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Opening up the Design Space of Neurofeedback Brain–Computer Interfaces for Children

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Brain–computer interface applications (BCIs) utilizing *neurofeedback* (NF) can make invisible brain states visible in real time. Learning to recognize, modify, and regulate brain states is critical to all children's development and can improve learning, and emotional and mental health outcomes. How can we design usable and effective NF BCIs that help children learn and practice brain state self-regulation? Our contribution is a list of challenges for this emerging design space and a conceptual framework that addresses those challenges. The framework is composed of five interrelated strong concepts that we adapted from other design spaces. We derived the concepts reflectively, theoretically, and empirically through a design research process in which we created and evaluated a NF BCI, called *Mind-Full*, designed to help children living in Nepal who had suffered from complex trauma learn to self-regulate anxiety and attention. We add rigor to our derivation methodology by horizontally and vertically grounding our concepts, that is, relating them to similar concepts in the literature and instantiations in other artifacts. We illustrate the generative power of the concepts and the inter-relationships between them through the description of two new NF BCIs we created using the framework for urban and indigenous children with anxiety and attentional challenges. We then show the versatility of our framework by describing how it inspired and informed the conceptual design of three NF BCIs for different types of self-regulation: selective attention and working memory, pain management, and depression. Last, we discuss the contestability, defensibility, and substantiveness of our conceptual framework in order to ensure rigor in our research design process. Our contribution is a rigorously derived design framework that opens up this new and emerging design space of NF BCI's for children for other researchers and designers.

There are no simultaneous or prior publications of this strong concept design framework research.

This submitted article is a design research article. It focuses on the derivation, description, and use of five strong concepts that can be used to design brain computer interface systems (BCI's) for children. This article is most closely related to the following paper:

Alissa N. Antle, Leslie Chesick, Aaron Levisohn, Srilekha Kirshnamachari Sridharan, and Perry Tan. 2015. Using neurofeedback to teach self-regulation to children living in poverty. In *Proceedings of the Conference on Interaction Design and Children (IDC'15).* ACM, New York, 119–128.

The cited IDC conference paper is a typical HCI evaluation paper. In it, we focus on describing the field evaluation of our Mind-Full Nepal BCI system at the post-point in the study. The only overlap with this current article is the brief system description that appears in the IDC conference paper. We are currently writing HCI evaluation papers on the full results of the Nepal study and the second field study with the two new prototypes. There will be no overlap with this current article other than elements of the system description.

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1 INTRODUCTION

Brain–computer interfaces (BCIs)[1] allow for direct communication between people and computers using electrical impulses generated by neurons within the brain as input to a computer program [16]. One form of BCI involves using an electroencephalogram (EEG) headset to determine the amplitude and frequency of brain waves in specific brain areas, which are correlated with different cognitive and emotional brain states. An EEG headset can provide information that indicates when a person is calm versus anxious or attentive versus unfocused. It can also transform and display brain state information on a computer screen to show invisible brain processes in real time. When a user can view and respond to this brain state information, it is called neurofeedback (NF). The ability to use NF BCIs to teach self-regulation of brain states opens up new doors in human-computer interaction research [62]. Most previous research in BCIs involved expensive, complex, fragile EEG headsets and required long sessions of calibration or training to account for individual differences in brain states. However, we now have access to consumer grade headsets (e.g., NeuroSky MindWave[2], Brainlink Pro[3], Muse[4]) that are cost-effective, robust, and simple to use. These headsets can be used to detect brain waves correlated to brain states including anxiety, relaxation, attention, positive affect, pain, and working memory load.

Using consumer grade headsets and custom software running on desktop computers or mobile devices (e.g., iPads, iPhones, Android devices) it is now feasible to design NF BCI games that may enable children to learn and practice self-regulation of different brain states. Such systems may provide cost-effective, robust, easy to use, and customizable ways to motivate and help children learn and practice self-regulation. Millions of children of all ages may benefit from this type of system. For example, 25% of the world's children face mental health issues including severe cognitive and/or emotional challenges that negatively affect their education and career outcomes, feelings of self-esteem and self-efficacy, social competence, and their physical and mental well-being [58, 59]. In addition, anxiety disorders are among the most common psychological problems in childhood—affecting about 5% of children—often lasting into adulthood with devastating social-emotional, health, and economic costs [47]. If we can provide children with an effective approach to improve their ability to recognize, modify and regulate their brain states this may improve mental health, social-emotional, educational, and economic outcomes for millions of children. The overarching research question for this design space is then: Can we design NF BCI systems for children that are usable and effective at helping children improve their ability to self-regulate their feelings and thoughts? And, if so, what are the important design features of such systems so that they are easy to use, easy to learn to self-regulate with, and promote repetitive practice?

