Brain-Computer Integration: A Framework for the Design of Brain-Computer Interfaces from an Integrations Perspective

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Brain-computer interface (BCI) systems hold the potential to foster human flourishing and self-actualization. However, we believe contemporary BCI system design approaches unnecessarily limit these potentialities as they are approached from a traditional interaction perspective, producing command-response experiences. This article proposes to go beyond “interaction” and toward a paradigm of human-computer integration. The potential of this paradigm is demonstrated through three prototypes: Inter-Dream, a system that integrates with the brain’s autonomic physiological processes to drive users toward healthy sleep states; Neo-Noumena, a system that integrates with the user’s affective neurophysiology to augment the interpersonal communication of emotion; and PsiNet, a system that integrates interpersonal brain activity to amplify human connection. Studies of these prototypes demonstrate the benefits of the integration paradigm in realizing the multifaceted benefits of BCI systems, and this work presents the brain-computer integration framework to help guide designers of future BCI integrations.

CCS CONCEPTS • Human-centered computing • Interaction design • Interaction design theory, concepts and paradigms

Additional Keywords and Phrases: Brain-Computer Interfaces, Human-Computer Integration, EEG

1 INTRODUCTION

The term brain-computer interface refers to technologies that facilitate the direct transfer of information between brains and computers [121]. With recent developments in technology, BCIs have emerged as a consumer product with an exponentially growing market size [80,180]. In the last 40 years, BCI has gone from a laboratory novelty to an assistive technology empowering sufferers of diseases such as paralysis, to what is now becoming a trendy consumer device [145,175,180]. We note that such consumer BCI devices have often been presented as mind-operated remote controls, intended for gaming and interacting with digital content through user brain activity [61,88,163]. While such devices indeed offer novel experiences, they are often just that - novel -, with BCI-driven control often tediously difficult to learn, slow to respond, and largely inaccurate in reading the user’s

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intentions [37,52,112,146]. Considering these issues, more contemporary BCI companies are beginning to realize that the strength of the technology is not in specific and intentional control, but rather in the sensing of more ambiguous and experiential brain phenomena, such as states of cognition and consciousness [1].

In the context of such trends, many have lamented a severe lack of applications [1,25,37,52,112,146]. Furthermore, major industry voices, such as Thomas Reardon - head of Facebook's CTRL-Labs - have stated that BCI is a technological dead-end that will be superseded by electromyography (EMG) - a technology that extracts and infers information from muscle signals [52]. While this notion should appear laughable, considering brain activity supersedes EMG by containing within it the informational source of muscle activity read by EMG, if the way we design BCI systems does not change, this negative assessment of the future of BCI technology leading to a dead-end may very well be correct. But why is this the case? Do we just lack the imagination and creativity necessary to go beyond brain-based remote controls [9,91,94,96,109,131,142,143,185]? We find this doubtful, especially when reconsidering the bountiful array of example applications provided to us through science-fiction, such as mind control, mind uploading, consciousness cloning, dream exploration, instant communication, telepathy, cognitive enhancement, superintelligence, infinite knowledge, and even immortality [55].

Through this article, we argue that many of the challenges that BCIs face as an emerging technology does not only concern engineering and technical implementation, but rather, we suggest that it is the absence of any formally articulated design knowledge to guide the development of BCI systems that maybe be contributing to stagnation in BCI development. With the most recent general design framework for BCI design being published in 2003 [107], the state of the art for conceptualizing BCI design has been limited to medical models with a dominant interaction design paradigm of technologies as tools whose relationships with humans are limited to command and response. Furthermore, we also acknowledge that BCI technology is still very much in its infancy when considering other domains of technological progress outside of design knowledge, such as its status from an industrial, business, legal, or regulatory perspective. For the stable maturation of BCI technology, it is important that developments in these domains are made in hand with application developments. Nonetheless, the scope of the present manuscript focuses on developing a high-level understanding of the hereto underexplored experiential affordances of BCI technology, and in turn guide the design of BCI systems. To drive this development, we employ the emerging paradigm of "Human-Computer Integration'' [32,117,150] to formulate a new framework to describe the design of BCI systems. It is through this framework that we ultimately argue that the future of BCI is not one of interaction between brains and computers, but one of "Brain-Computer Integration".

In this article, we therefore begin answering the research question: "How do we design brain-computer integration?" Integration refers to "human-computer integration" - an HCI paradigm that acknowledges that computers can be agential actors, allowing for the conceptualization of human-machine systems which merge to form one cohesive whole [117]. To answer the question, we followed a research-through-design lead process, including the development of three prototypal systems iterating over different aspects of brain-computer integration. Designing and studying these systems allowed for the exploration of brain-computer integration from a range of perspectives. Through the analytical reflection of each of these perspectives, the qualities that emerged from subsequent experiences these prototypes afforded were broken down and compared across each iteration, thereby leading to the creation of the brain-computer integration framework. Ultimately, it is the aim of this work that future designers are inspired to consider and understand how their systems can interact, and ultimately integrate, with brain activity through the brain-computer integration framework. Furthermore, it is intended that this work illustrates how the design opportunities afforded by brain-computer integration can be realized through actionable design strategies for designing new systems.

To summarize, this work makes the following contributions:

- This research contributes to design theory by extending the existing paradigm of human-computer integration to consider how technology can be integrated with the human brain to participate in, mediate, and modulate its underlying neurocognitive processes through brain-computer interfaces.
- This research presents the brain-computer integration framework. It is the first theoretical conceptualization of how to design for the integration of neurocognitive processes from humans-to-computers, and humans-to-humans. This framework describes the design space of brain-computer integration systems, providing HCI researchers with a language to describe integrated BCI systems and their associated user experiences. It is envisioned this will help progress BCI research through establishing a point of reference to unpack, interoperate and compare between integrated BCI systems and their user experiences.

This research also contributes a set of design strategies for practitioners designing integrated BCI systems. It is envisioned these design strategies will guide practitioners in designing systems capable of producing their intended user experiences. In the following sections, we first review related work, followed by an articulation of the three prototypes that informed this framework. We then present the brain-computer integration framework, including a visualization of the design space, a description of its composite dimensions, and provide prescriptive strategies to guide HCI researchers and design partitioners in applying our theoretical contribution. Finally, we discuss future work and limitations, before concluding this work.

2 RELATED WORK

This section delivers a review of the existing work preceding, informing, and leading up to the present investigation. We begin by describing the current state of the art in contemporary HCI-based BCI research. This is followed by a description of existing frameworks, and the observation of the opportunity for new developments in BCI design knowledge through the adoption of a human-computer integration perspective. Finally, these points are considered to ultimately produce the research question.

2.1 Brain-Computer Interface Research in HCI

While the majority of BCI research has been conducted in the context of neuroscientific, medical, and biomedical engineering research, BCI devices have also recently begun to be discussed in the context of HCI research.

2.1.1 Neuroresponsive BCI.

Considering the recent emphasis HCI research has placed on enabling reflection and supporting meditative practices [89,90,124,158,167], a large majority of BCI research in HCI has explored the representation of brain activity through various interactive technologies. These systems are typically designed to offer some form of neurofeedback, in which the system interprets an individual's neural activity and provides a representation of their mental state in real-time, which users can observe and learn to self-monitor or regulate, mostly for mindfulness training.

One example of this is "Inner Garden'', where a living world is projected onto a desktop-sized sandbox using augmented reality [141]. This world is populated in accordance to how frustrated or how meditative the participant is. Through monitoring any changes to this world, the participant receives information about their degree of focus in a neurofeedback loop, with the goal of encouraging mindfulness. Similarly, another example of this is "PsychicVR", which pairs BCI with VR to produce an immersive playful experience, allowing users to make changes to a virtual 3D environment when in a focused state of mind, and thereby encouraging mindfulness [2]. A system that also attempts to enable the regulation of brain activity is "Lucid loop", a neurofeedback system designed to simulate the experience of lucid dreaming and train participants in achieving lucid dream states [84].

Alternatively, rather than regulating brain activity, another class of neuroresponsive systems include BCI systems that adjust parameters of a task or application based on the user's brain activity, typically to accommodate the user's concurrent cognitive state. One example of this is the use of EEG in facilitating collaborative robot industrial applications [19]. Specifically, studies have demonstrated EEG to be a reliable way to detect potential emergencies in cases where robots work in proximity with humans, using markers from a worker's EEG, such as perceived safety, to reactively guide the behavior of their robotic collaborators [19]. Similarly, works done by Jacob et al. [67,159,179] have demonstrated fNIRS-based BCI can be used to monitor a user's cognitive load, allowing the system to thus adjust the difficulty of a task to compensate in the event the user is mentally overtaxed.

Taken together, these studies demonstrate the potential to enrich the human experience and promote a strong coupling between the processes of the technology and the user's underlying neural activity. With this considered, these BCI systems represent an alternative perspective in the application of BCI beyond its longstanding conception of a brain-based controller interface. However, neurofeedback is not the only way that HCI research conceptualizes BCI systems outside of a control interface paradigm, as we discuss below.

2.1.2 Social BCI.

Beyond the use of BCI for neurofeedback, BCI research in HCI has begun to consider social affordances facilitated by the technology, and the unique user experiences they evoke. One early exploration of this notion uses EEG data to attempt to extract an individual's experience of emotion from their neural activity [97]. This information is then used to animate the facial expression of a virtual avatar to match the emotional state of the participant. Furthermore, some of these related systems demonstrated the efficacy of BCI technology in augmenting interpersonal connections. For example, "Breeze", a wearable pendant that measures and displays breathing patterns, was found to increase connectedness and empathy with loved ones, as well as aid the user to control their breathing via BCI-driven neurofeedback [46].

Several studies have taken the BCI-mediation of interpersonal connections further by involving interpersonal neural synchrony as part of the system's functioning. These have mostly been artistic installations. For example, "Hive Mind'' is an installation in which two performers on a stage generate light pulses and sound in synchrony with the oscillations of their brains. "SocioPathways" demonstrates how to apply inter-brain synchrony to game design. Players are represented as dots on a screen and their dots become closer to other players as they become more synchronous with each other [122]. NeuralDrum is an inter-brain-synchrony-focused drumming game where the goal of the player is to hit objects in time with a musical rhythm [128]. By situating the experience within extended reality and employing players' EEG activity, the game expands traditional drumming games by adding visual and audio distortion as players become more synchronous. Through this mechanism, the game becomes easier while players are out of sync, and harder as they become more synchronous.

Taken together, these studies demonstrate the potential for BCI to play an influential role in interpersonal interactions and relationships. Thus, these examples further challenge the longstanding conception of BCI as a brain-based controller interface, instead demonstrating how these technologies can be used as novel mediums for communication and empathy. Furthermore, with these prior works considered, we see that HCI-based BCI research has demonstrated the potential for BCI to be more than a control interface. Yet despite this, we find that HCI-based BCI research has been currently conducted on a case-by-case basis, yielding application specific findings while falling short in generating overarching frameworks describing the design and user experience of BCI systems as a whole. With this considered, we look to earlier BCI frameworks outside of BCI research to guide the formulation of our own novel framework moving forward.

2.2 Brain-Computer Interface Frameworks

Despite the long history of BCI research, there has been little attempt to formally establish a framework for designing such technologies. The most current framework for BCI design was proposed in 2003, titled the "general framework for BCI design" [107]. Through their framework, the authors define a generic BCI system as a system in which a user controls a device through brain activity in an operating environment, through a series of functional components. These functional components ultimately represent the steps of processing undergone by BCI-extracted brain information; ultimately being interpreted by a computer to control a device as intended. The process is described as involving the user, who consciously modulates their own brain activity in an attempt to control a device (such as a wheelchair). This brain activity is sensed through electrodes, producing a signal that is amplified and then subjected to a feature extraction process, transforming raw data into values that operationalize the underlying neural mechanisms as a "feature vector". The feature vector is translated into a logical control signal interpretable by the target device, processes this information and responds with a corresponding output that the user observes as feedback on their performance in controlling the device.

The authors justify their method of partitioning processes into functional components, stating that their choice of boundaries between these components facilitates objective comparisons between systems. This approach creates a common language that can describe the information exchange between a user and a device [107]. They further suggest that this breakdown of the BCI process allows for specific objective measure and study of BCI systems, as well as their individual functional components, enabling the development of standardized testing of components and benchmarking control interfaces [107]. Ultimately, through their framework, the authors present a clear, detailed and modular description of the flow of information from a user's brain to a BCI-controlled device. However, while the basic steps in BCI signal processing as described by the authors remain relatively unchanged even in contemporary BCI technologies, there are many crucial aspects of BCI design that the framework fails to consider, perhaps due to the framework's antiquity relative to contemporary progress in BCI systems, being proposed in 2003. Recalling that, until recently, BCI research almost exclusively focused on medical and assistive technology applications, it is apparent that there are inherent limitations in the scope and generalizability of this apparently "general" framework as a result of the historical context of its creation.

Specifically, the exclusively medical context surrounding the construction of this framework appears to restrict the application of any possible BCI design to be solely directed to the conscious, intentional and purposeful control of an external device (i.e., the BCI as a control interface). As a result, the framework fails to fully describe many of the BCI systems from HCI discussed above in section 2.2, which move beyond mere control by considering how the feedback of system output may recursively influence the system as a whole, but also by affording implicit interactions, in which the signal is not consciously or purposely controlled, but rather processes and interpreted without the user's intentional input. For example, consider the use of BCI activity by the aforementioned study by Liu et al. [97] to detect emotion and animate an avatar's face in virtual reality, providing a passive channel of expression through the system's implicit interpretation of brain activity, rather than an active control channel. The framework also fails to consider BCI design intended for more than one user, which is becoming increasingly important with the rise of systems such as "SocioPathways" and "Hive Mind" discussed above in 2.1.2 [122]. Similarly, while Mason and Birch state how extraneous variables in the "operation environment" may confound the desired operation of a BCI system, studies of more recent BCI systems such as Inner Garden and SocioPathways hint at the possibility that the situational context of the BCI system may be a powerful design resource for enriching the affordances offered by the system [122,141].

