NeuroDesign: Greater than the sum of its parts

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Abstract

This chapter outlines the recent developments, such as Neuroscience on Design, Design Neurocognition, and NeuroDesign, in the intersection of neuroscience and design. This intersection of diverse disciplines, including psychology, neurophysiology, engineering, interaction design, and architecture, provides various opportunities and challenges to advance areas, such as design thinking, neuro-technology, embodied artificial intelligence (AI), and human-centered AI. We outline some of the opportunities and challenges with several examples, such as methodological and technological developments, necessary to develop this promising pan-disciplinary field. We emphasize the importance of educating researchers (i.e., NeuroDesign Researchers) and practitioners (Neuro-Designer/Engineers) to advance this intersection toward a new area that could be greater than the sum of its parts.

Keywords: NeuroDesign, Neuroscience on Design, Design Neurocognition, Design Thinking

1 Introduction

In recent years, neuroscientists examined brain activity in the context of design, and at the same time, design researchers employed neuroscience instruments to examine the thinking of designers (Balters et al., 2023; Ohashi et al., 2022; Pidgeon et al., 2016). For neuroscientists, design provides an exciting context to examine various psychological and cognitive phenomena, such as figural or visual creativity. From a design perspective, neuroscience instruments and methodologies provide new opportunities to investigate design thinking/cognition. Adapting research methodology from psychology, such as the think-aloud protocol and protocol analysis, allowed advancing the research on design thinking over the last half-century (Duncker, 1945; Eastman, 1970; Ericsson & Simon, 1998; Lawson, 1972). Neuroscientific approaches and instruments provide a similar opportunity to further advance research and an understanding of design thinking.

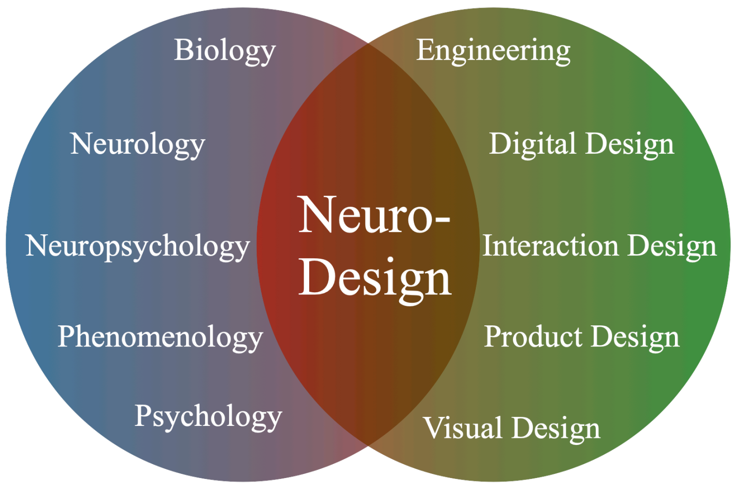
However, there are several challenges to bringing these two cultures to meet productively (Auernhammer et al., 2021). The highly reductionist approach in neuroscience contrasts with the holistic or situational approach in design. Researchers need to make tradeoffs in their designs to either increase the spatial resolution of brain scans or to increase ecological validity, i.e., the natural environment in which designers design. However, a pan-disciplinary intersection of NeuroDesign provides the opportunity to go beyond current tradeoffs and approaches. Designing new technologies, such as nonintrusive near-infrared optical technology, and developing new analysis techniques provides opportunities to investigate design thinking and advance neuroscience approaches (Jöbsis, 1977; Maki et al., 1995; Saggar et al., 2018). Such technological and methodological developments need both the "Neuro" (e.g., neuroscience) and "Design" (e.g., engineering design) perspectives, creating a field that is greater than the sum of its parts.