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[1] We refer to brain–computer interface based systems as BCIs.

[2] http://store.neurosky.com/pages/mindwave.

[3] http://store.neurosky.com/collections/brainlink-pro.

[4] http://www.choosemuse.com.

Clinical therapeutic NF BCI interventions for children have shown some positive results (e.g., [20, 49]), although there have been some methodological challenges (e.g., [61, 68]). However, clinical NF BCI interventions are costly; they involve specialized equipment and the support of highly trained psychologists and physicians in a clinic or hospital setting. As such, clinical NF BCI interventions are not available to most children. In the domain of HCI research, there have been descriptions of proof of concept NF BCI systems (e.g., [35, 39]), some informal user studies (e.g., [30, 43]), and some design-focused studies of NF BCI systems (e.g., [4, 46]). The recent availability of robust, inexpensive consumer grade EEG headsets that can be connected to widely available mobile platforms (e.g., iPads, Android devices) creates a unique and powerful research opportunity to investigate how to design usable and effective NF BCI applications for children on a platform that is cost-effective, mobile, and scalable. However, there are few rigorously validated BCI games for mental health [58], and there are no research-based design guidelines for the design space of NF BCI applications, children and mental health, or self-regulation training.

Our work addresses this opportunity and knowledge gap. Our goal is to provide design knowledge that can support other child-computer interaction (CCI) researchers and designers to explore and contribute to this new and important design space. We began to explore this research topic when we had the opportunity to design and evaluate a NF BCI system for self-regulation, called *Mind-Full*, for a small group of young girls (aged 5 to 10, $n = 22$) at a non-profit organization (NGO) funded school in Nepal who had suffered complex trauma related to poverty. The children had challenges self-regulating their anxiety and attention, which was interfering with their schooling. We realized that this challenge was faced by children world-wide, and began a research project to explore how NF could help children with anxiety and attentional challenges learn and improve their ability to self-regulate these mental states, in order to improve the likelihood of successful developmental and educational outcomes. The initial opportunity was serendipitous, presented to us through personal connections when Antle was in Nepal for a conference.

Our design approach was informed by expert review (e.g., trauma therapist, therapeutic counselors), grounded in current theories and interventions for anxiety and attentional challenges, and contextualized with user-centered fieldwork with our target population. After iterative cycles of design and technical experiments, we informally usability-tested our system twice, once with 11 children (aged 7–10) with similar attentional and anxiety challenges at a local school in our home country and again with two very young children (aged 5). While this was not our target population (wrong cultural group), we gave them almost no instruction to determine if very young children could use their body (e.g., breathing) and mental states (e.g., relax) to control the games and if there were usability issues. After further minor revisions, we then deployed and evaluated our NF BCI system in a field experiment with a waitlist, equivalent control group at the NGO-funded school in Nepal. The study involved 22 young girls (aged 5 to 10) who had suffered complex trauma due to poverty (neglect, domestic violence, sexual abuse) and civil war. We report results in [4, 5]. That paper focuses almost exclusively on the methodology and results from the field study, not the design of the prototype.

In this current article, we take a research through design approach [67] that is in line with Höök and Löwgren's proposition of strong concepts as a form of design knowledge [34]. Strong concepts are primarily derived using an inductive or "bottom-up" approach, with a goal of generating design knowledge that can be used in design practice [34]. They emerge through developing specific cases and abstracting knowledge from them [22]. We position our concepts as design knowledge that bridge theory and design particulars [22]. We begin this current article with a literature review, which we use to identify the essential design challenges for this class of artifacts. We next introduce the context for our first Mind-Full prototype (Nepal) and provide a summary of the system and evaluation results. We then present the methodology we used to identify the core design concepts that made our prototype viable and effective. We follow this by our articulation and grounding of our five strong concepts as well as a description of how they are interrelated and form a conceptual framework. To show generalization of our framework, we then summarize how we applied these concepts to design two new BCI prototypes, which we have just finished using in another field experiment with a different population of children, and to create three other conceptual designs. We conclude with a discussion of the criteria we used to assess the quality of our framework, its limitations, and expected usage by other designers. In this article, we focus on the derivation, articulation, and discussion of our design concepts, leaving the detailed methodology and results of all our evaluations to other articles. The rigor in the derivation of our framework comes from its grounding in theory and through concrete designs, which we validated by empirical study. We envision that other designers and researchers will apply, refine, and extend our framework to generate and inform the design of usable and effective NF BCI applications that may help children learn self-regulation of different brain states (e.g., anxiety, relaxation, attention, focus, pain, cognitive load). Our contribution opens up this unique and challenging design space so that others can design systems and run studies to understand how and why BCIs may improve the lives of millions of children.