An additional aspect that we believe to be important to BCI design but is seldom described in Mason and Birch's framework is neurofeedback. While the framework acknowledges in passing the propensity for feedback between the system and the user, the framework disproportionately focuses on user input and control (or, the "encoding" process), in turn failing to articulate in any sufficient detail the potential influence the system has on the user. This is clearly an oversight for describing systems like "PsychicVR" and "LucidLoop", which facilitate cognitive feedback loops [2,84]. Similarly, the framework makes no reference or allusion to the user experiences produced by BCI systems, nor design choices that may shape the user experience, thereby drastically limiting the design space of possible BCI systems an HCI designer may develop.

Considering these shortcomings of the framework, we acknowledge how well it describes the extraction of information from brain activity into a codified, computer-interpretable format, yet we also point out how it falls short in explaining the processes involved in the subsequent reception or interpretation of the resultant output signal. Typically, theories and models which describe the flow of information between bodies (i.e., information theory in electrical engineering and the encoding/decoding model of communication in semiotics) refer to these processes as encoding and decoding respectively [40,51,134,181]. Thus, we can say that while the framework does well in describing encoding processes in BCI design, the framework falls short in describing decoding processes in BCI design.

While newer BCI design frameworks have emerged since Mason and Birch's model, they focus heavily on the technology of BCI (versus the experience) [87], or focus on specific BCI applications such as medical risk management [47] and games [60], or concentrate heavily on the encoding of the system, ignoring peripheral components such as other users, situational contexts, or the feedback effects afforded by the interaction between the user's brain interpreting the system's output, and the recursive resulting input being driven by a BCI-altered brain [47,60].

For example, in contrast to Mason and Birchs's framework, a more recent attempt to provide a taxonomy of different variations of BCI systems is Kosmyna and Lécuyer's work "A Conceptual Space for EEG-Based Brain-Computer Interfaces" [87]. In this work, the authors strive to create an abstracted conceptual space providing a taxonomy of different variations an EEG-based BCI system can possibly take. The authors take a similar stance in that BCI systems appear to be underutilized and suggest this may be due to the observation that BCI interaction commands are not self-revealing, meaning that it is not inherently obvious what kinds of affordances a BCI might have, both from the perspective of the user and the designer. In response, the authors develop a conceptual space that is composed of nine axes: interface adaption; decision about execution; command initiative; neural mechanism; input type; pragmatism; interaction task; multimodality; and representation space. Overall, the authors present a framework that provides a comprehensive breakdown and analysis of the composite components of brain-computer interface systems. However, when translating this framework toward integration systems, especially when considering designing for experiences of the system as an extension of the user, the framework meets some limitations. Firstly, the framework is relatively focused on the technology first, comprehensively detailing the differing ways in which information may be collected, processed, and mediated at a mechanistic level, as considering how differing contexts and modalities may influence these mechanisms. While this puts the framework in a strong position to characterize, compare and design BCI systems, the focus placed on technological design decisions detracts from building an understanding of the phenomenology of the associated system. As a result, the framework falls short in describing, categorizing, and predicting the possible user experiences afforded by BCI. Furthermore, while there is opportunity to extend the framework beyond EEG, the framework's current state is EEG-specific, which limits the framework's ability to anticipate user experiences afforded by future BCI technologies that may allow for deeper "integration" between the user and the system.

As such, we consider these prior research projects to be good starting points for describing the information processing within a BCI system. However, they do not yet provide a full answer to our focus on how to design BCI systems that integrate with the user, and hence we now look to other biofeedback works to further inform our framework describing the design of BCI systems that aim to go beyond an outdated emphasis on input.

2.3 Learning from Biofeedback Frameworks

While BCI research has seemingly overlooked the importance of the decoding process, the more general investigation of biofeedback systems within HCI has acknowledged the importance of understanding this process. The "attention-regulation process" [123] appreciates how the design of feedback in terms of its "modality", "instructional cues'', and "judgement-free aesthetics'' is instrumental in the system's integration with the user's cognitive experience (specifically facilitating focused attention for mindfulness meditation in their case). Similarly, in their review of biofeedback systems for stress, Yu et al. suggest that the presentation of a biofeedback display can influence how the user interprets the information embedded in its encoding, but also the experience itself, stressing that the encoding is not only a carrier of information but also a stimulus that can alter physiology [182]. Although these frameworks acknowledge the propensity for an encoding to integrate with the recipient's neurocognitive processes when decoded, these frameworks often conceptualize feedback as something restricted to traditional screen-based interactions.

Moving forward, Lux et al. [103] proposed an integrative framework for live biofeedback, in which the authors translate the Shannon-Weaver model of communication toward the description of biofeedback systems [103]. In doing so, their framework includes an information source; a transmitter that encodes information; a receiver that decodes the encoded message; and a destination, which processes the message. Furthermore, they move beyond screen-based interactions, suggesting that a feedback channel can address more than sight, such as hearing, touch, etc. However, Lux et al. state BCI systems are beyond the scope of their framework. Additionally, while the authors acknowledge different channels through which a system can integrate with the physiology of the user, the underlying mechanisms of how this is completed are not described, nor do the authors investigate how changes in the code's expression (which they call a feedback channel) influences the resulting experience.

2.4 Need for Paradigmatic Shift

Considering the current state of BCI research and design knowledge, it is arguable that while the functions and mechanisms of the encoding processes of BCI systems have been steadily progressing, little is known about the decoding process. A comprehensive description of the decoding process - the "sense-making" step in BCI interaction - would entail how system output relates to the user, influences agency, interacts with its situational context, and also, opens (or does not open) channels of information exchange between other users or systems. Furthermore, the subjective experience of these components at play together would ultimately come from the user experience, something that, to the best of our knowledge, has not been discussed in any of the preceding frameworks.

We argue that the traditional interaction paradigm in which previous frameworks were created has led to the overemphasis on input and encoding, cursory examinations of decoding, and the extraneous variables interacting with codes themselves. That is, we argue these frameworks have been built with an episteme that understands the relationship between human and computer as ontologically distinct and therefore of command and response. As a result, these frameworks place an emphasis on encoding human intentions into computer-interpretable commands, with the human individual being the sole actor or agent, and the machine being a predictable static tool. However, we believe that with current advances in technologies such as artificial intelligence and devices that overlap with the human body as wearables or implantables, the validity of a command-response human-tool relationship is becoming an increasingly antiquated paradigm.

As such, it is being argued that we are beginning to see human-technology relationships in which the two no longer interact, but rather, integrate. This distinction is likely why previous frameworks have been unsuccessful in fully describing BCI systems and their design, as the relationship between a BCI and its user may be better described as integration rather than merely interaction. With this considered, the present work looks to the theory of Human-Computer Integration [5,6,31,43,44,115–118,126,147,148,150], the growing paradigm which studies and describes these new forms of human-technology relationships, to form a foundational perspective on which to build a new and more complete framework of brain-computer interface design.

2.5 Human-Computer Integration

In 2017, a panel at the ACM Conference on Human Factors in Computing Systems (CHI) titled “Human-Computer Integration versus Powerful Tools” [43] articulated what the authors deemed to be a new paradigm within HCI, “Human-Computer Integration”. The panel proposed a move in technology away from the “stimulus-response” paradigm we commonly think of when we talk about interaction and toward a “symbiotic partnership” between humans and computers, in which both parties are integrated and must be considered holistically.

Carrying forward the sentiment put forward in this panel, a Dagstuhl symposium was held in 2018, in which 29 leading experts came together over a five-day workshop to develop and discuss the future of Human-Computer Integration, or HInt [118]. The discussions during this workshop ultimately spawned an overarching work titled “Next steps in Human-Computer Integration” [117]. The paper defined HInt as “a new paradigm with the key property that computers become closely integrated with the user”, which included examples in which "humans and digital technology work together, either towards a shared goal or towards complementary goals (symbiosis)" and "integration in which devices extend the experienced human body or in which the human body extends devices (fusion)". Learning from this work and applying its insights to the development of a new perspective for BCI design, we deduce two fundamental axioms from which the framework should be built. One is that we should assume both the human and the system as agents, or as the authors describe, “partners”, rather than ontologically distinct entities. The second suggests we should also consider the integration between humans and BCI as scalable, suggesting that integration can occur beyond one machine agent and one human agent; as networks or assemblages can include many of each, all integrated with each other.

Because the previously discussed BCI systems illustrate how technologies can recursively influence, and become influenced by, the user's physiology (specifically their brain), we find that the fusion aspect of HInt is particularly relevant to BCI design. Moving forward, more recent developments in HInt have built on fusion's focus on the integration between humans and technology at the level of the human body. Specifically, Mueller et al. contribute the framework of designing "bodily integration" [116]. Through this framework, the authors elucidate how integration systems can be designed for closed coupling with the user's physiological form and processes, ultimately enabling users to experience technology as an extension of their own body, or conversely, experience themselves as an extension of the technology, depending on how the system is designed. Their thesis is that in designing systems capable of bidirectional agential actuation between the user and the system, they facilitate a tight coupling in which the two can be experienced as a unified whole. Furthermore, while the closeness of hardware to the human body is indeed an element or subset of human-computer integration, our interest and interpretation of human computer integration in the context of brain-computer integration takes a more functional and experiential approach in its focus than entertaining the centrality of physical hardware. As such, we are interested in systems that integrate with the body in the sense that they bidirectionally interact with the user's physiology and can be experienced as an extension of the user, which has been described as an important element of human-computer integration in several publications [31,116,118,147,151]. This allows for BCI systems that have a significant influence on user neurophysiology, such as many neurofeedback systems, to be considered as a form of integration.

2.6 Research Opportunity

Through examination of past research, we find that BCI has had a long and varied history. Research has largely focused on extracting information from brain activity, ultimately guided by the epistemic foundation that BCIs are control interfaces. Furthermore, there has seldom been effort to articulate a framework for the design of BCI systems, and the examples that do exist are antiquated and only describe the encoding of brain activity to digitized signals, while failing to elucidate how humans decode these signals, as well as the phenomenological experience of the decoding process. As such, there exists no formally articulated design knowledge detailing what kinds of BCI systems can be made (beyond control interfaces) and what kinds of experiences their users can expect to have. We, once again, argue that the etiology of the contemporary lack of BCI design knowledge stems from previous BCI frameworks being based in a traditional interaction paradigm that considers human-computer relationships as one of command and response, ultimately limiting BCI to a control interface. As such, we argue that to progress beyond this conceptual dead end, it is required that a more contemporary BCI design framework be contextualized in a new paradigm for describing human-computer relationships. This proposed paradigm is Human-Computer Integration, and as such we name this new framework the Brain-Computer Integration framework.

In learning from the most recent canonic works produced by HInt theorists [116,117], we have modified the implications for design practice the authors have offered into axioms on which to base the development of the Brain-Computer Integration framework we undertake throughout this work. The synthesis of these axioms was undertaken to serve as a guide for our design process and investigative exploration away from traditional interaction focused BCI's and toward integration focused BCI's. These axioms were developed through considering the definitions, insights, and strategies denoted by prior HInt works [31,116–118,147,151] regarding what properties of a system specifically and uniquely make it an "integration" system, which were presented as design strategies and design space dimensions in these previous works. We then distilled these strategies and dimensions into a minimalist set of properties that together allow systems to be defined as "integrated" by compiling system properties each publication listed as being unique to integration, and then coding each of these properties into themes through the process of thematic analysis [161] to produce a minimal set of properties with no overlap. This process ultimately resulted in four axioms, being:

- Humans and technology in a BCI system must both be considered agents, imbued with agency, existing on a flat ontology (existing on an equal ontological level). Thus, both human and artificial agents are parts of a BCI system, working together as partners toward a common goal.
- Integration in a BCI system must be scalable. Thus, a BCI system can be assumed to contain few or many human and artificial agents, all integrated with each other.
- Agency must be variable between agents within a BCI system. Thus, it is important to understand how agency is distributed across the agents constituting the system as a whole.
- Ownership must be variable between agents within a BCI system. Thus, it is important to understand how ownership is distributed across the agents constituting the system as a whole.

Equipped with the axioms provided by this new paradigmatic perspective, this work seeks to develop a more complete framework for BCI design that fully describes not only BCI's encoding processes, but also the decoding processes, the system's interaction with extraneous factors, and ultimately, the user experience provided by these elements in concert.

2.7 Research Question

With the above considered, it can be stated that the present work seeks to develop a novel framework for formally articulating the design of brain-computer interfaces from an integration perspective, rather than an interaction perspective. Doing so will provide the design knowledge necessary for the development of Brain-Computer Integration and BCI systems that integrate with the brain and its cognitive processes, rather than functioning as mere control interfaces. Thus, the present work seeks to answer the research question:

How do we design Brain-Computer Integration?

3 METHODOLOGY

The following section details the methods employed in this work in order to arrive at the Brain-Computer Integration framework.

3.1 Research through Design

To understand the design space of integration BCI systems and ultimately formulate the Brain-Computer Integration framework, a variety of methods have been adopted from the research disciplines this work touches, including psychology, neuroscience, philosophy, design and HCI. At a higher level, the structuring of the studies and general approach to the completion of this work has been largely informed by the research paradigms of HCI. The rationale for this is that while it is possible the research methods conventional to other approaches (such as systems engineering or psychophysics) might be applicable in the present exploration, the questions this work seeks to answer specifically focus on the interaction (or integration) between the human subject, and computer systems, rather than understanding the two entities dichotomously, or in isolation. As HCI can be defined as a field of study focusing on the design of computer technology and interaction between humans and computers [63,188], the method of this work aligns foremost with the methodological practices of HCI.

Considering the wide range of methodological approaches available within the field of HCI, this work engages with HCI centrally through the approach of "research through design" (RtD), which can be defined as the adoption of methods and processes from design practice applied toward the inquiry of new knowledge [186]. The strengths of such an approach can be seen in that it is effective in synthesizing many ideas together through processes of composition and integration due to its origin in design theory [50,186]. As such, these properties have rendered RtD well suited for the formation of theory in novel and emerging contexts, while also being robust enough to support the later development of more mature and comprehensive theoretical constructs [50,85]. With these properties of RtD considered, it is notable that this approach aligns well with the topics central to the present exploration. This can be initially seen in that brain-computer integration as a theoretical construct is a synthesis of ideas from diverse fields of research, including computer science, information theory, psychology, and neurocognitive science. Furthermore, this approach was taken considering that RtD permits researchers to focus on "research of the future" [187], allowing understanding of brain-computer integration as or before it emerges. This is important when considering that the present work focuses on a novel path of inquiry emerging from the design synthesis of cutting-edge technologies.