In this chapter, we outline some developments, challenges, and opportunities at the intersection of Neuroscience and Design. We believe by fostering researchers that are at the intersection of both Neuro (e.g., psychology, cognitive science, and anthropology) and Design (e.g., engineering, product design, and computer science) disciplines, we can advance and contribute to both fields in new ways. For example, a better understanding of design thinking through Neuroscience on Design and Design Neurocognition provides the opportunity to advance design education. In this way, education advances design practices, which, in turn, results in more advanced products and services. More advanced, designed, and developed neuroscientific instruments allow new, meaningful investigations of the human brain. Therefore, this innovative advancement of NeuroDesign is autopoietic (Auernhammer, 2012; Auernhammer & Hall, 2014). A better understanding of design thinking and its practice leads to better neuro-technological and products, which in turn helps investigate design thinking.

2 What is NeuroDesign Research?

NeuroDesign Research is the unique combination of neuroscience and design research and practice. Similar to developments in NeuroEconomics (Glimcher & Rustichini, 2004), NeuroDesign bridges disciplines of "Neuro," such as biology, neurophysiology, neurology, phenomenology, and psychology, and "Design," such as engineering, computer science, interaction, product, and visual design, as illustrated in Figure 1.

Figure 1. NeuroDesign: The pan-disciplinary intersection of Neuroscience and Design.



The intersection between "Neuro" & "Design" has existed for several decades. Early research on creativity and design thinking helped translate many psychological theories and principles into design practices (Arnold, 1959; Harman et al., 1966; Lawson, 1972; McKim, 1972). Sparked by the work of John Arnold (1954, 1959, 1962a, 1962b), Stanford's Design Division (today Design Group[1]) has a long tradition of integrating psychological insights, principles, and theories into design education and practices to develop students' potential (Adams, 2019; Arnold, 1959; Auernhammer & Roth, 2021; Fadiman, 1986; McKim, 1972; Wilde, 1972). Courses such as the ME101 Visual Thinking, Peopledynamics Lab, or ME211 Psychology of Design take an experimental approach to bring neuroscience and psychological insights into design education and practices (Bulletin, 2022; McKim, 1980; Wilde, 1972).

[1] About the Design Group https://me.stanford.edu/groups/about-design-group

One of the first scholars who bridged the two disciplines through an engineering and neurological approach was Larry Leifer at Stanford University in the 1960s. In his Ph.D. research on the *Characterization of single muscle fiber discharge during voluntary isometric contraction of the biceps brachii muscle in man*, supervised by Leon Cohen (neurology), James Bliss (electrical engineering), and Donald Wilson (biological sciences), Leifer (1969) investigated neurophysiological questions in the intersection of "Neuro" and "Design." More recent developments in NeuroDesign at Stanford University have emerged in the Hasso Plattner Design Thinking Research (HPDTR) program from neuroscientific research on creative thinking in design. The collaborative efforts at Stanford between Manish Saggar and Alan Reiss from the neurosciences and Grace Hawthorne from the Hasso Plattner Institute of Design (dschool), produced work investigating figural creativity and the effects of design thinking training on creative capacity (Saggar et al., 2016; Saggar et al., 2015).

Over the last two decades, the utilization of neuroscience instruments to examine various cognitive tasks and activities in design has emerged at various institutes, e.g., (Alexiou et al., 2009; Jenkins et al., 2009; Petkar et al., 2009; Steinert & Jablokow, 2013; Sun et al., 2013). Notably, Steinert & Jablokow (2013) aimed to understand the relationships between engineering design behavior in situ, problem-solving preference, and real-time physiological data of engineers measured through electroencephalogram (EEG). The study was executed in the design observatory at Stanford's Center for Design Research. The neuroscience research on creativity in design within the HPDTR program sparked in 2018 the establishment of *Stanford's NeuroDesign Research*[2]. NeuroDesign emerged as a global community that included the Hasso Plattner Institute at the University of Potsdam (Germany), Tokyo Tech (Japan), Beijing Normal University (China), and several other institutions. The NeuroDesign symposia in Potsdam and California, and online seminars, advanced the conversations in this intersection further (von Thienen et al., 2021). In 2019, the special issue on Design Neurocognition, by John Gero, Kosa Goucher-Lambert, Tripp Shealy, and Yong Zeng, in the Design Science Journal provided space for stimulating publications (Fu et al., 2019; Hay et al., 2019; Hu et al., 2021; Shealy et al., 2020; Vieira et al., 2020; Zhao et al., 2020).