2 BACKGROUND

BCIs can collect, measure, process, and use information generated electrically by our neurons. As we think, feel, sleep, exercise, and learn some of this electrical activity escapes through our skulls. An EEG is a device that uses electrodes placed on the scalp to sense, record, and measure the electrical activity of neurons [38]. Onboard chips can process this data to determine the amplitude and frequency of brain waves in different regions. EEG frequency distributions are very sensitive to cognitive and emotional states depending on the location of the electrode(s). This enables us to measure brain waves and infer brain states using EEG. By transferring this pre-processed data into a computer, we can then further transform it, and display the information in a variety of forms as NF about current brain states and ongoing brain processes.

2.1 NF BCI for Children

The foundation for our strong concept framework comes from a detailed literature review of the successes and failures of the small number of NF BCIs for children that have been studied. In this section, we describe these works in detail to provide evidence for the five key challenges we have identified in this design space. Our framework is a response to these challenges.

Lim et al. created an EEG-based puzzle for children with attention deficit and hyperactivity disorder (ADHD) (aged 7–12, $n = 20$) to help them improve their ability to self-regulate their attentive state [43]. A child's attentional level, as measured by an EEG headset, was sent to a desktop application and controlled his/her movement forward in a puzzle. When the child was less attentive, his/her avatar stopped moving. The direct link between a child's attention and avatar movement as a form of control was understandable to the children. This system highlights an important challenge and related design requirement: children must know what they need to do to use the BCI. However, it is unclear if children knew intuitively or were taught how to achieve a more attentive brain state. Therefore, it is important that they not only know *what to do to* interact with the BCI but also *how to do it.*

Gruzelier et al. conducted a study of an EEG NF application for relaxation that was built to improve creative music performance, attention, and well-being of children (aged 11, $n = 33$) [30]. Pleasant sound feedback was used to reward relaxation. This research highlights another important challenge and related design requirement: children *must understand the feedback about their brain states.* The children in this study understood that they received pleasant sounds when they were more relaxed.

Huang et al. presented FOCUS, an application designed to improve children's engagement (related to attention) during reading (aged 6–8.5, $n = 24$). The system included an EEG headset, a physical book, and a projector used to create an augmented display over the book [35]. When a child's EEG engagement index dropped below a threshold, the system's training mode was triggered. Reading could not continue until a related training session, projected onto the book, was completed. For example, when reading about nature, the training involved focusing on a projected image of a flower. Increases in EEG activity triggered the flower to open, at which point reading could resume. This system highlights another important point: using the BCI during reading did not *detract* from paying attention to content during reading. This highlights the challenge that the feedback should be integrated into the task at hand and *should not detract* from the task.

Mandryk et al. created a NF overlay for video games for children and youth (aged 8–17, $n = 16$) with attentional challenges due to fetal alcohol syndrome [46]. The system included an EEG-based textural overlay application designed to turn off-the-shelf computer games into NF systems. The overlay was related to the video game's theme (e.g., frost over a hockey game) and obscured the game interface until the player improved his/her attentional brain state. The link between clearing the screen and an attentive brain state is analogical (i.e., focusing your brain is like clearing a screen) and likely was understood by children. Again, the mapping does not provide feedback on how a child is supposed to create a more attentive brain state. Two children in this study were excluded from analysis due to poor signal quality in their sessions, raising another challenge that must be addressed when using consumer grade headsets: poor signal quality and noisy data. We have identified this challenge in our own work. NF system response must be able to *accommodate noisy and inconsistent data* as much as possible.

Other work to date (e.g., [27, 42, 50, 58, 60]) shows a breadth of design approaches and like the systems described above, analysis reveals similar key challenges. From our review of the literature and our own early design explorations, we next present five challenges for the design space of NF BCIs for children and self-regulation training.