Considering the latter sentiment, a critique of RtD is that the field is dominated by the sentiment that "being first" or designing something "new" takes precedence in value, recognition, and motivation over in-depth analysis and critique [187]. As a result, it has been suggested that practitioners of RtD often squander the potential strengths of RtD in theory formation by instead shifting attention to the development of the next design prototype. This has been considered and avoided in that the primary contribution of this work is a completed theoretical framework. Furthermore, the approach of the present work is iterative and reflective, necessitating that the process of prototyping becomes the source of research outcomes. In turn, artefacts become a conduit for "transforming the world from its current state to a preferred state" [187]. Such a future-oriented focus consequently leads to an emphasis on the phenomenological experience, motivations, and mechanisms of interaction (or even integration), rather than realizing a fully developed system or product.

3.2 Research-in-the-wild

To complement the exploration of the future enabled by RtD, the present work also employs a "research-in-the-wild" (RITW) approach to the design of its constituent studies [27]. Research-in-the-wild can be described as a research design in which studies take place outside of the lab, often instead being situated within communities or homes for extended periods of engagement. The strength of such an approach allows researchers to develop a deep understanding of the impacts and affordances technologies have on day-to-day life and in the "real world" [18]. Its proponents argue that setting studies within home and community life presents a rich context for understanding challenges and possibilities of the technology of interest, as researchers can examine reactions to everyday activities [10,18,23,27,82]. Furthermore, participants are offered novel opportunities for participation as they also act to understand the technologically facilitated interactions between people afforded to them by the novel technologies deployed in their home or community [23]. Since RITW includes naturalistic social interaction in its research design, it benefits this work by providing a rich contextual environment to understand the experience of integrated consciousness from its necessary interpersonal perspective [10,18,23,27].

Furthermore, it could be argued that the first case study, Inter-Dream, breaks from this RITW approach in that the system was not deployed for participants' longitudinal personal use, but instead in an installation space during an allotted time. However, we maintain that Inter-Dream still follows a RITW approach as it employs a subset of the approach known as "performance-led-research-in-the-wild" [15]. In this approach, the design and presentation of an artefact is led by an artist following artistic processes. In turn, research findings emerge from reflection on the artefact and the participants' experience. Considering Inter-Dream specifically, the artefact was originally designed by the artists with the intention of producing an interactive public art installation that explored the speculative future concept of interpersonally sharing dreams through BCI. Nonetheless, the findings of this study prompted the adoption of a more traditional RITW approach in which systems are deployed to participants for longitudinal use that persisted for the remaining two case studies. Similar examples of this approach to BCI RITW include the work of Kosmyna [86], who employed a "controlled in-the-wild" research design to develop a framework of BCI interaction based on the behavioral patterns of 1563 people who engaged with their BCI system as part of several public demonstrations. The author motivates their use of this approach, stating that BCI's rarely leave the lab and that only a small number of in-the-wild BCI studies exist (citing Guger [59], and Pfurtscheller [132]). The author argued that researching BCI systems in-the-wild provides the opportunity to unveil different patterns of usage which may not manifest during lab-based interactions, with the "interaction language" of BCI being particularly unique, novel and unlike any other existing interaction modality.

Developing the framework

Through employing the methodological approaches discussed above, we explored the design space of brain-computer integration through the design, development, deployment, and evaluation of three novel brain-computer interface prototypes. Each prototype served as a case study in which we could learn about the user experiences afforded by different BCI designs in different application domains, with the findings of each preceding case study guiding the direction of the next. Each prototype was evaluated through a mixed methods study design, taking psychometric, physiological, and qualitative interview data from participants in order to build a holistic understanding of the mechanisms and phenomena which comprise the design space of brain-computer integration. The insights gained from the evaluation of all three prototypes were then ultimately considered together to synthesize the brain-computer integration framework. This was completed through a process in which the themes yielded from the study of each prototype via thematic analysis of user interviews were compiled and further thematically analyzed as a single corpus as a qualitative meta-analysis [169]. Furthermore, we note that the analysis of findings across a set of prototypes to arrive at design knowledge is a conventional method in HCI, typically referred to as annotated portfolio research [49]. As such, our approach can be seen as a qualitative meta-analysis using our annotated portfolio showcasing three brain-computer integration prototypes.

4 DESIGN PROTOTYPES

The following section details the three design prototypes which were developed as case studies to explore and study the design space of brain-computer integration. In addition to their descriptions below, each prototype has been detailed and evaluated individually in their own separate publications [42,149,152,153]. These prototypes will also be used for the remainder of the articles as concrete examples to ground the unpacking and articulation of the brain-computer integration design space and are summarized here for the reader's benefit.

4.1 Inter-Dream

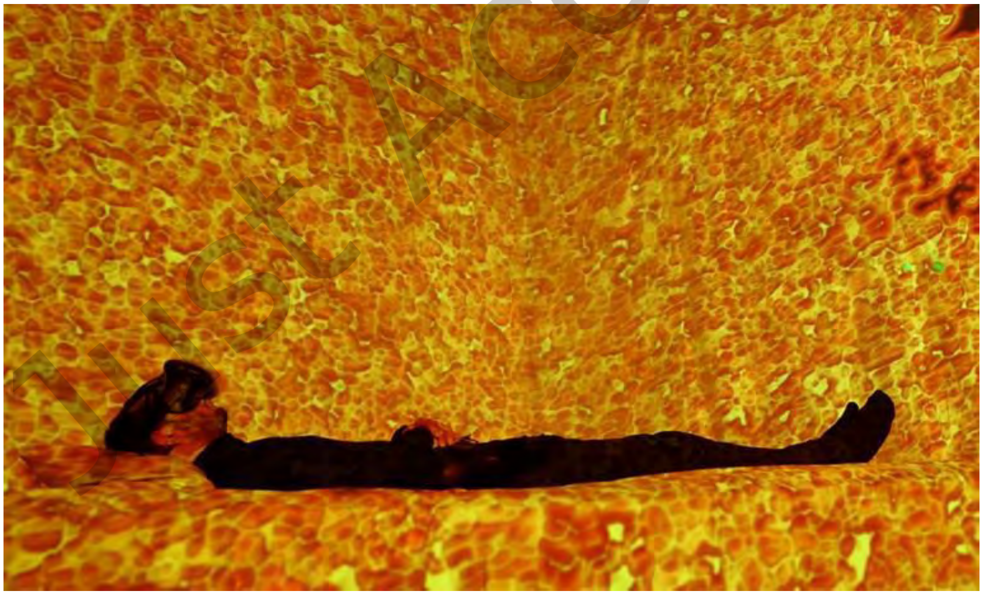

Figure 1. Inter-Dream, a system that integrates with the brain's autonomic physiological processes to drive users toward healthy sleep states.

The first case study aimed to answer the sub-research question: "How do we design integrated brain-computer interfaces for regulating brain activity?". To do this, this case study explored how BCIs can regulate brain activity by studying the system "Inter-Dream" (figure 1), a multisensory, neurofeedback-driven, interactive art installation in which participants rest in a haptic bed whilst their brain activity is fed back to them in virtual reality. In a study of Inter-Dream [152], twelve participants individually rested, augmented by Inter-Dream. In evaluating the system and its associated user experience, a mixed method research design was employed that utilized a combination of physiological recording through EEG, self-report psychometric scales to measure pre-sleep affect, arousal, and emotion, and thematic analysis of participant interviews recounting their experience with the system. Results demonstrated: statistically significant decreases in pre-sleep cognitive arousal and negative emotion, and negative affect. EEG readings were also indicative of restorative restfulness and cognitive stillness, while interview responses described experiences of mindfulness and playful self-exploration. These results lead to forming the foundation of the brain-computer integration framework. Namely, the insights gained from the exploration of this first case study were that feedback and agency are two critically influential factors of a BCI system when considering the user experience.

4.2 Neo-Noumena

Figure 2. Neo-Noumena, a system that integrates with the user's affective neurophysiology to augment the interpersonal communication of emotion

The second case study aimed to answer the sub-research question: "How do we design integrated brain-computer interfaces for communicating brain activity?" To answer this question, this case study explored how BCIs can communicate brain activity (in this case emotion) by studying the system "Neo-Noumena" (figure 2). Neo-Noumena is a communicative neuro-responsive system that uses brain-computer interfacing and machine learning to read one's emotional states and dynamically represent them to the user and others in mixed-reality through head-mounted displays. In the study [153], five participant pairs were given Neo-Noumena for three days, using the system freely. In evaluating the system and its associated user experience, a mixed-methods research design was employed that utilized a combination of self-report psychometric scales to measure the system's influence on change of participants' emotional competence before and after system use, and thematic analysis of participant interviews recounting their experience with the system. Measures of emotional competence demonstrated a statistically significant increase in participants' ability to interpersonally regulate emotions. Furthermore, participant interviews revealed themes regarding "spatiotemporal actualization", "objective representation", and "preternatural transmission". Through Neo-Noumena, the framework was extended through the realization that brain activity could not merely be conceptualized as "feedback" but rather as abstract information. Thus, BCI processes can be likened to encoding-decoding processes through evoking Shannon Information Theory and Verbeek's post-phenomenological framework of human-technology mediation [144,176–178]. Furthermore, the findings of Neo-Noumena suggested that BCI-related agency has a variable distribution between the agents and actors participating in the flows of information mediated by the system, informing the framework with the knowledge that agency was not only something possessed by users' brains, but also by other agents acting on or within the system, such as the environment.

4.3 PsiNet

Figure 3. PsiNet, a system that integrates interpersonal brain activity through brain-to-brain interfacing to amplify human connection.

The third case study aimed to answer the sub-research question: "How do we design integrated brain-computer interfaces for synchronizing brain activity interpersonally?". This case study explored the interpersonal integration of consciousness through brain-to-brain integration of participants via the system "PsiNet" (figure 3). PsiNet is a networked wearable brain-to-brain system designed to amplify inter-brain synchrony across its users by sensing brain activity through electroencephalography (EEG) and by modulating brain activity through transcranial electrical stimulation (tES). The system classifies the dominant cognitive activity of each user in a group, and then, based on this information, attempts to synchronize the dominant group's cognitive activity through strategically selecting unique tES stimulation protocols for each group member, selected by a reinforcement learning agent running remotely on a server. Regarding physiological measures, group inter-brain synchrony was assessed through measure of the circular correlation coefficient taken from the group's concurrent EEG recordings, with sample comparisons of group EEG circular correlation coefficient before and after synchronizing brain stimulation. We also employed thematic analysis of participant interviews. The outcomes of this in-the-wild study [42,149] suggested that brain-to-brain interfaces are feasible for supporting interpersonal connections. The analysis of EEG data revealed a statistically significant increase in inter-brain synchrony, and interviews revealed three themes that describe a user experience, inclusive of "hyper-awareness"; "relational interaction"; and the "dissolution of self". The findings of this case study extend the framework through the realization that brain signals can be received without the need for user interpretation, permitting the user to experience them as if they were generated by their own body. This finding, distinguished from the findings of the previous case studies regarding how information is presented, ultimately lead to the formulation of the framework's axis "neural congruence". Furthermore, the case study demonstrated that sense of agency and sense of ownership are things that can be distributed between brains, which when considered with the results of the previous case studies, synthesized into the "distribution of agency" axis of the brain-computer integration framework.

5 THE BRAIN-COMPUTER INTEGRATION FRAMEWORK

This section introduces the brain-computer integration framework (figure 4). The framework depicts the design space of Brain-Computer Integration as a two-dimensional cartesian plane. This framework is a synthesis of the knowledge gained through reflecting on the design of the three prototypes, in conjunction with their results. The emergent framework describes the design space of brain-computer integration systems, as well as prescribes strategies for designing brain-computer integration systems in order to reach an intended user experience. It is intended this framework will ultimately help designers and practitioners navigate this design space to generate the desired user experiences when designing future integrated BCI's. This was inspired by previous works in HCI that have used two dimensions to describe design spaces, prescribing names to each quadrant which resultantly represent unique types of user experiences [3,21,22,113–117].

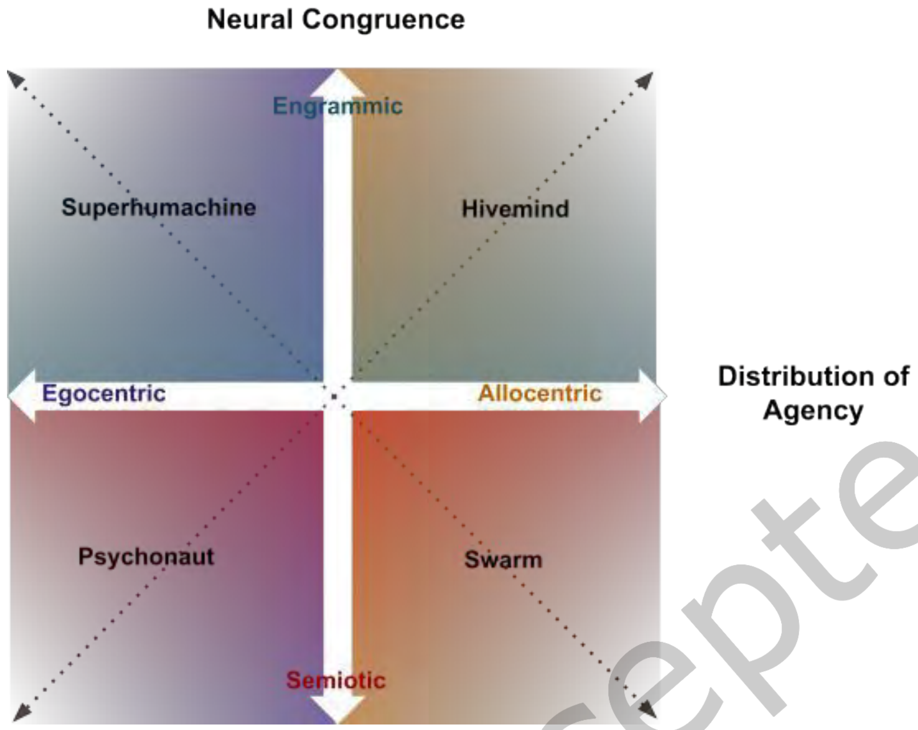

Figure 4. The brain-computer integration framework.

