding of the senses as "modalities" that cross-over their functional (*partes-extra-partes*) determinations: for example, the now well-demonstrated capacity of human consciousness to have "visual perceptions" through touch, as is possible for blind individuals with the aid of a device that transforms a digital image into electrical impulses on the skin. If perception is something we do, not something that happens to us (like other autonomous internal physiological processes), it is obvious that our intellectual and motor skills are fundamental to cognition.[21] By the same token, the external world *truly matters*, i.e., the city and architecture, and we don't relate to it as if it were a text in need of interpretation or "information" conveyed to a brain: interpretation comes after we have the world in hand, and in this way architecture affects us, along the full range of awareness, from pre-reflective to reflective. We are "already" in a shared social context and in the "game," as we might participate in a sports match, depending on motor intentionality and skills for our perceptions. As Merleau-Ponty points out, the consciousness of the player "is nothing other than the dialectic of milieu and action. Each maneuver undertaken by the player modifies the character of the field and establishes in it new lines of force in which the action in turn unfolds and is accomplished, again altering the phenomenal field." Thompson emphasizes a crucial point for architecture that has escaped Heideggerian philosophers like Hubert Dreyfus, and was always a difficult question for Merleau-Ponty as well as a hotly-debated issue for poststructuralists that denied art its capacity for "meaning as presence": Reflective self-awareness is not the only kind of self-awareness. Experience also comprises a pre-reflective self-awareness *that is not unconscious* but is not representational. This includes particularly the pre-reflective bodily self-consciousness profoundly affected by the environment (architecture) that may be passive (involuntary) and intransitive (not object-directed). Thompson adds that there is every reason to think that this sort of pre-reflective self-awareness animates skillful coping.[22]

Thus contrary to some fashionable misapplications of the term *autopoiesis* (a term reserved by Varela and Maturana for metabolic, autonomous life) to parametric architecture and the desire to create "intelligent" buildings that cater to our comfort by emulating the systems of a "computerized mind," neurophenomenology's understanding of architecture would be as a *heteropoietic* system, capable of harmoniously complementing the metabolic processes of human consciousness, seeking a balance between the need to provide for a sense of prereflective purposeful action and a reflective understanding of our place in the natural and cultural world. Limits, here, would be articulated not as part of a system (as in a cell) but through language, in view of intersubjective expression. It bears recalling, though this complex issue cannot be developed in a short essay, that language also has its roots in the prereflective realm of gesture and the body as a primary expressive system. It is not a more or less arbitrary, constructed code. Merleau-Ponty's work is crucial for this issue (as are Heidegger's intuitions): language is "emergent," it "speaks through us" and captures meaning in its mesh; words point towards meanings but never fully coincide with them.[23]

I would argue that the unique gift of architecture is to offer experiences of sense and purpose not in the mere fulfillment of pleasure, but in the *delay* (Duchamp's famous word) that reveals the space of human existence as a space of desire, actually bitter-sweet, never ending with a punctual homeostasis (i.e., never reduced to the search of ever-increasing comfort or fulfillment). The so-called meaning of existence then appears profoundly grounded in our biology, yet as a true human alternative where desire is never-ending -- and yet may be always sensed as purposeful in our actions amidst appropriate environments, particularly when framed by attuned works of architecture. In other words, architecture's gift is to reveal *the true temporality* of the space of human experience, one indeed open to spirituality: the experience of a present moment that while it can be conceptualized by science (and our clocks) as a quasi-inexistent point between past and future, is experienced by us as thick and endowed with dimensions and -- in a sense -- eternal. This has always been the time "out of time" which is the gift of ritual, festival and art, or the time of "silence," evoked by Louis Kahn and Juhani Pallasmaa for architecture. This present "with dimensions" corresponds to Merleau-Ponty's *écart*, the delay between prereflective experience and reflective thought in all its modalities that is paradoxically present in experience and that neuroscience has substantiated.

Indeed, as I have suggested, according to neurophenomenology the formal structure of time-consciousness or phenomenal temporality has an analogue in the dynamic structure of neural processes.[24] This uniquely human temporality is generally hidden under scientific and hedonistic interpretations of meaning. Architecture's well-documented gift throughout history, like poetry's, is indeed to allow humans to perceive their sense in the experience of a coincidence of opposites: Being and non-being beyond theological dogma.[25]

Mood and Meaning

Once we start to understand through recent cognitive science that our consciousness doesn't end with our skulls, it becomes easy to grasp that the emotive character of the built environment matters immensely: what matters, in other words, is its material beauty; its power to seduce us on the one hand, and its capacity to open up a space of communication for inter-subjective encounters on the other. The cognitive sciences' engagement of phenomenology has been productive, and we must expect that in the future this cross-disciplinary pollination will yield important insights for architecture.