2.2 Summary: Five Challenges for Designing NF BCIs for Children

A NF BCI must be both usable and effective. Based on our review of the prior literature (above) and our own previous explorations, we identified five challenges.

1. *Interaction Model*: Prior work has shown that children must understand the interaction model; they must know how to change their brain state to interact with the system (e.g., [30, 43]). That is, children must know *what to do* to interact with the BCI and *how to do it*.
2. *Feedback*: Prior work has shown that children must get feedback related to their brain state that shows them—in a way they understand—that they have done it right; and if they have not, they need corrective feedback that guides them (e.g., [30, 35, 46]).
3. *Input*: Prior work has shown that children must be able to complete the NF training task(s) and to use other functions of the BCI by enacting input actions that do not detract significantly from the brain state that they are trying to achieve.
4. *Calibration*: Working with children requires that the system must not require lengthy calibration or training procedures, in particular any that require children to be able to attain a specific brain state for a prolonged period.
5. *Sensing*: In order to use commercially available headsets (which are accessible, inexpensive, and easy to put on) the system must function reliably even when the sensed data is noisy and/or the signal quality is poor.

These five challenges help us define the design space we are working in. Throughout the rest of this article, we refer to both abstract design concepts and concrete design elements that we used to address these challenges in our first fully function system, two subsequent systems, and three conceptual designs.

3 NF BCI DESIGN EXEMPLAR: MIND-FULL (NEPAL)

The Nepal House project was our first NF BCI design research project. In this project, we designed and evaluated a NF BCI system, called *Mind-Full*. We provide an overview of the project including context, BCI system description, design rationale, NF game application, customization application, and a summary of our field evaluation. In the subsequent section, we present our derivation methodology and resulting five strong concepts, adding in details and rationale from the system we created in the Nepal House project. In this way, we present our design research process in the order it actually happened.

3.1 Project Context

The Nepal House project involved working with an NGO, called Nepal House Society Kaski, that funded, built, and operated a school for young girls (aged 5 to 11) living in poverty in a Pokhara, a small urban city in Nepal (population ~250000). Even though the NGO had provided a school, curricula, teachers, and counseling for the children, many of them were having difficulty learning. We worked closely with co-author Chesick, a trauma therapist, on the project. The main problem the trauma therapist cited was that the children had suffered multiple complex traumas (e.g., from domestic violence, neglect, malnutrition, illness, civil war) and that as a result, their ability to self-regulate around anxiety and attention was underdeveloped. Delayed development of self-regulation is associated with complex trauma [21]. The children were often anxious, particularly if something upset them. They had trouble calming themselves when they came into the classroom, or after a break, or during transitions. They also had difficulty paying attention to instructions and focusing on their learning tasks. In order to learn in a classroom, children must be able to reliably calm themselves and focus their attention. The children needed to learn self-regulation. Emerging best practices in industrialized countries for dealing with post-traumatic stress disorder (PTSD) and resulting anxiety and attention challenges includes EEG-based NF [14, 31, 54, 66]. Prior to this project, we had already conducted several design experiments (unpublished works) using biofeedback (BF) based on physiological measures (e.g., heart rate variability, galvanic skin response). As a result, for the Nepal House project, we decided early on to explore using EEG-based NF rather than BF. EEG can be used reliably to detect anxiety and attention and is less subject to movement artifacts common in young children. Working with the trauma therapist, we came up with an idea to see if we could build a robust, portable, EEG NF application that young girls who were illiterate and had suffered severe trauma could use to improve their ability to self-regulate anxiety and attention. The overlapping project phases included conceptual design, technical prototyping, interface and activity design, integrated system development, formative usability testing, and then an eventual deployment in the Nepal House Kaski school (Pokhara, Nepal) and waitlist control group field experiment that ran over 4 months. The development team included a senior CHI researcher (Antle), the therapist (Chesick), and senior students in roles of project manager, software programmer, hardware programmer, digital artist, and interface designer. We worked through iterations of design and development including technical experiments, concept designs, and two rounds of formative usability testing that revealed challenges with user management and enabled us to determine default game parameters related to brain state thresholds. We worked closely with counselors at the school at the beginning of the project during conceptualization, through several remote check-ins during the project (e.g., determining technical requirements, vetting culturally specific decisions), and for a week prior to beginning the field study (refining and troubleshooting).