5.1 The Framework Axes

The first dimension concerns "neural congruence", spanning from semiotic to engrammic. The second dimension concerns the "distribution of agency", spanning from an egocentric distribution to an allocentric distribution. The following section defines, describes, and differentiates these dimensions and the quadrants that result from their interaction.

5.1.1 Neural Congruence.

The first dimension of the design space is "neural congruence". This dimension is concerned with the extent of congruence between the source experience the BCI is encoding from neurocognitive activity, and the resulting user experience of the recipient when decoding BCI data. For example, if a user feels sad, and the underlying neurocognitive processes behind this feeling are encoded and represented on a screen as a sad face, what is the similarity between the feeling that generated that sad face, and the feeling one would get when looking at it? That extent of similarity, or neural congruence, is the focus of this axis.

Systems that exhibit a low extent of congruence generally encode brain data via semiosis, meaning that they translate the source experience into abstracted signs, symbols, or representative metaphors

[39,130]. Recipients of such signals usually need to decode the signal by engaging in the more active cognitive processes of perceiving and schematizing these symbols in order to extract meaning. This process ultimately renders the user responsible for sense-making, as they are required to consciously act as a decoder.

Conversely, we find that systems that exhibit a high extent of neural congruence generally encode brain data as an "engram", meaning that they relay the source experience through stimulating neural activity in the recipient which is congruent with the neural activity that was previously encoded [75]. Recipients of signals with a high extent of neural congruence decode these signals more passively, as their brain is entrained to produce a distribution of neural activity similar to that underlying the source experience. This process ultimately distances the user from being involved in sense-making, as information is instead decoded unconsciously by the user's brain as the system's output merges with the user's neural activity.

The dimension of neural congruence speaks to postphenomenological conceptualizations of human-computer relations. Specifically, we refer to Verbeek's "theory of technological mediation" [176] that was formulated to analyze how different technologies can mediate the relations between users and the external world. In applying Verbeek's theory of mediation to the context of a brain-computer integration framework, our work supports this previous work by demonstrating how different forms of Verbeek's human-technology relations are manifested by systems at different points of the neural congruence spectrum. Furthermore, our work extends this work by describing how Verbeek's human-technology relations are mutated into modified variants of the theory's original relations due to unique properties of BCI systems, as we will discuss in the following paragraphs.

Verbeek uses the term "hermeneutic relations" [144,176] to refer to human-technology relations in which a system is used via the act of perceiving and interpreting a system's semiotic output. Through this process, the user experience is a transformed encounter of what is being represented through the direct experience and interpretation of the technology itself. An example of this in the context of BCI would be a representation of brain activity through a graphical visualization. In this example, the user experiences symbolically translated access to the cognitive processes of the brain being encoded. This resulting experience can be considered to have a low extent of neural congruence, as the human decoder is perceiving and actively interpreting the semiotics of the technology itself, rather than the source experience it is translating. Thus, it can be said that BCIs transmit semiotic signals through hermeneutic relations. However, due to the nature of BCI, the subject that is being hermeneutically related as semiotic information via technology is itself the subject (i.e., a user) which interprets it. Specifically, neurocognitive activity is what is both being represented via hermeneutic relation, but also, what is being used to interpret the hermeneutic relation. This process creates a hermeneutic feedback of semiotic brain data that ultimately puts the user's conscious cognitive processes at the center of sense-making in the experience, both in terms of encoding and decoding information.

Alternatively, "embodiment relations" [144,176] are human-technology relations that transform a user's behavior and perception of the world. In the context of BCI, embodiment relations facilitate experiences in which the user's neurocognitive processes are mediated through the system, rather than being represented by the system. That is, the user's experience of reality is modulated through the device, with the device in some ways taken into the user's bodily awareness. An example of this is a system that modulates the user's brain to produce an altered state of consciousness, like how PsiNet was able to modulate users' brains to have them enter a state of focus. This thereby changes the way the user perceives the world. Such systems are able to facilitate a high extent of neural congruence as they are able to shift a decoder's experience of the world to resemble that of the encoder. However, while Verbeek describes embodied relations as relations in which the human uses a system as a mediational lens through which to see the world, embodiment relations in the context of BCI are unique in that the mediational lens through which the human interacts with the world is their own brain. That is, while the human sees the world through technology in typical embodiment relations, the human sees the world through their technologically altered brain in BCI embodiment relations. Here, humans are not perceiving through the technology, but rather the technology is part of the perception process itself. Through this insight it can thus be seen that in the context of BCI embodiment relations, the separation of human and technology becomes incredibly difficult, suggesting that embodiment relations align closer to what Rosenberger and Verbeek describes as "fusion" or "cyborg" relations [144].

Fusion relations describe embodiment relations taken to a deeper form in which it is no longer enough to say that the user experiences through the device, as no clear distinction can be made between the human and nonhuman elements in these relations, referring to neural-implants for deep-brain and cochlear stimulation as examples of technologies enabling fusion relations [144]. The experiences afforded by fusion relations can be considered to possess a higher extent of neural congruence than embodied relations, as they enable the activation of specific neural distributions necessary to reproduce the originally encoded source experience in the decoder. That is, the signal takes the form of an engram. With this considered, such systems find themselves at the highest end of the neural congruence spectrum.

To further unpack the dimension of neural congruence, we also consider Zander and Kothe's distinction between active, reactive and passive BCI systems [183]. The authors first define active BCI as an interaction paradigm in which the user must directly and consciously produce an input signal with their brain with intention to control the system, independent of external events. Conversely, they describe reactive BCI systems as those whose input signals are consciously controlled by the user, derived from the brain's response to external stimulation. Finally, the authors describe passive BCI systems as those in which system input is derived from brain activity that arises arbitrarily without intentional purpose or voluntary control (i.e., autonomic neurophysiological and cognitive processes), which the authors state "enrich human-machine interactions with implicit information" on user states [172]. This paradigm thus allows for implicit interactions where input is not actively chosen by the user but rather, where the system infers information about the user's physiological, psychological, or contextual state to consequentially guide the heuristics of a system to ultimately produce a desired user experience based on those parameters [172].

With these distinctions considered, we argue that the prototype systems that were investigated in the synthesis of this framework are all passive BCI systems, and thus the brain-computer integration can only be said to describe passive brain-computer integration systems with confidence. Nonetheless, we also believe that the framework could be successfully translated or generalized toward active or reactive BCI systems, with the active/reactive/passive distinctions possibly serving as additional dimensions for the framework, which can be further developed through future research. For instance, it is likely the distinction between active/reactive/and passive BCI is not dichotomous but rather continuous. For example, the prototypes that were of lower neural congruence tended to facilitate self-regulation through a form of neurofeedback. Typically, in these instances, while the system began as "passive", they would become "reactive" as the output generated by the user's brain was fed back to them, thereby influencing the system's input signal. This was oftentimes intentional on the part of the user, as they consciously attempted to change their own physiological, cognitive, or affective state to influence the system's functioning. This in turn initiated what has previously been described as an "affective loop experience" where in a user interacts with a system intentionally and physiologically, to which the system responds through affective expression (e.g., through hermeneutic relations of using semiotic encodings of affect). This is thereby interpreted by the user, which in turn makes them respond, and this process iterates ad infinitum. Thus, we can see there is some continuous spectrum between passive and reactive BCI systems, with temporality, context, and user intention being factors deciding whether the system is more passive or reactive. Furthermore, it is likely that in this hypothetical spectrum, reactive systems exist in the center, with active and passive systems existing at either extreme.

5.1.2 Distribution of Agency.

The second dimension of the design space is "Distribution of Agency". This dimension is concerned with causal influence distribution amongst agents participating in the system. This dimension describes how the brains of users of the system control its processes, how equally that control is distributed amongst users, and how much other causal factors, such as situational context, influence the user experience. It illustrates this by placing egocentric BCI systems, in which agency is centralized in a single actor, on one side of the dimension, and allocentric systems, systems in which agency is decentralized amongst actors, at the opposite end. This dimension considers interactions between causal agents within the system holistically, imagining them as a network which can be described as a whole. For example, imagine a user is part of a BCI experience in which the neurocognitive activity of themselves and a group of other users are influencing the flocking behavior of a swarm of drones. In analyzing this experience, this axis would pose the questions "how equally is control distributed across users' brains?" and "how much does situational context influence the experience?", e.g., nearby drafts and airflow, or the social norms around using drones (such as air traffic laws). Furthermore, the formation of this network of users, technologies, environmental conditions, and abstracted socio-semiotic factors can then be taken together to be described as a singular agent in itself through conceptualizing it as a network.

While it may be easy to quickly assume this axis refers to how "social" a system is, this is not entirely correct. The distribution of agency within a BCI system is not merely a measure of how many users are in the system, but rather a description of the distribution of the causal agents acting within the system. For example, a neurofeedback system in which a single user's brain drives the experience (i.e., the system completely stops if the user removes the BCI) is highly egocentric, even if other people were involved in this experience. Furthermore, this axis does not just concern how many people are wearing BCIs. For example, a system in which a group of users' brains are stimulated in accordance with the activity of a single user's brain would be considered highly egocentric.

The dimension of distribution of agency speaks to Latour's "Actor-Network Theory" (ANT) [93], which seeks to define and describe the relational ties between human and non-human actors by describing them as nodes within a network, with each node being called an "actant". This network is placed on a "flat ontology", meaning that all actants within the network can equally be assumed to have implicit value or agency. This is the case regardless of what the actant is, be it human or not, and as such it treats humans and technology equally in terms of possessing agency and value within the network, thus favoring neither social nor technological determinism. Taken together, the amalgamation of actants within a given network can be conceptualized as an "assemblage", the sum total of individual actants forming the whole. With these points considered, we can thus state that ANT explains how material–semiotic networks (networks of physical artefacts and living organisms (material) and transmissible information (semiotic)) come together to act as a whole.

For example, consider the network of PsiNet. The actants in this network include not just the users, but also the algorithms driving the system, the hardware mediating the exchange of information between the system and its users, and the contextual factors present around the users. Together, these actants connect to create a joint agency from which a "brain of brains" emerges, imbued with its own novel ontological experience. Furthermore, in describing the actants within this brain of brains as networked nodes, its composition can be further described through "node centrality", which will ultimately allow us to determine the distribution of agency of this brain assemblage [17]. Node centrality [17] is a descriptor of the importance of a given node in a network (i.e., how central it is to the network). This importance can be established in various ways, such as by considering the number of connections to a given actant, or also the number of important actants connected to a given actant. Important nodes are integral to the identity of the network and have the most agency over the flow of information throughout the network; thus, dictating its ontology. Highly centralized networks would tend to have a single or small number of important nodes which boast a disproportionately large number of connections relative to other nodes. Conversely, the connectivity of nodes in decentralized networks would tend to be homogenous, with many nodes sharing a similar number of connections resulting in no nodes being of particular importance.

Returning to BCI's, we find that human-system assemblages with an egocentric distribution of agency can be described as centralized networks. In such assemblages, a small number of important nodes, or actants, exist, most often a single user and the interface itself, with all other actants (e.g., observers, other participants, etc.) participating in the network through connections to these actants (e.g., rather than to each other). As such, the experience is highly contingent on these specific actants and their actions, giving them a disproportionate amount of agency over the experience. In turn, other factors such as context and situatedness present little influence over the system. Consequently, the removal of said important highly connected central actants would ultimately destroy the assemblage, in turn ending the experience.

Conversely, we find that human-system assemblages with an allocentric distribution of agency can be described as decentralized networks. In such assemblages, there are no "important" actants but rather all actants have homogenous degrees of connectivity within the assemblage, resultantly supplying similar amounts of influence over the network. As a result, this creates a joint agency in which agency is not centralized within a given actant but rather in the gestalt of the assemblage. As such, the system is not contingent on a single actant. This comes with the benefit of rendering such systems scalable, specifically in that actants can be added and removed from the assemblage (e.g., more and more users can join) without disrupting the experience or needing to re-engineer the system. Furthermore, such distributions place a larger emphasis on situational factors, as each actant is not more or less connected to their semiotic (informational) or material (physical) space. Additionally, it is likely in such networks that BCI interaction paradigms are bi-directional, able to both read and write neural information [66].

With the assumption that in a BCI system, important nodes will tend to be brains considering they are the system's subject of interest, a system's distribution of agency can simply be summarized in the notion of "whether there is a central brain or not", with this outcome being resultant on whether the designer configures flows of agency within the system to be either allocentric or egocentric.

In addition to the shape and connectivity of the network, an additional important factor in the distribution of agency is the directness of control between actants within the network (i.e., in what direction causal influence flows between nodes). This can be further unpacked with the help of Benford et al.'s concept of "contesting control" [16]. Specifically, the authors discuss how in embodied interactive experiences, control is something that is contested between the human and the machine, with the user battling for direct control of the interface. The antagonist in this struggle for control could even sometimes be the user's own body, as the authors describe autonomic physiological processes that serve as the input signal to the system (e.g., cognitive state) are often the subject to regulation by the user in order from them to gain control over the interaction. The authors discuss how this contest of control can be further broken down into three dimensions: self-awareness of control; extent of awareness of control; and looseness of control. Surrender of control describes the feeling of battling for or losing control, which can be experienced to varying extents, from feeling as though the user is in control of the system and their body is part of an interactive loop; to the user completely relinquishing control of the system and their body to the processes of the loop. Self-awareness of control describes to what extent the user is aware of how their input is influencing the system, with experiences ranging from a complete awareness of how the user is influencing the system, to complete unawareness as to how they are influencing the system. Finally, the dimension of looseness of control is concerned with the reliability of the control signal from the human to the system, and the predictability of the system's response, ranging from tight to loose control. When translating this framework to help unpack our dimension of distribution of agency, it could be said that the relationship between each actant in the network (or each edge joining to nodes in the network graph) is characterized by varying degrees of surrender, self-awareness, and looseness of control. Furthermore, as distribution of agency is ontologically flat, and agnostic toward whether a node or actant is a human or non-human agent, control may also be contested between humans, extending the scope of Benford et al.'s original envisioning of their framework toward human-to-human contests of control [16].