Most of the research in this intersection focuses on using neuroscience instruments to examine cognitive tasks associated with the human activity of design (Balters et al., 2023;

[2] Stanford's NeuroDesign Research https://neurodesign.stanford.edu

Ohashi et al., 2022). This area of the Neuroscience on Design and Design Neurocognition is one of the emerging fruitful spaces within the intersection of Neuro and Design. However, we emphasize that this pan-disciplinary intersection of NeuroDesign contributes to various other developments. NeuroDesign provides fruitful areas to advance our understanding of creativity, design thinking, and creative design education, by developing technologies to advance research and design products to augment human capabilities, as exemplified in Table 1.

Table 1. Opportunities of the pan-disciplinary intersection of NeuroDesign

Neuroscience	**NeuroDesign**	**Design**
Neuroscience	Neuroscience on Design and Design Neurocognition (Balters et al., 2023; Gero, 2019)	Design thinking research
Neuroscience	Creative Design Education (e.g., Saggar et al., 2016)	Design education
Neuroscience	Neuro-technology (e.g., Maki et al., 1995; Zhang et al., 2020)	Engineering
Biology, Neuroscience, Phenomenology	Embodied Artificial Intelligence (e.g., Pfeifer & Iida, 2004)	Engineering (software, electronic, and mechanical), Robotics, Biomechanics, Material sciences
Neuroscience, Psychology	Augmenting human Capabilities (e.g., Flesher et al., 2021)	Human-centered Design, Product Design, Software Engineering
"Neuro"-disciplines	*Further interesting intersections*	*"Design"-disciplines*

For the development of this pan-disciplinary intersection, we need to educate researchers, e.g., through Ph.D. programs, who will develop new research methodologies and enable practitioners (e.g., neuro-designers/engineers) to create new neuro-technologies (e.g., functional near-infrared spectroscopy (fNIRS) and Hyperscanning) and neuro-products (e.g., mind-controlled robot arm). However, we must first tackle several challenges to take advantage of these opportunities. This means going beyond individual perspectives in the context of the other.

3 Opportunities and Challenges

Developing the intersection of NeuroDesign beyond the application of neuroscience instruments to design or the investigation of cognitive phenomena in the design context, provides new opportunities and incorporates several challenges.

3.1 Neuroscience and Design Research on Cognition in Design

The two paradigms of “Neuro” and “Design” can be integrated in three different ways: (1) Neuroscientists investigating cognitive tasks in the context of design (*Neuroscience of Design*), (2) design researchers using neuroscience instruments to investigate design thinking/cognition (*Design Neurocognition*), and (3) the development of new techniques and methodologies that advance both fields (*NeuroDesign*).

3.1.1 Neuroscience of Design

The Neuroscience of Design applies a neuroscience approach to the investigation of cognitive tasks, such as creativity, related to the fundamental human activity of design. Various neuroscience scholars examined figural creativity, brain synchronicity, and generation and evaluation of ideas in the context of design (Ellamil et al., 2012; Jia & Zeng, 2021; Mayseless et al., 2019; Saggar et al., 2015). Depending on the neuroscientific instrument, these cognitive tasks are investigated through specific experimental designs. For example, functional magnetic resonance imaging (fMRI) studies primarily use experimental paradigms of two categories, namely (1) block design (BD) or (2) event-related design (Chee et al., 2003). Figure 2 illustrates the investigation of creativity through a block design experimental paradigm.