Indeed, if the quality of the lived environment is lacking, if we don't even look out to our surroundings for orientation and instead employ technological devices like GPS to find our locations in the world, for instance, our skills are continually jeopardized and our actions actually reinforce our pathological (and ultimately nihilistic) assumptions that “life is without orientation,” indeed, meaningless. Rather than accepting that the built environment is merely a shelter and all that matters is our possession of a sophisticated computer or intelligent phone, these insights from neurophenomenology point to the crucial importance of our habitat, one that for humans includes the complexities of material cultures and spoken language. The place of embodied appearance, where we find ourselves through the presence of others, is indeed nothing like the computer screen. Such spaces need to embody appropriate moods or atmospheres to further our spiritual well being. Architecture has to speak *back* to us without becoming merely invisible, acting like a numbing drug or the perfect fit dreamt of by functionalists and today by the architects of ever more "intelligent," i.e., comfortable, efficient buildings.

In fact, already fed up with functionalism in the mid-twentieth century, Frederick Kiesler imagined in his *Endless House* project an environment that would respond to our moods not by pleasing us (or perhaps simply hiding our mortality) but by challenging us, promoting the use of our imagination, so that every time we open the tap, for example, we would no longer perceive a liquid that circulates composed of hydrogen and oxygen, but experience instead the real (poetic) nature of water: its qualities as life-giving and primordial liquid, vehicle of purification and remembrance. Such intention offers difficult challenges to a contemporary practice driven by pragmatic and economic imperatives, and yet it is a challenge we must take seriously. In other words, sustainability, ecological responsibility, and efficient construction -- important as they are -- are not enough to fashion a human environment.

Hubert Dreyfus has speculated on the importance of understanding moods for architectural design.[26] It is easy to observe that human actions can change the mood in a room: a charismatic speaker, lighting effects, artificial acoustics, etc., can all transform a place substantially. On the other hand, architects are capable of incorporating in their designed spaces a more lasting mood, one that we may associate with the room itself: solemn, strange, quiet, cheerful, reverential, oppressive, etc. It is important to point out that regardless of these precisions, our architectural experience is always ultimately dependent upon our participation in an event housed in the space; it is in such circumstances that architecture "means."

This contemporary concern is rooted in the Romantic concept of *Stimmung,* mentioned earlier; an attunement that evokes interiority. *Stimmung* is related etymologically to the central questions of harmony and temperance in music, philosophy and architecture, going back to the origins of European thought in Ancient Greece.[27] Significantly, traditional treatises on architectural theory always characterized this concern through the objectivity of mathematics (proportions, geometry), encompassing both form and space. This understanding became problematized by the end of the European eighteenth century. In his treatise, *Le Génie de l'architecture* (Paris, 1780), Nicolas Le Camus de Mezières addressed the "same" traditional issue but thought that the only way to incorporate the need for harmony in design (an “analogy with our sensations” as he put it), was to characterize the moods or atmospheres of rooms through *words*. He describes a sequence of spaces in a house, rooms with different attributes (light, color, textures, decoration, etc.) related appropriately to the focal actions to which they gave place. It was in this manner that the harmonic potential of architecture, i.e., its meaning, could be sought.[28] Let me emphasize: this expressive and musical potential was set out *in words*, as descriptive narratives -- and no longer in numbers referring to proportions, as had been traditionally done when referring to architectural beauty and convenience in most previous treatises on architecture in the Western corpus.

Indeed, the Cartesian model of reality fails to explain the way moods are normally shared in the everyday world, and the fact that though they appear to be eminently internal they are actually “out there;” so at the time when Descartes' dualistic concept was becoming accepted as a fact by the culture at large, architects like Le Camus felt moods had to be made explicit in language, a vehicle of our primary intersubjectivity -- bringing forward what remains a central issue for architectural meaning today. In the everyday world our bodies spontaneously express our moods and others directly pick them up and respond to them. Merleau-Ponty calls this phenomenon intercorporeality: "It is as if the other person's intention inhabited my body and mine his."[29] According to Gaston Bachelard, we literally resonate with another's experience. First there is reverberation, followed by the experience of resonances in oneself, and these eventually have repercussions in the way we perceive the world. This is how the poetic image is communicated, and how we can all have the experience of being co-creators.[30]