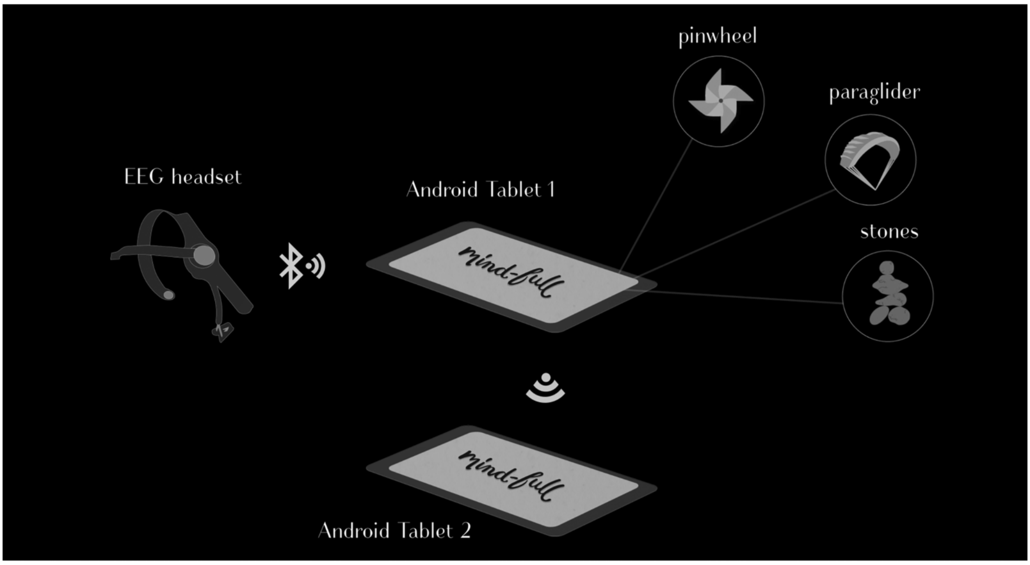

Fig. 1. System configuration.

3.2 System: Components and Technical Implementation

The Mind-Full NF BCI system was composed of two Samsung Galaxy 10.1 touch tablets that ran the Android operating system (OS) and Unity 3D (a mobile game development engine), and a NeuroSky MindWave headset[5] (Figure 1). We built two identical systems, each with two tablet devices: one for games and one for real time calibration. The NeuroSky MindWave headset was the only headset approved for use with children at the time. The NeuroSky MindWave is a commercially available EEG headset that uses only one dry electrode to record electrical activity in the left pre-frontal cortex. Compared to most EEG units, it is robust, non-invasive, adjustable, and easy to wear due to the single dry electrode. A predecessor of the system was validated in terms of its ability to reliably measure attentional states using Neurosky's proprietary algorithm [53]. Developers have integrated the NeuroSky headset into a number of toys for children including Mattel's MindFlex and the Star Wars Force Trainer. These prior-use scenarios provided evidence of the system's successful use with children.

Our software was comprised of two Unity 3D applications, each running on a separate tablet. We connected our *Game* tablet to the headset using wireless Bluetooth. This tablet ran a user set up module (login, management, progress, history) and the three games designed to train children to self-regulate attention and anxiety. The Unity game scene was updated at 60 frames per second. The Unity program also provided a data store for saving each user's sessions. We wrote a custom Java bridge program to connect the headset to the Android OS and Unity application on the Game tablet. The Java program polled the headset 60 times a second for EEG power spectrum data in all bands, a signal quality data stream, and eSense Relaxation (R) and Attention (A) data (0–100, where 40 is the baseline for relaxed or attentive states). We used the second tablet for customization and calibration (we call it the *Calibrate* tablet). We connected the Calibrate tablet to the Game tablet using WiFi Direct (rather than the internet, for stability).

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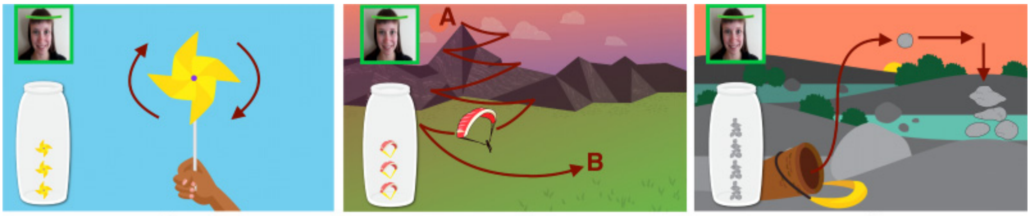
[5] http://store.neurosky.com/pages/mindwave.