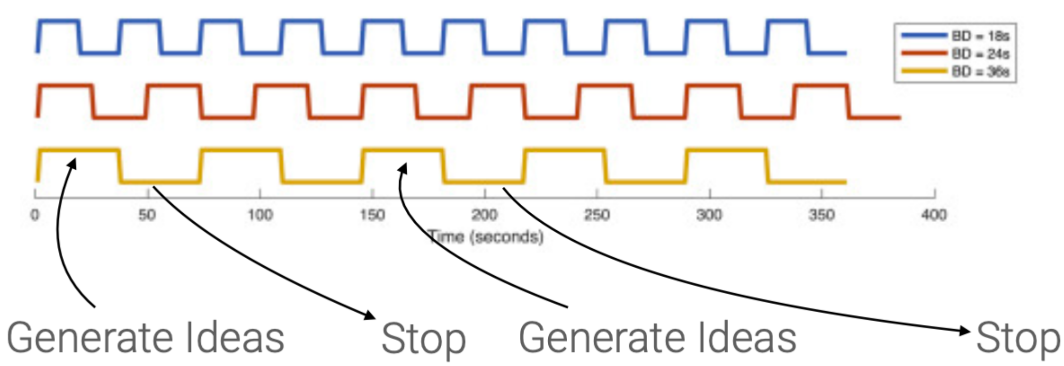


Figure 2. Prototypical Block design

While such block designs allow superior statistical power relative to event-related designs, they reduce ecological validity. This is especially problematic when studying design thinking, which cannot be broken into discrete cognitive tasks. For example, sketching ideas and concepts is a fluent task in which one move informs the next (Bamberger & Schön, 1983; Goldschmidt, 1991, 2014; McKim, 1972; Schön, 1992). In such cases, event-related paradigms can be useful.

The main idea of an event-related design (e.g., stimuli and response) is the separation of cognitive processes into discrete points in time (i.e., events), allowing differentiation of their associated fMRI signals (Huettel, 2012). However, event-related paradigms also present challenges. Designers often create their own stimuli that occur naturally rather than act on provided stimuli. These created stimuli (e.g., sketches) are seen in new ways as the "situation talks back" (Bamberger & Schön, 1983; Goldschmidt, 1991; Schön, 1992; Wertheimer, 1922, 1923). Thus, the intended experimental control and statistical power are diminished. NeuroDesign provides an opportunity for the development of new research paradigms that allow researchers to observe the neurocognitive activities of designers when they freely engage in the design task.

3.1.2 Design Neurocognition

In contrast to Neuroscience on Design, Design Neurocognition is the application of neuroscience instruments to investigate questions related to thinking/cognition associated with design activities. Design Neurocognition emerged from earlier developments in research on creativity and design cognition (Gero, 2019; von Thienen et al., 2021). Design researchers examined neurocognitive activities in design through instruments such as EEG, fMRI, and fNIRS (Alexiou et al., 2009; Balters et al., 2023; Goucher-Lambert et al., 2018; Hay et al., 2019; Shealy et al., 2020; Vieira et al., 2020). For example, Goucher-Lambert et al. (2018, 2019) used an fMRI block design to investigate neural activity during successful and unsuccessful design solution generation. Other researchers studied brain activation in the prefrontal cortex of engineering students while they utilized different design concept generation techniques such as TRIZ, brainstorming, and Morphological analysis (Shealy et al., 2020).

Many of the studies by design researchers utilized generalized linear modeling in fMRI and fNIRS studies to identify brain activation within specific regions and networks (Balters et al., 2023). However, such data analysis techniques model small portions of an expected hemodynamic response. Integrating more advanced techniques from neuroscience would advance research in Design Neurocognition networks (Balters et al., 2023).