Now neuroscientists have found an explanation for this important phenomenon in mirror-neurons, that fire both when one makes a movement and when one sees another person make that sort of movement: when we observe the actions of others, our nervous system literally "resonates" along with the Other.[31] Heidegger had already observed this: "Attunements.... in advance determine our being with one another. It seems as though an attunement is in each case already there, so to speak, like an atmosphere in which we first immerse ourselves... and which then attunes us through and through."[32] Like an atmosphere, a mood is shared, and is contagious, just like laughter or yawning. This contribution of neuroscience to the understanding of our "virtual" body through mirror neurons has enormous potential to grasp the possibilities of "telepresencing" in multi-media spatial installations, for example,[33] and in the consideration of digital media in design. In all these considerations, however, we must not forget that even more fundamental than neural effects is our embodied consciousness, our intercorporeality. Gestures and actions generate habits that are at the root of understanding; we are *primarily* social beings and thus any concern for architectural meaning must build its formal and spatial decisions upon this foundation.[34]

Heidegger specifies further: "Moods are precisely a fundamental manner of being with one another... and precisely *those* attunements to which we pay no heed at all... are the most powerful." In a sense, conscious existence, "*Dasein*, is always already attuned... There is only ever a change of attunement."[35] Being attuned to a situation makes things matter to us: we feel more complete and become participants; our lives matter. This could be the humble yet crucial contribution of architecture in a secular age. But to get there, we must engage language in design practice to articulate human action, avoiding the merely pictorial. Indeed language, particularly in literature, has a greater potential for creating vivid images than "pictures in the mind."[36]

Heidegger recommends spaces that gather self-contained local worlds, gathered around "things thinging." For example, the family meal: a "focal practice" that draws everyone together into a shared mood, so that the action "matters."[37] Such moods "can bring us in touch with a power that we cannot control and that calls forth and rewards our efforts," a power that could be recognized as sacred. The sense that the mood is shared is constitutive of the excitement, as used to happen in traditional rituals and in some contemporary performances, or in our experience of art. The architect can therefore try to bring about the appropriate moods for human actions that reveal life as purposeful by designing spaces that are attuned to an appropriate range. I would argue that literary language can describe these possibilities as one imagines a proposed space being used, in manifold contexts, to invite in the unexpected: thus architecture is never static, neutral or merely devoted to one use.

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[1] See Alberto Pérez-Gómez, *Architecture and the Crisis of Modern Science* (Cambridge MA: MIT Press, 1983).

[2] See ch. 8 in volume 1 of this collection.

[3] See Claude Perrault, *Ordonnance for the Five Kinds of Columns after the Method of the Ancients* and my own introductory study, trans. by I.K. McEwen of the 1683 first edition (Santa Monica, CA: The Getty Center, 1993), and C. Perrault, *Les dix livres d'architecture de Vitruve* (Paris, 1684).

[4] Human visual perception includes peripheral vision and haptic qualities; it is not passive; our understanding of depth is the result of our motor bodily engagement with the world. Visual perception is therefore not analogous to a constructed perspective. This problem been discussed exhaustively by Maurice Merleau-Ponty, *Phenomenology of Perception*, new translation by D. Landes (New York: Rutledge, 2012), and in his essays on art, particularly "Eye and Mind," and "Cezanne's Doubt," collected in Johnson G., ed. *The Merleau-Ponty Aesthetics Reader* (Evanston IL: Northwestern University Press, 1993). See also, Alva Noë, *Action in Perception* (Cambridge MA: MIT Press, 2004). The far-reaching implications of this issue for architectural representation have been discussed in Alberto Pérez-Gómez and Louise Pelletier, *Architectural Representation and the Perspective Hinge* (Cambridge MA: MIT Press, 1997).

[5] See George Gusdorf, *Fondements du savoir romantique* (Paris: Payot, 1982). Gusdorf has been instrumental in describing the importance of this revolution and its connections to later Continental philosophy and phenomenology.

[6] The main figures are Friedrich Schelling, Friedrich Schlegel, Novalis (Georg Friedrich Freiherr von Hardenberg) and Carl Jacobi.

[7] See Maurice Merleau-Ponty, *Phenomenology of Perception*, and especially M.C. Dillon, ed., *Écart et Différence; Merleau-Ponty and Derrida on Seeing and Writing*, (New Jersey: Humanities Press, 1997), chs. 1, 6 and 11.

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[8] See Daniel Heller-Roazen, *The Inner Touch, Archaeology of a Sensation* (New York: Zone Books, 2007).