5.2 Introducing the Quadrants

With the axes taken together, four quadrants emerge, each representing unique ways BCI systems that integrate with the user's neurophysiological processes can be experienced based on design decisions relating to neural congruence and distribution of agency. The design space helps designers to identify the quadrant for which they are designing, further guiding the design process towards attaining the desired user experiences. The following section describes the opportunities and challenges that designers may face when designing for each user experience which we encountered through the evaluation of our prototypes, summarized below in table 1. We also note that there may me more opportunities and challenges that have yet been uncovered, but nonetheless present the following as a starting point.

Table 1. Opportunities and challenges for each quadrant of the design space.

Quadrant	Opportunity	Challenge
Psychonaut	Ability to actively explore, understand, and regulate one's own mind	Providing a sufficiently deep level of exploration to keep users engaged
Swarm	Ability to actively contribute an individual subject to a gestalt object	Finding the optimal tradeoff between simplicity and complexity of symbols
Hivemind	Ability to passively enhance interpersonal connections	Managing the complex input/output interactions that arise from a highly connected network
Superintelligence	Ability to passively enhance or modulate neurocognitive processes	Dealing with the loss of habituated increased mental capacity

5.2.1 Lower Left: Psychonaut.

In the bottom left quadrant sit systems that are characterized by a low extent of neural congruence and an egocentric distribution of agency. We call this user experience "psychonaut" (greek for "sailor of the mind") in reference to "psychonautics": the method of inducing altered states of consciousness through the use of meditation, psychoactive substances or biofeedback, to explore the self and consciousness [20]. We find that through employing systems in this quadrant, users generally become psychonauts as the system facilitates the exploration of their own consciousness in the form of semiotic sensory feedback.

The majority of contemporary BCI systems find themselves in this quadrant, namely those labeled "neurofeedback" systems. An example of such a system would be the first prototype, Inter-Dream. Psychonautic systems often facilitate solitary experiences in which the user's brain is a centralized focal point of agency in the human-computer assemblage, although other people can be included in the experience, e.g., see "the moment" [140], a cinematic experience in which an audience watches a film where cuts are decided by the brain activity of a single audience member. Through these systems, the user's neurocognitive activity is interpreted by the BCI and fed back to the user symbolically, typically in the form of sensory metaphors that represent cognitive processes or affective states.

For example, Inter-Dream provides the user with visual feedback in the form of a spherical distribution of motes of light, which change in color and movement in response to the band powers of the user's power spectral density. Through this mechanism, unique visual displays are dynamically generated based on the concurrent cognitive processes of the user, communicating this back to them in VR through a kaleidoscopic display of movement and light. Similarly, in "Lucid loop" [84], lucid dreaming skills are trained through the visual metaphor of "becoming lucid". Specifically, users begin in a VR environment with blurry visuals. These visuals become clearer as the user becomes more "lucid" as indicated by their EEG, ultimately training the user to move their mind into a lucid state through the system's feedback.

In psychonaut-type experiences, users learn to connect the presented metaphorical symbols to their underlying meaning as they reflect on how they feel while the system dynamically represents their introspective journey. In doing so, an emergent lexicon is formed that users can then use to make sense of future thoughts (e.g., some users of Inter-Dream noticed they could produce specific colors by trying to move toward specific states of mind [152]). Through this affordance, users are enabled to explore their feelings in novel ways, as the system provides the ability to ask, "how do I feel about this thought?", or "how do I feel now?", with the question being met with an informational response in the form of neurofeedback. Again, this was exemplified in the study of Inter-Dream, with one participant describing how the system "*encouraged introspection, jumping to different thoughts more than usual because it made me a bit more excited about those thoughts* [...] *I was more active in them and engaged with them more quickly*" and explaining how "*I was thinking about my math assignment, and then the introspective nature changed my thoughts on the math assignment, why do I feel the way I do about that assignment? And they were generally more positive*".

Through this process, users are ultimately provided a platform through which they can explore and learn about their brain, a channel to observe and monitor their mind's reactions to certain thoughts or perceptions. This also opens the potential for users to experience their "body as play" [114]. For example, the study of Inter-Dream concluded that the affordance of playful self-exploration was instrumental in producing positive affective and arousal states indicative of healthy pre-sleep physiology [152]. We believe that the more immersive and complex the metaphor being provided, the deeper the user can sink into their introspective journey, opening more opportunities for self-discovery, self-mastery, and self-play. Notable examples push these systems toward digitally facilitated lucid dreams in which users can craft digital worlds reflective of the contents of their own mind for them to explore, for example see [8,26,78,120,135].

Self-exploration provides the user with a heightened ability to self-regulate neurocognitive processes, as they are provided with feedback on how their mental actions bring them closer or further away from their target mental state [157]. These regulatory abilities can be quite profound

[24,157], with cases demonstrating the ability to regulate oneself into altered states of consciousness, e.g., promoting pre-sleep states in Inter-Dream [152]. These regulatory abilities can be learned and strengthened with repetitive use, providing users with a translational skill that they can continue to leverage even without the use of the system [157].

The opportunity for designers creating systems in this quadrant is to help people actively explore, learn about, and understand their own minds, whilst ultimately providing them with mental self-regulatory skills that can hopefully be translated beyond the use of the system. We acknowledge that the self-regulatory abilities provided by these systems have been widely documented [157]. However, due to their historical origins in clinical neuropsychological practice, the affordances of engaging with these systems with rich sensory metaphorical symbolism have been given less attention. We, therefore, extend this prior work by contributing the knowledge that these systems provide a platform for the user to experience their body as play [114], as "players" observe and explore with their own neurocognitive processes that can be fed back to them in the form of engaging sensory metaphors (e.g., procedurally generating a game level based on their neuronal activity) allowing them to "play" their brain. This may be particularly useful in instances in which users are trying to explore sensitive or difficult thoughts or feelings, perhaps providing a means for this challenge to be fun, less daunting, or empowering, making these systems possibly even better suited for psychotherapy than former clinical incarnations.

One challenge is the design of a suitably "deep" level of exploration with regard to the ways in which the system can metaphorically communicate the user's neurocognitive processes. For example, while the commonly employed simple visual metaphors of colors or symbolic objects [136] are a good starting point for the user to familiarize themselves with their own neurocognitive processes, they may quickly exhaust the educational and exploratory affordances offered by this medium over multiple uses. Future work may consider the generation of more complex, multisensory metaphorical representations such as narratives or characters, or open-ended environments to keep exploring. An example from science fiction of such a system taken to its extreme would be the "Aleph" from William Gibson's novel "Mona Lisa Overdrive" [54], a BCI system in which the user's mind projects an artificial reality in which they can learn, grow, and act independently.

5.2.2 Lower Right: Swarm.

In the lower right quadrant sit systems that are characterized by low neural congruence and an allocentric distribution of agency. We call the user experience "swarm", as the experience and its tendency to form emergent properties are analogous to the process of semiochemical signaling that many eusocial swarming insects are capable of. One example of this is ant pheromone trails, which have been described as a set of "chemical symbols" [65] that ants use to autonomically signal information to other members of its colony in reaction to that ant's experience of the world. When the colony collectively contributes to this signaling behavior, this leads to self-organizing patterns (such as trails, rafts, structures made of bodies), ultimately forming a set of chemical symbols and interpersonal interactions that provide a gestalt "body" for the embodiment of information about the colony and the summed experiences of its members [33,56,168].

Systems that sense and symbolically represent brain activity as a sensory metaphor that can interact with the environment or brain activity representations of other users find themselves in this category. An example of such a system would be the second prototype, Neo-Noumena, as the system utilizes affectively generated fractals that interact with the physical environment (e.g., avoid and land on surfaces) as well as the fractals generated by other users (e.g., they form a single swarm when both users are experiencing the same emotion). Another example is the game "Socio-pathways" [122] in which users (usually five at a time) are represented on a screen as dots. As one user's brain activity becomes more synchronous with another, their dots move together, with the goal of the game being the assimilation of all dots into a single ball. This then gives rise to emergent behaviors in the players as they attempt to synchronize with each other, e.g., such as doing the same repetitive movement.

In these examples, the system offers a shared experience in which each individual contributes to the pooled symbolic representations of brain data, in turn altering the gestalt interpretation of that set of data. As a result, the meaning of an individual's brain data evolves when interpreted alongside the brain data of others, as opposed to if it was presented in isolation. Furthermore, such systems can allow for representations of brain data to dynamically interact with each other to further provide information regarding the gestalt of the group. For example, when users of Neo-Noumena were experiencing the same emotion, their procedurally generated fractals would join to create a single flock, signifying affective unity. Similarly, in "Socio-pathways" the dots representing the brains of the users would join as they became more synchronous, signifying a convergence of mental state. In both these examples, the system provides representations of brain data that can be both interpreted to inform one about an individual or interpreted to understand the group dynamic as a whole.

Taken together, these systems allow users to collectively contribute to a gestalt of brain data that can interact with itself and combine to form new emergent meanings. This ultimately creates a "semiosphere" of brain data, with semiosphere being defined by Lotman as "the sphere of semiosis in which sign processes operate in the set of all interconnected Umwelten" (from the German Umwelt meaning "environment" or "surroundings") [100]. Specifically, Lotman's Umwelt theory states that the mind and the world are inseparable, because it is the mind that interprets the world for the individual. Consequently, the Umwelten of each individual differ due to the uniqueness in the biology, history, and lived experience of each individual. When two Umwelten interact, this creates a semiosphere. Thus, for swarm systems, the contribution of one's Umwelt through their brain data ultimately generates a semiosphere of neurocognitive information in which brain data interacts to generate a narrative of the group's Umwelten.

This can be further unpacked through the Körper - Leib and Erfahrung - Erlebnis distinctions given by Mueller et al. [113]. Here, the authors use the German lexicon to describe the user experiences afforded by bodily systems. Specifically, they evoke Körper to refer to the objectified body that performs its individual functions like maintaining homeostasis and sensing the environment but holds no lived experience. In contrast, Leib is used in reference to the subjective body, imbued with an ontological sense of being that is experienced (i.e., having lived experience). In further unpacking the experiences of the Leib, we can evoke Erlebnis to signify declarative or procedural knowledge which can be gained and consciously processed; and Erfahrung to describe pre-reflective knowledge or lived experience, which only becomes accessible in the process of Erlebnis. Using this lexicon, we can then describe the user experience of swarm systems by stating that through using these systems, the neurocognitive data, produced by the Leib of the group is given a collective Körper, embodied by the gestalt sum of the group's neurogenerated semiosphere. In turn, this translates the Erlebnis of the group into a Körper that provides group Erfahrung which can be accessed by the observers or the group itself.

With the above considered, we see that the design opportunity presented by swarm systems is the enabling of individual agencies to contribute their lived experience to the generation of a gestalt body that can provide information about the emergent group as a whole. In turn, designers can use these resultant experiences to engage users and observers to cognitively appraise and extract information about how a group "feels" as if it is a "superorganism" (a term used to describe how ants and other eusocial species act together as a single body). Furthermore, these systems still retain the opportunity to allow for further investigation of the feelings of individuals within the group if they so wish. From the perspective of a group member, this can allow the individual to ask questions such as "how do I feel", while concurrently enabling the inquiry of "how do we feel?" and being able to receive an Erfahrung (objective) answer to both these Erlebnis (subjective) questions. This provides an additional dimension in engaging with a group, as in allowing users to perceive and assess how it "feels" they have access to information we might not otherwise have.

A key challenge designers might face when designing for this quadrant is how to appropriately design semiotic signals that balance complexity, simplicity, and informativeness in representing the gestalt. Specifically, more complex generations of symbols to represent neurocognitive processes can provide the recipient with more details about the feelings that generated them. However, as complexity increases, so too does the cognitive effort to interpret them. This is compounded in swarm systems as each user is contributing their own feelings toward the semiosphere. While designers could aggregate the representations of all users into a single representation, this would disable any ability to make inferences about specific individuals in the group. Instead, designers should consider how to communicate the group gestalt, while still facilitating the opportunity to interpret neurocognitive activity on an individual basis as well. For example, Neo-Noumena dealt with this using boid behavior (the logic underlying the behavior of flocking birds, schooling fish and swarming insects [64]), where signifiers of similar emotions flocked together across users, but contrasting emotions avoided each other. While this worked with two users, it is anticipated that this may not translate as well for larger user bases.

5.2.3 Upper Right: Hivemind.

In the upper right quadrant sit systems that are characterized by a high extent of neural congruence and an allocentric distribution of agency. We call the associated user experience "hivemind", as the experience is likened to being part of a decentralized telepathic collective consciousness common in science fiction literature [30,92,127,137], such as "the Borg" from the television series "Star Trek" [125] - cybernetic organisms whose minds are linked to form a gestalt consciousness called "the Collective".

Systems in the hivemind quadrant often harness brain sensing and stimulation technologies to facilitate brain-to-brain neural entrainment or amplify inter-brain synchrony. An example of such a system is the third case study, "PsiNet". Another example is the performative art installation titled "Hivemind" [122], in which two performers have the oscillatory electrical activity of their brain converted to strobing light, which in turn entrains neural oscillations in the opposite performer. This process of oscillatory strobing and neural entrainment is continued in a turn-taking manner (like a conversation) until the neural oscillations of the performers synchronize, ultimately achieving inter-brain synchrony localized in the visual cortex.