3.1.3 Pan-disciplinary NeuroDesign

Our novel approach is the development of new research techniques and methods by integrating perspectives and approaches from “Neuro” and “Design.” *NeuroDesign* takes a pan-disciplinary standpoint to overcome some challenges inherent in approaching the question from a neuroscience or design research perspective. We are exemplifying this third perspective based on our current study.

We approached the investigation of creative and design thinking through an fMRI study in free flow, overcoming the limitations of the block design and event-related design paradigms to yield higher ecological validity. We also utilized the opportunity to investigate brain activation underlying conceptual design activities (i.e., concept sketching) in free flow with high spatial and temporal resolution through a multiband, multi-echo fMRI sequence. To study designers in a naturalistic setting (i.e., free flow) a major challenge is the collection and analysis of the data. We combined the perspectives, research methods, and analysis techniques from both neuroscience and design fields, and specifically measured brain activity during a free-flow design activities using sketching and screen capture video recording. Next, we applied a post-scan Think Aloud Protocol and video analysis of the sketching activities commonly employed in design thinking research (Eastman, 1970; Goldschmidt, 1991, 2014; Lawson, 1972, 1979; Lloyd et al., 1995). Then, we matched the fMRI-based brain activation time course with the time course of design activities. Finally, we used a recently developed data-driven method, Topological Data Analysis to examine: (1) the underlying manifold (or shape) of brain’s dynamical organization; and (2) the transitions between states over time at the level of individual samples (or time frames) (Saggar et al., 2022; Saggar et al., 2018). We briefly present our approach in Figure 3 and preliminary results from one participant in Figure 4.