[9] For the linguistic roots of *Stimmung*, see Leo Spitzer, *Classical and Christian Ideas of World Harmony: Prolegomena to the Interpretation of the Word 'Stimmung'* (Baltimore MA: The John Hopkins Press,1963). For an elaboration of the consequences of this analysis in architecture see A. Pérez-Gómez, *Attunement, architectural meaning after the crisis of modern science* (Cambridge MA: MIT Press, 2016).

[10] See Francisco Varela, Evan Thompson and Eleanor Rosch, *The Embodied Mind* (Cambridge MA: MIT Press, 1991), especially chs. 10 and 11.

[11] This argument has been brilliantly put forward by Hans-Georg Gadamer, *Reason in the Age of Science* (Cambridge MA: MIT Press, 1981), ch. 8.

[12] Friedrich Nietzsche, "On the Advantages and Disadvantages of History for Man," in *Untimely Meditations* (Cambridge UK: Cambridge University Press, 1983).

[13] Evan Thompson, *Mind in Life, Biology, Phenomenology and the Sciences of the Mind* (Cambridge MA: Harvard University Press, 2007), 4.

[14] Ibid., 5.

[15] Ibid., 8.

[16] Ibid., 9.

[17] Ibid., 10.

[18] See Antonio Damasio, *Descartes' Error* (Toronto ON: Penguin Books, 2005); and *Looking for Spinoza; Joy, Sorrow, and the Feeling Brain* (Toronto ON: Harcourt, 2003.

[19] Thompson (2007), 15

[20] See, for example, Shaun Gallagher, *How the Body Shapes the Mind* (Oxford UK: Clarendon Press, 2006) and Louise Barret, *Beyond the Brain, How Body and Environment Shape Animal and Human Minds* (Princeton NJ: Princeton University Press,

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2011). While not all on exactly the same footing, these books contribute enormously to our understanding of the issues raised by enactive cognition and neurophenomenology.

[21] Alva Noë, *Out of our Heads: Why you are not your Brain and other Lessons from the biology of consciousness* (New York: Hill and Wang, 2009), 7. See also his more technical *Action in Perception* (Cambridge MA: MIT Press, 2004).

[22] Thompson (2007), 315-6.

[23] See Maurice Merleau-Ponty, "The Phenomenology of Language," in *Signs* (Evanston, IL: Nothwestern University Press, 1964), 84-97.

[24] Thompson (2007), 356-7.

[25] This is also Octavio Paz's universal definition for a "poetic image." Octavio Paz, *The Bow and the Lyre* (Austin TX: University of Texas Press, 1991).

[26] Hubert Dreyfus, "Why the Mood *in* a Room and the Mood *of* a Room Should be Important to Architects," in *From the Things Themselves, Architecture and Phenomenology,* Kyoto University Press, Kyoto, 2012, pp. 23-39.

[27] I examine this problem extensively in *Attunement,* op.cit.

[28] Nicolas Le Camus de Mézières, *The Genius of Architecture; or the analogy of that art with our sensations,* trans. D. Britt (Santa Monica CA: The Getty Center, 1992).

[29] Dreyfus, op .cit., 26.

[30] Cited by Susan Kozel, *Closer, Performance, Technologies, Phenomenology* (Cambridge MA: MIT Press, 2007), 25.

[31] This is the neurological phenomenon that now explains the "phantom limb" syndrome of amputees. See V.S. Ramachandran and Sandra Blakeslee, *Phantoms in the Brain: Probing the Mysteries of the Human Mind* (New York: William Morrow and Co., 1998).

[32] Cited by Dreyfus, op.cit., 27.

[33] See Kozel, op.cit.

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[34] See Nick Crossley, *The Social Body Habit, identity, desire* (London: Sage, 2001).

[35] Martin Heidegger, *Fundamental Concepts of Metaphysics* (Bloomington IN: Indiana University Press,1995), 67-8.

[36] This is the main argument developed by Elaine Scarry, *Dreaming by the Book*, (Princeton NJ: Princeton University Press, 2001), 3-9.

[37] Dreyfus, op.cit., 35.

Neuroscience and Architecture Books

The Richard P. Welsh Library at NewSchool features a special collection for neuroscience and architecture. All titles are listed here and shelved under call number 720.4356.

A natural history of the senses. Author: Ackerman, Diane. Call Number: 720.4356 ACK

Action in perception. Author: Noë, Alva. Call Number: 720.4356 NOE

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