The users of such systems form a decentralized network of minds, with each user being a locus of agency that contributes democratically to the gestalt brain activity of all users in the network. This is ultimately experienced by users as "phenomenological unity", a notion defined by Danaher and Peterson as "*when there is some unity of phenomenological experience across individuals, i.e. where in some sense they are seeing, feeling, hearing, touching, or tasting the same thing*" [30]. This was demonstrated in the study of PsiNet, where one participant reported "*I'd feel like I just had heaps of caffeine or coffee or energy drinks or something*" as a result of other users concentrating or being engaged in work. Similarly, when one participant was rationalizing why another participant may have been stimulated in the way they did, they stated: "*I think maybe if someone was quite agitated or aggravated by the work that they were doing or whatever the topic was, that might explain why our housemate got a phosphene*". These examples demonstrate how Hivemind experiences involve an interpersonal integration of the neurocognitive processes through the sensing and distributed stimulation of brain activity throughout the network. This ultimately leads to a unity of phenomenological experience in which users feel similarly to other group members.

As the phenomenological unity of Hivemind experiences is achieved through neurally congruent signaling, the similarity in how the group "feels" is experienced implicitly and passively, as users are not required to divert their attention to the interpretation of symbols to receive this feeling. For example, participants of PsiNet reported a "*feeling of connection and being able to affect each other without having to really act and do something*" and that "*it automatically sent stuff out, picking up on your emotions and brain states and sending that out for you*". As such, users experience the output of other brains directly as if it were their own conscious experience, exemplified in the study of PsiNet where participants stated that "*you kind of don't know why you are doing things or to what degree you're doing things or influencing each other. You don't really know where things are coming from*".

This ambiguity ultimately allows the output of other brains to be experienced with a high sense of ownership, meaning these individuals feel their cognitive experience to be their own (i.e., generated by their brains' own endogenous neurocognitive processes). As users can find it difficult to separate their own unique cognitions from the collective cognitions of the group, this suggests users can at times experience exogenous feelings which come from the stimulation of the system as their own naturally occurring endogenous feelings. This is further benefited by the notion that in a Hivemind experience, users feel that agency is homogeneously distributed across all users, as each brain has an equal ability to change the functioning of the system. This allows Hivemind systems to facilitate experiences of collective agency, characterized by the feeling of "we did that" rather than "I did that". An example of this can be demonstrated when PsiNet participants were questioned about who had control in the network, responding "*it was with us*"; "*it seemed pretty equally distributed*"; and "*we had control via our inputs and how we responded to the outputs of the system as well [...] so it was everyone*".

The design opportunity provided by Hivemind systems is for designers to facilitate experiences of phenomenological unity to amplify interpersonal connections and neurocognitive cohesion within a group. Given that humans are highly social, this could provide benefits in many aspects of life. It has been demonstrated that inter-brain synchrony is much greater when measured between people with close relationships, such as family members and romantic partners [28,71,71,83,83,154,174]. This suggests that Hivemind systems could potentially amplify otherwise weak social connections (e.g., co-workers) toward a more empathetic and familiar standing that would ultimately generate a sense of comradery. This comes with functional and performative benefits too, as higher levels of interbrain synchrony have been demonstrated to assist in improved group performance, decision making, cohesion, agreeableness, and empathy [28,71,71,83,83,154,174]))..

The main design challenge of the Hivemind quadrant is the logistical complexity of identifying the best information exchange protocol for the system. In simple terms, this is the issue of knowing when to send what and to who. Based on input x from user a, which other users should receive output y and when? Should all inputs and outputs be averaged? Or considered on a case-by-case basis? This was perhaps the biggest design challenge in the design of PsiNet, and we answered it by outsourcing the solution to a reinforcement learning algorithm motivated to increase the inter-brain synchrony of the group. While this method worked, we imagine future work would benefit from exploring alternative solutions to this issue. This challenge also raises ethical questions. What if user x does not want to receive a specific input, or does not want to feel how a specific other group member is feeling? What if the collective's phenomenological unity is moving toward a direction one user is uncomfortable with? Should we exclude people with psychopathologies from the Hivemind to prevent the spread of maladaptive cognitions to others?

5.2.4 Upper Left: Superhumachine.

In the upper left quadrant sit systems that are characterized by high neural congruence and an egocentric distribution of agency. We call the associated user experience "Superhumachine", referring to Mann's description of the humachine as a closed-loop feedback system between human and machine from which a symbiotic "cyborg" emerges, which has superhuman intelligence [105]. In this work, however, we extend the definition to include humachine systems that yield any superhuman ability, intelligence or otherwise, which also do not exclusively have to be of positive benefit for the human component of the feedback loop. One example of such a system is Machine_in_the_middle [34], a system that classifies the concurrent emotion of the user through EEG, and uses EMS to force the facial expression of the user to match that emotional classification. As consequence of the system's design, the humanchine closed-loop feedback system forms a kind of symbiosis which is parasitic, rather than mutualistic, forcing the human to sacrifice their ability of expressive deception and affective privacy in order for the machine to achieve its purpose in expressing emotion. The result is a

Superhumachine assemblage that has enhanced abilities of emotion expression (in contrast to other affective systems) through borrowing the user's body as a display, at the cost of the expressive agency of the human. This raises the question as to whether such as relationship is inducive to being a cyborg or not, given that the "vironment" (with vironment being Mann's articulation of the interface between the users inner body and the outside world) is no longer an extension of the user's agency, but rather the user is an extension of the viornment's agency, similar to Mann's question of whether a slave galley - a ship powered by slave labor - can be considered a cyborg [105].

Systems that sense neurocognitive processes and then reflexively entrain desired neural activity through stimulation find themselves in this quadrant. These systems provide an experience in which the user's neurocognitive processes are passively modified by the system. This modulation may be imperceptible as users experience their exogenously altered neurocognitive processes as their brain's own endogenous activity, providing a strong sense of ownership in the user over the changes the system makes to their brain (such as in the case of PsiNet). This sense of ownership is closely tied with the sense of agency, and in this instance specifically relates to the degree in which an individual feels their cognitions are their own. This is mostly completed through brain stimulation but can also include sensory stimuli that can cause neural entrainment (e.g., slowly blowing air through the nasal passage can slow cortical oscillations, leading to altered states of consciousness [133]). We also note, however, that this is not the only type of experience afforded by systems in this quadrant, and that the locus of agency and ownership can be flipped to be possessed by the machine rather than the human - as demonstrated by "Machine_in_the_middle". Furthermore, this example also demonstrates that if the machine is the source of agency, the actuation of the human body, while still passive, is no longer required to be imperceptible to the human, as the human's sense of agency is sacrificed to the functioning of the machine. We note that the experiences of superhumachine systems are typically solitary experiences, although they could also be designed to include others (e.g., a system in which one person's brain controls the brain activity of many, yet the many have no control over the system).

Beyond Machine_in_the_middle, contemporary superhumachine systems typically exist as medical devices designed to treat clinical populations. These systems are often referred to as "brain-pacemakers" [166], an umbrella term that encompasses devices that sense neural activity and stimulate specific neural structures to correct pathological neural activity. Some example use cases are the treatment of tremors in Parkinson's patients [102,111], and the treatment of seizures in epilepsy patients [184]. In translating this method toward the stimulation of key neural structures in healthy brains, these systems could be designed to not only maintain the user's homeostatic neurocognitive functions but modulate or even enhance them. An example of such a system would be one that notices a user's brain activity that the user intends to move, and thus preemptively stimulates the motor cortex, allowing to perform that movement quicker and with greater control (similar to studies employing preemptive muscle stimulation to increase reaction time [79], or having your brain connected to an ebike, helping you slow quicker in the event of danger [4]). Similarly, a user may be performing a cognitively intensive task and the system might detect the user is concentrating. In turn, the system stimulates the frontal cortex to give an intellectual boost.

As demonstrated in studies of long-term use of neural stimulation, through regular use these systems may induce long lasting effects on the synaptic plasticity of the individual, thereby quickening the rate they acquire new skills [77,98,160]. However, as the user is not involved in this process, this is not an ability they themselves can regulate (unless of course the designer has given them such control over the system's functions). Furthermore, the augmentation of the individual is entirely dependent on the system, as users are not taught how to regulate cognitive activity though system use due to its regulation being a passive ongoing process. As such, if the system were to be removed, the benefits it provides would slowly fade away, rendering the user lesser without the system in contrast to with the system. This contrasts with psychonautic systems, in which the system teaches the user cognitive regulation skills they can then perform without the system.

The opportunity provided to designers creating systems in this quadrant is to help users extend or enhance their neurocognitive capabilities. With the potential for these technologies to become not only wearable, but implantable in the very near future, this implication goes beyond simply providing users with empowering tools. Rather, users are provided with a potentially permanent passive enhancement to abilities and skills such as learning, reaction times, attention, information processing, and memory for as long as they use the system [77,98,160]. While this has obvious benefits for clinical applications such as the treatment of epilepsy, dementia, and Parkinson's disease, these systems can go beyond therapy by enabling healthy individuals to passively become their better selves with little to no training, all the while perceiving this enhancement to be their own endogenous abilities.

The challenge faced by superhumachine systems is that the extended abilities provided by such systems might become part of the user's perceived self. As such, if the system is removed, the abilities it provided will eventually subside. Consequently, users may feel lesser, or no longer feel like themselves with the system's absence. The design challenge in this quadrant is similar to the design challenges that face the "super body" user experience in Mueller et al.'s "bodily integration framework" [116].

5.3 Applying the Brain-Computer Integration Framework

This section describes how the brain-computer integration framework can be applied to describing and modifying the three prototypes presented in this work to demonstrate how the framework can be used in design practice. The three systems support a variety of application domains and employ different technologies (all the while maintaining the commonality of a focus on BCI as part of the system) (summarized in table 2). This demonstrates the general applicability of the framework to most types of BCI systems.

Table 2. The three systems and their characteristics

System	Technology	Application	Aim
Inter-Dream	BCI + VR	Sleep	Facilitate healthy pre-sleep
Neo-Noumena	BCI + AR	Communication	Augment emotion communication
PsiNet	BCI + tES	Synchrony	Amplify inter-brain synchrony

5.3.1 Design 1 - Inter-Dream.

Inter-Dream is now examined through the brain-computer integration framework to clarify the advantages of the design while also articulating opportunities to extend Inter-Dream.

Inter-Dream is situated in the Psychonaut quadrant of the design space. Inter-Dream allows users to experience their own brain activity through a hermeneutic relation as semiotic information. This provides the user with objective feedback about their subjective states that they can attenuate to in order to infer knowledge about themselves they would otherwise not have access to. Furthermore, this feedback dynamically changes as their subjective state changes in response to their appraisals of the semiotic representations of their brain activity, creating an ever-shifting feedback loop. This puts the user in a position in which they can objectively explore and learn about their own subjectivity, and even regulate their brain activity if they choose to do so. Furthermore, the Inter-Dream user experience is highly egocentric. The user is almost completely cut off from the outside world: VR obscuring vision beyond their neurofeedback, auditory sensation occupied by the ambient score, and even proprioception being obscured to some degree by the weightless sensation provided by the bed. The only causal influence on the system other than the user's brain is the occasional shifting of the bed's position by the artists. Interestingly, participants found that elements of the experience that were under control from external influences to be intrusive to the experience overall (specifically the bed and the score), which at the time led to infer that all dynamic elements of the experience should be designed to be neuro-responsive.

In using the brain-computer integration framework, one can envision moving Inter-Dream from the Psychonaut quadrant to the swarm quadrant, where the system has a more allocentric distribution of agency. The conceptualization of this movement allowed to develop Inter-Dream's follow-up project, Neo-Noumena, which takes the artistic generation of semiotic information from brain activity and turns this outward to other users through AR. As such, rather than being disconnected from outside interference like Inter-Dream, Neo-Noumena was more open to situational influences, with the digital representation of brain activity being accessed in and interacting with the material world. This allowed users to access gestalt information about the group, the environment, and the influence of the environment on their group. While Neo-Noumena's application domain was emotion communication, we can imagine an allocentric Inter-Dream in which the gestalt brain activity of themselves, and perhaps a partner they are sharing the bed with, is visualized and projected onto the roof. This would allow them to interpret their joint brain activity as they fall asleep hermeneutically, while also being situated enough to interpret how environmental factors might interact with this physiological process (e.g., a notification on their phone triggering a beeping noise might be followed by a change in the visualization).

Alternatively, one can envision Inter-Dream being designed for the superintelligence quadrant. In keeping with the application domain of sleep, an example of a superintelligence-type Inter-Dream version might take the form of a wearable BCI system. This wearable would detect if the user was becoming sleepy based on an increase in delta wave amplitude. In detecting this, the system would then employ some form of stimulation to increase the entrainment of slow wave brain oscillations, thereby making the user even more sleepy, helping them fall asleep quicker. This could be done through a neuromodulatory technology such as tACS, or even through mechanically stimulating the olfactory epithelium with slow bursts of air [133]. Alternatively, the system might also be able to tell if the user does not want to go to sleep (e.g., there is a growing delta wave amplitude, but the user's brain activity also demonstrates high levels of cognitive load, suggesting they are working). In such an event, the system might stimulate their frontal lobe with a high frequency stimulation to help them stay more alert.

5.3.2 Design 1 - Neo-Noumena.

Neo-Noumena is now examined through the brain-computer integration framework to clarify the advantages of the design while also articulating opportunities to extend Neo-Noumena.

Neo-Noumena sits in the swarm quadrant of the framework, yet its degree of allocentricity oscillates depending on the actions of the user. For example, Neo-Noumena could be used individually, with the system providing a situated visualization of the emotional state. However, as the visualization is situated, interacting with the environment to a similar degree as it interacts or is changed by its user, the system is still allocentric enough to not be considered psychonautic (or perhaps just on the border between the two). However, when another user enters the experience, the distribution of agency shifts greatly toward the allocentric end of the spectrum, as the visualizations now not only interact with the environment but interact with each other and the perceptions of the group witnessing its gestalt brain activity. This provides users with the opportunity to interpret information about the group that is not readily accessible when the semiosphere is populated by a single individual (with semiosphere being an abstract epiphenomenal space in which physical, energetic and material phenomena interact as informational signals).