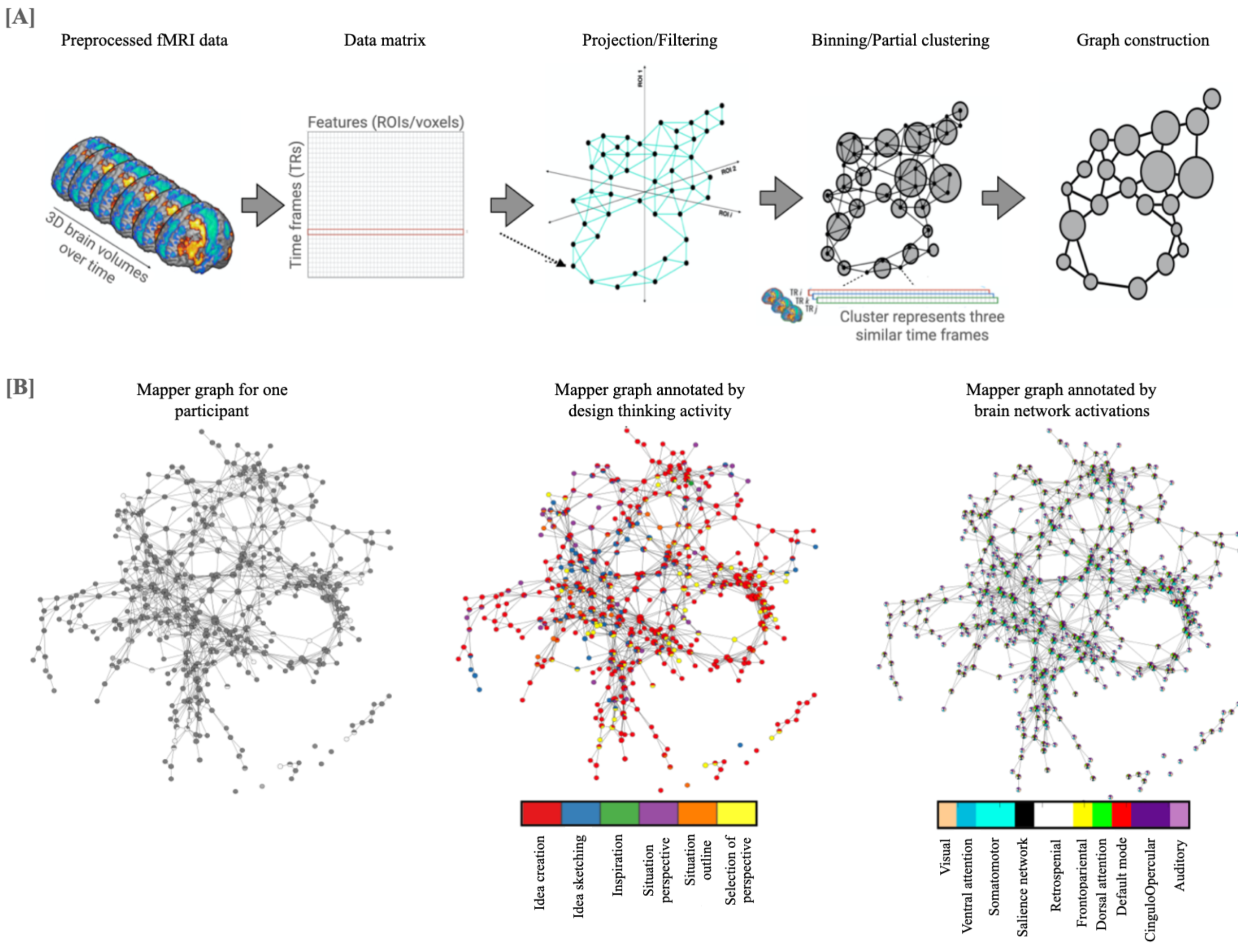


Figure 3. [A] Topological Data Analysis (TDA) based approach, Mapper, which allows extracting the underlying low-dimensional manifold from spatiotemporally rich high-dimensional fMRI data at the single participant level, without averaging or collapsing data at the outset (Saggar et al., 2022; Saggar et al., 2018). [B] Mapper-generated manifold graph from one participant while engaged in the free-flow design task. We also present annotations of the manifold graph based on the design thinking activity and brain network activations.

Figure 4 shows how we can project the Mapper-generated manifold back to the time domain, to extract and match moment-to-moment transitions in design activity as well as activation in brain networks. This analysis could allow us to identify which brain networks are associated with specific heuristic design activities, such as a moment of insight or change in problem perspective.