(a) (b) (c)

Fig. 2. (a) Pinwheel game animation. (b) Paraglider game with 3 tokens. (c) Stone game with green signal quality.

3.3 The Games Application

A key insight that drove the game design was that even very young children already know how to relax (e.g., at bedtime) or pay attention (e.g., to a story). We based each game on a familiar, culturally relevant activity in which a child would relax or attend if they did it in real life. In this way, a child using our system already knows what to do, and how to interact. In addition, we chose activities that we could represent digitally in ways that were analogous to how a child might act and cause an effect in the real world. That is, we chose activities in which the child's body-brain state could be represented by an input–output system effect. We did this to ensure that a child would understand the feedback by relating it to analogous real world effects in an activity that was familiar.

We created three games that ran in a single application on one Android tablet: two games for relaxation (calming down) and one for attention because these were the challenges identified by the school staff that impeded the girls' ability to learn. The source of input to the games was the child's brain wave activity. The simple, robust NeuroSky headset monitored and provided a value between 0 and 100 for relaxation (R) or attention (A).

The first game, called *Pinwheel,* was a simple relaxation game (Figure 2(a)). To make the pinwheel spin a child needed to relax ($R > 40$ default) and stay relaxed (5 seconds default). These parameters were based on previous testing with young children but could be changed in real time using the Calibrate application (described below). If their R value fell below threshold then the pinwheel slowed down and eventually stopped. Focusing on breathing and the culturally familiar act of blowing on a pinwheel showed the children what they needed to do and how to do it, using a familiar and culturally appropriate activity, and provided simple feedback they could understand when they got it right.

The second game, called *Paraglider*, was a sustained relaxation game (Figure 2(b)). The school sits at the foot of the Annapurna Range of the Himalayas. It is an ecotourism hub and tourists often paraglide from the hills. We observed children watching paragliders land and swirl back upwards on thermals (gusts of wind), and building their own toy paragliders from found materials. To land the paraglider a child needed to relax ($R > 40$ default) and stay relaxed (11 seconds default). If their R value fell below threshold then a thermal, pushed the paraglider a little ways back up the mountain. Once the child relaxed again, the paraglider continued its descent. Each successful landing earned a paraglider token in the jar (Figure 2(b), left-hand side).

The third game, called *Stones*, was a sustained attention game (Figure 2(c)). Many of the children's parents earned money by collecting stones into baskets for building material. We observed children watching their parents stacking stones on the side of the road, which were later picked up for construction. We also observed children playing stacking games with stones and building stones sculptures. In the Stones game, to create a stack of five stones, a child had to visually attend

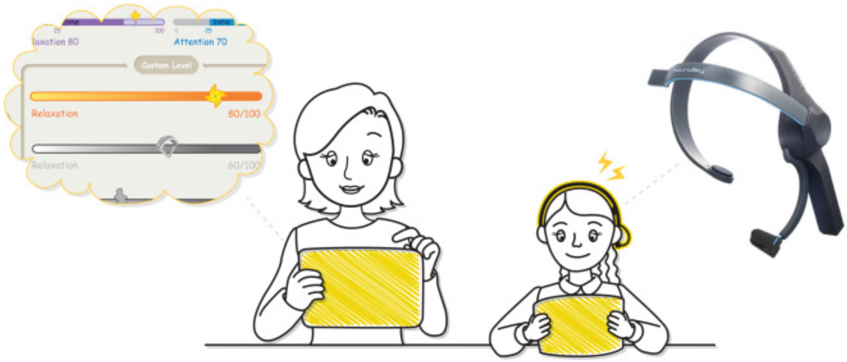
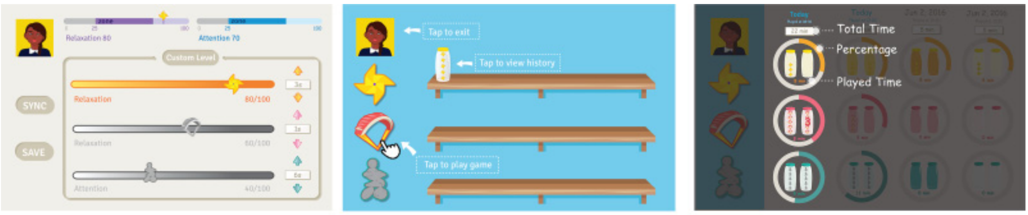


Fig. 3. Mind-full game application in use with calibration application.