In using the brain-computer integration framework, one can envision moving Neo-Noumena from the swarm quadrant to the hivemind quadrant, where the system transmits information engrammically rather than semiotically, allowing for a higher degree of neural congruence between users in the group. The conceptualization of this movement allowed to develop Neo-Noumena’s follow up project, PsiNet, which uses neurostimulation to synchronize the brain activity of users in the group, rather than generating visualizations to communicate activity. The original design of Neo-Noumena afforded a hermeneutic relation with the system, in which users had to actively engage in the cognitive task of attenuating to semiotic information, and then applying their cognitive schemas to extract meaning from it and make sense of it, allowing to appraise it objectively. However, in PsiNet, changing the information from semiotic to engrammic afforded a fusion relation, in which users no longer actively engaged in the extraction and interpretation of information objectively, but rather subjectively and passively experienced the brain activity of other users with a high sense of ownership, as if it were their own brain activity.

Alternatively, we can envision moving the system back toward the psychonaut quadrant, albeit keeping the application domain of emotion communication. Such a system might take the form of a virtual garden or ecosystem, which represents the user’s emotions semiotically in the form of parameters within that ecosystem. As the user experiences certain emotions, elements in the ecosystem might change (e.g., more sun when they are happy, rain when they are sad, increased predation when angry, etc.). Thus, if the user maintains a healthy emotional balance, they would expect to see a healthy and thriving ecosystem. They may also be able to share this environment with others, allowing them to explore that user's emotional state as a visitor, but not change it (thus keeping it in the psychonaut quadrant).

5.3.3 Design 3 - PsiNet.

PsiNet sits in the hivemind quadrant of the framework. Agency is distributed allocentrically throughout the group, with each group member having an equal opportunity to influence the brain activity of the group. Furthermore, due to the absence of centralization, the system is scalable, with new users being able to leave and join the group without disrupting equilibrium in the distribution of agency. Furthermore, as the system works passively (i.e., the user is not required to expend cognitive effort or attention to receive information from it), users are free to engage with the environment, adding another channel of influence over the group's collective brain activity. The system also exhibits a high degree of neural congruence, with an oscillation pattern in one person's brain leading to the actuation of that same oscillation pattern in another person's brain. As this information is transmitted engramically, it produces a fusion relation between users, ultimately allowing them to experience each other's brain activity subjectively with a high sense of ownership.

The design space can now be used to help envision alternative versions of the system. For example, we can envision an alteration placing the system in the superintelligence quadrant, in which a single master user has their brain activity sensed by an EEG, and all other users are synchronized to that individual via tES. In turn, the agency of the system is centralized in the master user, being the only one able to have genuine cognitive experiences. In contrast, the brains of other users will be enslaved to feel what the master user is feeling, in a sense becoming "possessed" by the master user. Frighteningly, given that the insights from the study of PsiNet suggest that individuals experience altered brain activity with a high sense of ownership, users with enslaved brains might not even realize they are being manipulated (besides the obvious fact that they are wearing a mind-altering wearable). This would be particularly problematic in the cases in which the system's neuromodulatory capabilities were obfuscated by being incorporated invisibly into a hat or bike helmet for example. Furthermore, with sufficiently advanced brain stimulation, it is possible that such systems might result in the master user imprinting their "self" onto the enslaved users, with the enslaved users experiencing a high sense of ownership to the master's brain activity wherein they ultimately believe they are them. This would in effect clone the master's consciousness, making copies of themselves, similar to agent Smith in the Matrix movie trilogy.

Alternatively, there are several existing examples of systems which represent what PsiNet might be like after being moved toward the swarm quadrant. One of these is the game "SocioPathways" [122], which we described earlier in section 2.1.2.

6 DESIGN STRATEGIES

While the framework can be used to descriptively provide a taxonomy of the possible user experiences afforded by brain-computer integration systems, it must also be considered how the framework can be used prescriptively to elucidate how designers can evoke these experiences. Therefore, we now present a set of strategies that designers might benefit from when developing brain-computer integration systems. These strategies are informed by our own experience in designing, developing, deploying, and trialing brain-computer integration systems. Furthermore, these strategies are also grounded in our own studies evaluating these systems. Considering that these design strategies have been synthesized through our interpretation of the results yielded by the study of our prototype systems, the mapping of the brain-computer integration design space, and through our craft knowledge gained through the act of developing these systems, we further stress that these do not represent an exhaustive completed set of strategies fully dictating the design of brain-computer integration systems. Rather, we suggest that these be seen as an initial set of strategies to guide further investigation into the design of brain-computer integration whilst also providing actionable advice for BCI design practitioners, and we expect with further research we will come to a more complete and concrete articulation of brain-computer integration design strategies. Taken together, our research insights and craft knowledge have been synthesized into the following strategies (table 3). Three strategies focus on neural congruence, an additional three on distribution of agency, and an additional strategy concerned with the design of BCI integration systems in a more general light.

Table 3. Seven Design Strategies

Dimension	Title	Strategy
Neural Congruence	Exploration	Consider procedural generation to facilitate exploration
	Continuity	Consider continuous metrics for more nuanced output
	Perceptual transparency	Consider perceptual transparency to support high neural congruence
Distribution of Agency	Centrality	Consider maximizing centrality for egocentric experiences
	Spatiotemporality	Consider how data is actualized spatiotemporally to better facilitate the intended distribution of agency
	Social Context	Consider how social context can enhance playful BCI experiences in games and play
Integrated BCI in General	Learning	Consider fostering ongoing integration through learning

6.1 Exploration: Consider Procedural Generation to Facilitate Exploration

BCIs provide users with a powerful means to learn about themselves and develop a more nuanced understanding of their brain activity, and the complex thoughts and feelings it drives. Semiotic encodings of brain activity fed back to the user provide a medium to explore the mind through informative or metaphorical codings, and the stories these codings generate through the brain's dynamically reactive and ephemeral processes. However, as these representations, metaphors, and narratives typically require a designer to design them, the array of forms these representations can take are limited to how many hours designers are able to spend creating content for each given state.

This in turn either limits the permutations of outputs a system is capable of generating or leads to designers creating very simple representations in order to communicate varied information efficiently (e.g., associating emotion with color or using graphs and charts). As a result, the explorative affordances of these systems can often suffer from a deficiency in depth and breadth of explorable content, limiting the user's engagement and learning potential.

To avoid this limitation, designers should consider incorporating procedural generation in the design of BCI output to facilitate exploration. Procedural generation is the method of creating digital content algorithmically as opposed to manually, typically involving the use of mathematical parameters and some degree of stochasticity to guide the modification of designer-generated content into entirely new and unexpected forms [45,57,58,138,139,156]. This is a common strategy in video games in which exploration is a core gameplay mechanic, as new and varied content invites exploration from users, procedural generation provides a breadth of experience far more expansive than what can be hand-crafted by a designer [73,139,156]. For example, the game "No Man's Sky" places players in a universe containing 18 quintillion fully explorable planets which are generated as the player discovers them, each with their own unique terrain, weather, flora, fauna, and even alien civilizations for the player to explore [165]. Taking inspiration from such applications of procedural generation, future BCI designs could facilitate deep self-exploration through the generation of detailed and expansive content generated by dynamic brain-data-fed algorithms.

However, procedural generation does not necessarily require the complexity of a universe simulator to benefit the design of BCI systems. For example, consider Neo-Noumena, whose application domain of emotion communication imposes the tradeoff of a need for complexity to adequately express the user's emotion, while also requiring simplicity enough for the recipient to effectively interpret it without overloading their senses. Here, rather than generating universes, procedural generation was employed to subtly assist the semiosis of emotion between individuals. For example, the procedurally generated behavior was given to the fractals to give the fractals an added extent of emotional expressiveness through their movement. Specifically, the fractals were programmed with "boids" behavior [64] that procedurally generated movement in a group of agents ultimately simulating flocking behavior of birds. Here, the brain activity of the user was fed into the parameters of the boids in order to change the fractals' movement behavior based on the user's emotional states. These movement patterns were not manually animated, but rather procedurally generated from user's brain activity. Similarly, the fractals representative of user emotions were generated by information extracted from the user's brain activity, in turn representing the user's emotion through the symmetry and geometry of the fractal. Thus, it is demonstrated that brain-driven procedural generation need not be limited to the creation of expansive vast universes for the individual to explore, but also in the creation of simple but unique semiotic signifiers. These are examples of procedural generation that can serve as a method to drive the exploration of both the self and others, and as such we suggest designers consider procedural content generation to facilitate exploration.

6.2 Continuity: Consider Continuous Metrics for More Nuanced Output

Coding brain activity into categorical classifications (e.g., designating a given set of brain data as “sad”, “relaxed”, “awake”, etc.) comes with some advantages when designing a BCI system. Categorical codings allow BCI designers to develop a fixed amount of discrete and hence predictable outcomes, making it relatively easy to curate the resulting experience of every system state permutation. For users, this comes with the added benefit that the output of the system is easily interpretable and associable with single word categories that can compress a lot of information into a single code. However, there are also significant tradeoffs. We found through the studies of our systems that participants interpreted categorical classifications as authoritative and objectively correct. For example, even though Neo-Noumena’s classification accuracy was around 56%, participants always interpreted the system’s output to be the objective truth, even rationalizing classifications they found inconsistent with how they were feeling by reasoning that it was they who were wrong, that they were perhaps not in touch with their inner selves, and that the system was correct.

This aligns with the fact that others within HCI have stressed the importance of refraining from designing categorical feedback for biofeedback systems due to their oversimplification, arguing that it may lead to the “calculability of human subjectivity” quantizing the individual into information for psychographic models through which individuals can be digitally categorized against their best interests [161,162]. Considering this, it has been suggested that rather than designing for discretely classified presentations of BCI activity, designers should instead consider ambiguous representations that allow the user to form their own meaning [69,70]. However, the proponents of this argument push this direction perhaps too far in suggesting that it is incorrect to consider psychological phenomena and the physiological mechanisms underlying it stateful. The postulation of the denial of states in biological systems runs contrary to the contemporary understanding of human physiology [74,129]. For example, recent discoveries in neuroscience point to clear states, boundaries, and transitory tipping points in between, which characterize the dynamics of networks of brain structures and their functions [48,95,110]. Proponents against a stateful approach to physiological activity sometimes also advocate against the computational processing of biodata, suggesting this should be left to the human decoder [70]. This approach is particularly non-progressive in the context of BCI, where it is often the case that much of the informative content of a given physiological signal is embedded in its frequency component, or in some other extra dimensional geometry of the signal that is not accessible in its time series form [173]. Thus, such an approach would limit BCI to pre-1960’s capabilities, where the height of neurotechnology were machines that spat out batches of paper with scribbled lines which took teams of trained neuroscientists weeks to decode by visual inspection [155].

With these points considered, we suggest designers adopt a more nuanced approach to dealing with brain state classification, rather than refraining from classification all together. Specifically, we encourage designers to consider that the brain is a highly dynamic networked system, and that the recognition of any given state is highly dependent on the frame of reference and the question being asked. In practice, we suggest that designers consider translating categorical classifications to continuous metric predictions (a brain-derived metric that is represented as a continuous variable rather than a categorical variable). Rather than classifying if someone was “sad” or “happy”, the system could provide a normalized dynamic happiness quotient that rises, and falls, based on the valence of the user (rather than switching a binary category). Similarly, in the case of a system designed to interpret someone's state of consciousness, it may be more helpful to derive a continuous metric describing their state of consciousness on some sort of scale (e.g., like using the metric of integrated information "phi" [170]) and using that to drive representation generation or neurostimulation, rather than using the outputs of "awake" or "asleep". Such an approach would increase the ambiguity of the output, whilst also increasing its informativeness, thereby avoiding the absolutism, oversimplification and technological determinism that comes with a categorical approach. Thus, to facilitate more nuanced output in BCI integration systems, we suggest designers consider adopting continuous metrics.

6.3 Perceptual Transparency: Consider Perceptual Transparency to Support High Neural Congruence

Low neural congruence does indeed have advantages. Abstracted semiotic representations of brain data promote hermeneutic human-technology relations in which the user can access subjective experience as objective information. This allows users to extract easily interpretable and actional information from coded brain data. However, this comes with the cost that using such a system requires the user's attentional resources, adding to the ever-growing ecosystem of displays, apps, and notifications that compete for our attention. This is particularly the case for semiotic information communicated visually, as vision is a channel already heavily occupied through our interactions with the world [7,12,13]. Other HCI works suggest that people engage in bodily activities such as sports and physical exercise to unplug from or escape the "always on" and constant connectedness afforded by contemporary pervasive media [119]. However, as integration systems lend themselves to being designed to always be on the user [116], integration BCI's with low neural congruence would make this escape impossible, as the body itself becomes a channel for pervasive media to manifest in the user's life.

In contrast, high neural congruency affords the design of BCI systems that allow for unplugging, whilst still being connected, as brain-computer technology integrates into the brain's pre-reflective endogenous processes, freeing up attentional bandwidth and facilitate fusion human-technology relations. To do this, we suggest considering designing interfaces with "perceptual transparency" [117]. This involves the communication of information through artificial sensory experiences [117], borrowing parts of the user's body for input and output [99], and exploiting psychological phenomena such as intentional binding – strategically timing the reaction of the system to a user's biophysical output to create the feeling the action was congruent with their intention [31], to ultimately intertwine the user and the technology for seamless bilateral information exchange without the necessity for attenuating to the system's output. Ultimately, the use of a BCI system with high neural congruence should feel as if the user is not using technology at all, but rather performing mundane bodily processes that are as unconscious as, for example, breathing and digestion. Such processes do not sit at the forefront of perception, competing for the user's attention, but rather are so integrated with the body that they are in essence part of the process of life.

One example of this in action are people with magnetic implants, who's brains have adapted to perceive magnetic fields as though it is an endogenic ability rather than a technologically afforded novelty [36]. Studies of the nervous systems of these individuals demonstrate that the body physically incorporates the input of these implants directly into its self-schema, undergoing synaptogenesis and innervation to accommodate for this new sense [36,164]. Another example is the work of neuroscientist David Eagleman, who designed a haptic vest that leverages the largely unused real estate of the user's back to communicate auditory information through haptic vibration, allowing deaf people to understand speech [38]. Similarly, the cyborg Neil Harbisson is implanted with an artificial sensory device that allows him to perceive color through intracranial neurostimulation even though he is color blind [62]. Neurological studies have demonstrated that his brain has learned to integrate this information into his physiological processes as if this were the endogenous input of color information from auditory receptors, which phenomenologically allows Harbisson to experience color as sound, rather than vibration [76]. Therefore, taken together, we suggest designers of integrated BCIs striving for a high degree of neural congruence consider perceptual transparency.