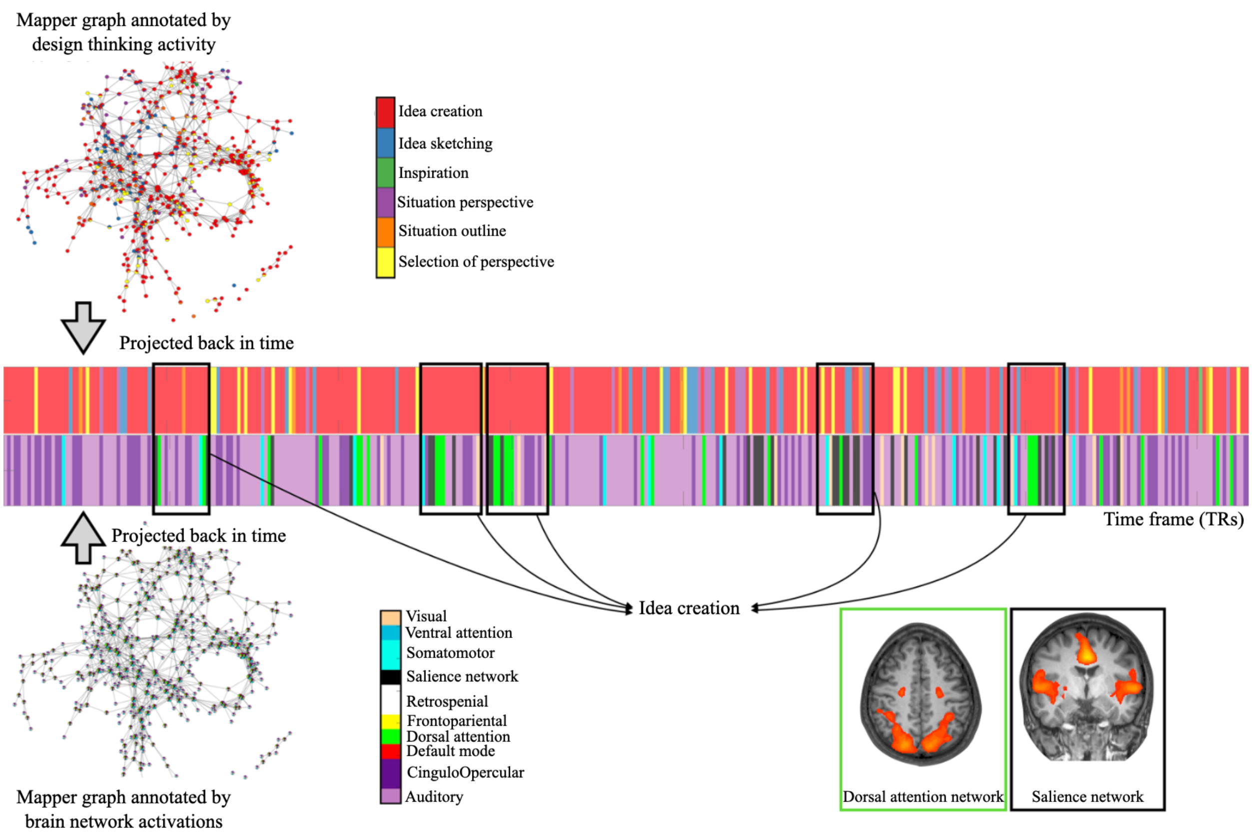


Figure 4. Projecting annotated Mapper-generated graphs back to the time domain could allow us to identify which brain networks are associated with different design activity states.

Overall, using this fMRI study design, we aim to investigate transition states between specific events that occurred naturally in the free flow, making it a novel approach in both fields. This pan-disciplinary development of new research designs, through such integrated data collection and analysis methods from diverse disciplines, is greater than the sum of its parts.

3.2 NeuroDesign to Advance Neurotechnology

Another fruitful area of NeuroDesign is the integration of neuroscience and product design/engineering. The technological development of noninvasive infrared and near-infrared topography allows researchers to examine changes in tissue blood volume and the average hemoglobin-oxyhemoglobin equilibrium (Jöbsis, 1977; Maki et al., 1995). For example, recording brain activity using near-infrared light to measure and visualize the pattern of hemodynamic changes in the cerebral cortex at the brain surface allowed neuroscientific research on infants in situ (Taga et al., 2003). Designers and engineers need to design from a neuroscience perspective to develop Neuro-technologies and products (Maki, 2021). Designing from a neuroscience perspective is greater than the sum of bringing an engineering perspective to neuroscience and vice versa.

These technological advancements allowed various neuroscientists and design researchers to investigate creative collaboration and sketching in design. For example, the fNIRS allowed Kato et al. (2018) to examine Blood Oxygenation Level Dependent (BOLD) in the prefrontal cortex during different sketching tasks. Others investigated the differences in prefrontal cortex activation in situ (Shealy et al., 2020; Shealy & Gero, 2019). These technological advancements sparked new research areas, such as Interaction Neuroscience, the neuroscience that investigates collaboration (Baker et al., 2016; Cui et al., 2012; Liu et al., 2016; Mayseless et al., 2019; Miller et al., 2019; Xie et al., 2020). For example, Mayseless et al. (2019) observed neural synchronicity in creative design tasks using fNIRS and Hyper-scanning. This pan-disciplinary approach to neuro-product design and neuro-technology development is a great opportunity to advance neuroscience research and product design. NeuroDesign is greater than the sum of its parts.