6.4 Centrality: Consider Maximizing Centrality for Egocentric Experiences

Moving a BCI system toward a higher degree of egocentricity is not solely a matter of designing solitary experiences or single user systems. While this is indeed a factor which may influence how egocentric a given BCI system is, this is not enough on its own. Rather, designers should consider how strongly connected elements of the system are to the user intended to be the "ego" in the egocentric experience. That is, designers should consider maximizing centrality when designing egocentric systems. To do this, designers should strive to minimize the influence of externalities, confounding, or extraneous variables on the processes of the system, especially in the coding and generation of the system's output. At the same time, designers should also strive to make all other components of the system highly reactive to the brain activity of the "important node" of the network - the central user. This should be apparent to the user or observers to the degree in which the system obviously fails to function if it is not being fed the brain activity of the central user.

In the study of Inter-Dream, participants reported feeling that elements of the experience that did not respond to brain activity detracted from the experience, specifically noting that they found the movement of the bed and the music discordant or intrusive as those elements commonly stole their attention while they puzzled over whether they could control these elements or not. At the same time, the user experience of Inter-Dream was designed to draw attention to the neuroreponsivity of the system through the careful design of the user's journey in interacting with it. When participants were introduced to Inter-Dream, the system was running, albeit in a static state due to the absence of input. The visualization was still and lifeless, an unmoving sphere. However, as soon as the EEG was fitted to the participant, the visualizations came to life instantly and explosively, often followed by an exclamation of excitement from the participant. Here, the neuroresponsivity of the system was made obvious though demonstration of how much the presence of the participant's brain activity influenced the system.

Initially, these findings from Inter-Dream led to consider that it was of utmost importance for BCI systems to provide users with a high sense of individual control, with demonstrable neuroreactivity and a high degree of responsivity. However, in later studies, we found this property to be increasingly less important the more allocentric the distribution of agency was. For instance, during the development of Neo-Noumena, we encountered a bug in which the fractals swarms would leave their users and instead join together in the middle of the room when a pair of users were experiencing the same emotion. We opted to keep this as a feature, appreciating the visual metaphor of unity and oneness the display communicated, which participants also found equally appropriate despite the lack of control over the flocks that came with it. Similarly, individual control was further relinquished in PsiNet: control over the analysis of inputs and choice of output was ultimately given to the reinforcement learning agent managing the group's stimulations. This dynamic ultimately allowed participants to feel like each had an equal contribution of agency in the group, rather than a sense of unease or discordance, as we would have originally assumed from the findings of Inter-Dream alone, demonstrating that emphasizing centrality becomes less desirable as the system becomes increasingly allocentric. Thus, we suggest that designers consider maximizing centrality for egocentric experiences.

6.5 Spatiotemporality: Consider How Data is Actualized Spatiotemporally to Better Facilitate the Intended Distribution of Agency

Regardless of the distribution of agency in a BCI integration system, the spatiotemporal actualization of brain data - how information changes (or does not) over time and how it is manifested in the world - was found to be consistently important to how users interacted with brain data throughout the studies. In actualizing brain activity into the world either semiotically or engrammically, it becomes subject to interaction with other properties such as location. Furthermore, if this information can be revisited, either by its creator or an observer, this thereby alters the way it is interpreted, thus highlighting the influence of time. Taken together, these properties of space and time can ultimately dictate or modify how a user interprets the actualized brain data, while also providing unique affordances for the embedding of additional information in actualized brain data specific to those spatiotemporal conditions. In the study of immersive analytics, this property has been referred to as "situated" data [41]. However, spatiotemporal actualization of integrated BCI data tends to go beyond the boundaries of situatedness as described by immersive analytics, in that BCI data can also be situated within the biology, or physiological processes and rhythms of a user's brain, particularly when information is actualized engrammically.

With this said, we suggest that designers consider the spatiotemporal affordances of the application domain when designing an integrated BCI. For example, Neo-Noumena could be rebuilt to be a BCI-powered, neuroreactive, automated version of the review system Yelp. In this variant, the brain data of the users, specifically measures of valence, could be sensed and then communicated to other users in and around the restaurant they are dining in, which then other users can interpret to help choose a restaurant to eat at while they browse the city by interpreting the BCI output of other users while also noticing what restaurant they are eating at. Furthermore, the BCI output of diners could remain in the space they were dining at after they leave, and remain there over time, similar to how Yelp reviews are not taken down after a given length of time but are instead persistent and added to a pooled aggregate of reviews. Taken together, the strategic spatiotemporal actualization of brain data in this context has ultimately reproduced enhanced decision making processes found in nature, like how ants use the pheromones of explorers from the same colony to better inform themselves of where good sources of food are.

Designers could also take advantage of the contextual information of the application domain itself, and its interaction with neurophysiological processes, to further capitalize on this. For example, it has been well documented that smell is strongly connected to the formation of memory, emotion, and also the experience of taste. With this considered, in returning to the aforementioned Yelp-like BCI system, it would make sense to use olfactory stimulation as the information communication medium of this specific BCI integration system. As smell is strongly related to emotion, the BCI valence readings of diners would cause the interface to produce positively or negatively valanced smells. Due to the connection between smell and memory, other users passing by will have either positive or negative experiences autonomically recalled when passing by the olfactory output of other users dining, producing a strong reaction in the brains of the observers. Furthermore, as smell interacts with the perception of taste, diners could have their eating experience augmented positively or negatively by the output of co-diners, leading to a powerful feedback loop in which the valence of the food items being served are strongly reinforced in proportion to the number of people eating in that given space. With this in mind, it is evident the amount of interplay between the brain and the environment the system permits greatly influences the resulting user experience the system can produce. Controlling the impact the environment can have on the user's brain (e.g. by blocking out sound and vision) would limit the amount of impact the environment can thereby have on the resulting user experience, pushing the system toward an egocentric distribution of agency. Conversely, opening up the system to environmental influences (e.g., brain data controls the behavior of a robot which also interacts with the environment autonomously) pushes the system toward an allocentric distribution of agency. Thus, we suggest that designers consider how data is actualized spatiotemporally to better facilitate the intended distribution of agency.

6.6 Social Context: Consider How Social Context Can Enhance Playful BCI Experiences in Games and Play

Similar to how time and space are influential on the interpretation of BCI data, social context is also particularly impactful. As the human brain is constructed to extrapolate inferences about the state of the world through interpersonally oriented neural processes like empathy and social comparison, interpretation of a BCI output is highly influenced by the social context it is appraised within [53]. For example, users of Neo-Nomena believed that they were able to determine if other players were dealt good or bad hands while playing a card game based on their emotional output; and users of PsiNet reported feelings of cooperatively distributing cognitive processing abilities across group members when playing a videogame together. With this in mind, we suggest that designers consider how social context can enhance playful BCI experiences in games and play. Furthermore, while play presents a promising social context based on the findings, it is also anticipated that these affordances will be translatable to many social applications in general. One notable context that represents a promising opportunity for further exploration is that of VR social spaces (such as VR chat).

One application domain that would particularly benefit from this is that of games and play. While the potential for BCI as a gaming technology has been explored to some depth [81], we find that the role of the BCI in such explorations is usually limited to that of a game controller, most typically in a single player experience. However, rather than their traditional role as a controller, we propose that BCIs in a social gaming context could instead fulfil their potential as channels of communication between players, or in-game systems (such as game-world game-states). From this perspective, one could imagine a game of charades where the subject matter is hinted exclusively though BCI output, or a team strategy game where team members are neurostimulated with enhanced concentration if all other team members are concentrating, encouraging participation. Alternatively, one could also imagine a variant of Monopoly, a game notorious for triggering fits of rage. In this variant, players could be given the impossible task of trying to not upset any of the other players (detected by the BCI), as this would trigger a "game over" for all, leading to play strategies that oddly contradict the central aim of the game. Thus, we suggest designers consider how social context can enhance playful BCI experiences in games and play.

6.7 Learning: Consider Fostering Ongoing Integration Through Learning

A key part of the integration between the human body and technology is the process the body takes in integrating the technology into the user's body schema [106]. This is particularly prevalent in BCI, as BCI use is often a skill that the user must acquire over time to make full use of the system [108]. This is a process that necessitates that the user learns to think differently to gain full leverage of the system's affordances, which ultimately culminates in notable adaptive changes in neurophysiology and synaptogenesis. However, we suggest that this is only half the story, and encourage designers to consider how their BCI integration system can be designed to learn from and adapt to their users over time, reaching an understanding on how to better integrate with them. This is particularly important in the context of BCI as every brain is unique, making it difficult to design general purpose algorithms that are consistent between users [108]. With that said, designers should be aware that BCI use is a skill that the user and the system must learn together.

One implementation of this is the use of machine learning to improve the system's interpretation of brain activity. This is often completed as some form of supervised machine learning task and has been demonstrated to be very effective in applications in which the system has complete information, such as games [68,101]. However, this becomes challenging when the system has incomplete information, or no way to verify if what it is learning is in fact correct. One way to address this challenge would be to design BCI systems with contextually aware computing capabilities in mind, allowing the system to associate brain activity of its user with their concurrent context and extrapolate patterns and inferences from that [72]. However, another less explored approach that could be applied in tandem would be to have the system learn as an agent through reinforcement, being rewarded for helping the user achieve personal goals. For example, PsiNet exhibited this form of learning in that it was rewarded every time the group's neural synchrony increased, helping the system learn how it could best help its users become more synchronous. Similarly, an app by the neurotechnology company

"Neurosity" builds Spotify playlists based on how long they can keep users in a flow state. Thus, in allowing the system to learn, both the user and the system can work together as an integrated entity to help each other achieve their goals synergistically.

7 LIMITATIONS AND FUTURE WORK

One limitation of this work is that the brain-computer integration framework has been articulated from a mostly qualitative perspective. While some quantitative methods were employed in the analysis of each of the case studies, this was mainly applied toward the validation of specific parameters of each corresponding prototype (e.g., sleep or inter-brain synchrony) rather than toward the establishment of the higher-level concepts of the framework itself. The framework was synthesized through the combined thematic analyses of qualitative user interviews describing the experiential properties of brain-computer integration systems. Considering that this is a new and underexplored area of research, we argue that a qualitative approach was the correct path to take, as it has been acknowledged that qualitative research is particularly useful for theory building, especially in areas where little exploration has been made. Nonetheless, given that this work articulates the brain-computer integration framework, there is now the opportunity to operationalize the framework such that brain-computer integration systems can, in the future, be evaluated though objective quantitative methods [14,29]. For example, future work could explore how the axis "neural congruence" can be operationalized through information theory analyses [35,171], rather than this work's approach of posthenomenology [144]. Similarly, the axis "distribution of agency" could be operationalized through dynamic network analyses [11], rather than this work's approach of actor network theory [93]. Neuroscience and engineering research fields in particular are well equipped with methodological conventions and procedures that have been tried and tested in understanding informational flows within a system, and the network dynamics of systems as a whole, whether it is electronic or biological. Connecting both of these disciplines is a heavy use of quantitative analyses and research methods stemming from Shannon information theory, particularly when understanding information flow within a system, which makes it a strong approach for measuring neural congruence. Similarly, these fields also commonly employ complexity theory, chaos theory, and graph theory-based analyses and methods when understanding the dynamics of either network machines or networks of neurons, and thus could also be employed in quantitatively measuring distributions of agency. Furthermore, this transition of a quantitative rendition of the framework also brings the opportunity to use already existing terminology (e.g., such as terms from information theory, graph theory, etc.) to discuss the concepts presented. The density of novel terminology present in the framework may be a barrier to entry; the adoption of existing terminology from well-established fields may be helpful in communicating these ideas beyond HCI.

A further limitation of the framework is that it condenses the complex phenomena of brain-computer integration into two dimensions. While this allows for a parsimonious and arguably neat articulation of the user experiences afforded by brain-computer integration systems, particularly in the generation of four UX quadrants, this may also be a hindrance to the framework's ability to explain more nuanced experiences or interactions. As such, future work could also further contribute to understanding the design of brain-computer integration by expanding or extending the framework. It should be noted that distribution of agency and neural congruence are not the only factors present in the experience of brain-computer integration. For example, future studies may do well in understanding how crowd size influences the experience of brain-computer integration systems. While such a factor has some overlap with the already present dimension of "distribution of agency", distribution of agency is chiefly concerned with how causal actors interact within the system rather than the sheer number of humans. Furthermore, it is also possible to deconstruct the distribution of agency into two factors: "crowd size" and "free will", the degree to which actions originate from the user's own mind without outside influence [104], allowing for more nuanced expressions of combinations of agency and number of agents. For example, this would allow for the design space to illustrate the experiential distinction between an individual acting on their own free will or not independent from their immediate social surroundings.

Finally, an additional shortcoming of the framework as it currently stands is that it has only been used to evaluate and describe systems designed by the authors. To evaluate the validity of the framework's ability to generalise and describe and guide the design of brain-computer integration systems beyond those of the authors, future work involving validation studies of the framework through workshops or fitting novel BCI systems to the design space would help mitigate this shortcoming.

8 CONCLUSION

Through this work, we sought to answer the research question: How do we design Brain-Computer Integration systems? We have answered this question through the exploration of three prototypes and the development, presentation, and analysis of three integration BCI systems and their resulting user experiences: Inter-Dream, Neo-Noumena, and PsiNet. In synthesizing the results yielded from the evaluation of these prototypes, we constructed the Brain-Computer Integration Framework. This framework descriptively explains the user experiences afforded by BCIs that have been designed to both interpret and manipulate user neurophysiology, and prescriptively demonstrates how designers can develop systems to produce an intended user experience. Ultimately, it is intended that this framework contributes a theoretical basis through which theorists and researchers can discuss integration BCIs, while also providing practical guidance in the design of future integration BCI systems.

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