3.3 Further Opportunities for NeuroDesign

The pan-disciplinary integration of the "Neuro" and "Design" disciplines incorporates several other productive areas, such as embodied and human-centered AI and augmenting human capabilities through neuro-technology.

Artificial Intelligence

NeuroDesign provides new opportunities in embodied AI, such as visual and haptic perception (Ullman, 1986; 2019). For example, neuromorphic engineering and resulting technologies represent a promising approach for the creation of robots that can seamlessly integrate into society (Bartolozzi et al., 2022). NeuroDesign research also adds an additional productive perspective to other Human-centered AI Research approaches (Auernhammer, 2020). Intelligent systems have the potential to profoundly impact people and society. For example, a neurophysiological investigation through eye-tracking identified that individuals' selective information search rather than algorithmic curation of search results might result in filter bubbles (Ekström et al., 2022). NeuroDesign research has the potential to evaluate various aspects of impact on the human psyche, behavior, and well-being, advancing practices in Human-centered AI.

Augmentation of Human Capabilities

Developing new neurotechnology through a human-centered design approach provides opportunities to augment human capabilities (Engelbart, 1962). For example, brain-computer interfaces allow voluntary motor output from brain activity and the mimicry of sensory input from the skin of a hand (Flesher et al., 2021; Gerven et al., 2009; Green & Kalaska, 2011). Such Neuro-design/engineering augments human capabilities, particularly for people with physical disabilities and injuries. In doing so, the pan-disciplinary intersection advances the field of design, such as the augmentation of human capabilities through robotics (Burgar et al., 2000; Engelbart, 1962). The pan-disciplinary intersection of NeuroDesign provides opportunities to integrate the cognitive disciplines of "Neuro" and engineering and making disciplines of "Design" to develop intelligent systems and advance human capabilities.

4 Developing the Pan-Disciplinary Field of NeuroDesign

In this chapter, we illustrated that Neuro-disciplines and Design-disciplines together form a prolific pan-disciplinary field that is greater than the sum of its parts. Developing this pan-disciplinary field of NeuroDesign provides many opportunities to advance design thinking, creativity, design education and practice, neuroscience research, artificially intelligent systems, and technologies to augment human capabilities. For such progress to happen, one of the main challenges is funding. For sustainable development and advancement of NeuroDesign research, education, and practice, large-scale funding (that spans several typical NSF/NIH grants) is required. Philanthropic and foundation grants and National institutes need to come together to provide such critical funding.

4.1 NeuroDesign Research

To expand and develop NeuroDesign research, we envision pan-disciplinary research centers, incorporating Ph.D. research programs. These programs would integrate classes from the Neuro- and Design-disciplines to develop the next generation of NeuroDesign researchers and engineers.

Such efforts would incorporate various creative design and research practices, inspiring the development of new techniques, methodologies, and technologies. Bringing together practices and individuals in this way creates a pan-disciplinary research intersection greater than the sum of its parts.

4.2 NeuroDesign Education and Practice

The NeuroDesign centers and programs bring together individuals from the humanities, sciences, and the arts to develop design practices for the next century. Over the last century, psychology theories and principles advanced the ways we design today (Adams, 2019; Auernhammer & Roth, 2021, 2022; Card et al., 1983; Chapanis et al., 1949; Lawson, 2006; Norman, 1988). Similarly, advancements in NeuroDesign provide new educational principles, allowing the development of new creative design practices. Classes taught in collaborative teaching teams made up of neuroscientists, computer scientists, engineers, and creative designers allow for the development of experts across different fields. Individuals such as Larry Leifer (engineering design and neurology) from the late 1960s and young rising stars that combine multiple fields bridge the domains of "Neuro" and "Design" in new and meaningful ways. Training NeuroDesign researchers, designers, and engineers, who creatively approach methodological and technological challenges is an essential part of advancing the pan-disciplinary intersection of NeuroDesign, creating a field that is something other than the sum of its parts.

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