(a) (b) (c)

Fig. 4. (a) Calibration UI on Tablet #2. (b) Game selection and progress interface. (c) History interface.

to each of the stones as it crossed the screen from a basket to a pile on the side of a road (8 seconds per stone, at $A > 40$ defaults). If a child's attention fell below threshold, the stone would waiver in the air and would eventually fall to the ground and roll back into the basket. Each stone stack was slightly different, adding a fun element to achieving each stack. Five stones were required to make a stack, which earned one token.

3.4 Calibration and Customization Application

We developed a real-time calibration application running on a second Android tablet (Figure 4(a)), which was connected using WiFi Direct to the Game tablet. This enabled another person (e.g., counselor) unobtrusively to observe the child's R/A values to determine if they were systematically different from the defaults, and calibrate the application by changing the R/A thresholds in real time (Figure 3). For example, if in an early session a girl appeared relaxed and was taking deep breaths but could not reliably land the paraglider and the data showed her R value varying between 25 and 35 (close to the 40 default) then the threshold could be reduced to 35 to calibrate the application to match her R values. Once individual calibration was achieved (and stored as new defaults for that child), this application could also be used to adjust the difficulty of the games in real time during game play. Both R/A and hold-time thresholds could be changed to adapt the task to the child's ability.

3.5 Summary of Nepal Field Evaluation

We ran a 14 week, randomly assigned two-equivalent group, repeated measures, field experiment with 22 children aged 5–11 with a waitlist control group [4, 5]. The intervention group of children did 3–4 × 10–12 minute sessions each week with their counselor for a total of 20–24 sessions over about 6 weeks. In order to offer all the children at the school a possible benefit, the second group then had the same intervention. We collected data about usability and effectiveness. We collected usability data in the first week and included observational notes and video related to any issues the children had in understanding what they needed to do to succeed in the games, what the feedback meant, how to navigate and see their progress. We found no usability challenges. With very little prompting, children knew how to move or be in their bodies (e.g., blow softly, take deep breaths while relaxing, visually track objects) and understood the resulting feedback through the game activities. Analysis of observational notes and log data showed that all children were able to successfully interact, modify their actions based on feedback, and earn tokens beginning in the first session. In terms of effectiveness, we assessed all the children in a pre-test, post-test (after intervention group completed the intervention), and follow-up test (after waitlist control group completed the intervention). The children's teachers working with trained facilitators from our project assessed the children. They were not blind to condition. We collected quantitative ratings (scale 1–5) for a variety of statements about each child's ability to calm down and focus their attention in different contexts (e.g., classroom, playground) as well as qualitative comments from their teachers about their attentional and anxiety challenges. Analysis of this behavioral data indicated that children in the intervention group improved significantly across most measures compared to the waitlist control group. In addition, in a follow-up assessment the intervention group continued to improve on some teacher-reported behavioral measures even when they were not using the system. System logs (game performance and EEG data) show the type of variability in performance and EEG data associated with NF training. It also showed variable but gradual improvement in the game challenge levels (e.g., hold time) that were often first decreased by a child's counselor using the Calibrate application and later, in some of the last sessions, increased for many of the children. We report further details in [4, 5]. We do not provide all the details of our evaluation in this article, but instead provide a summary of evidence that our design solution was usable, viable and effective. This is important to ensure that we used an empirically validated system to derive our concepts.

4 METHODOLOGY: DERIVING STRONG CONCEPTS

In our work, we have often tackled design in new technology areas and as such we have a history of design research informed by theory (e.g., [3, 6, 65]). However, rather than focusing on theory generation exclusively, we also marry theoretically driven work with research that explores how and why key concepts may improve situational outcomes. We also follow a situation-driven approach, such as research through design [67]. Our goals are to explore how we can use design concepts to generate and refine effective designs for a particular situation, guided by the principles that our work should also be generalizable to other, similar situations. As a result, we focus on intermediate level knowledge, which we find is more useful than analysis of particulars of design situations exclusively or high-level design theories, which would be premature to propose at this stage for BCIs for children.

A strong concept carries a core design idea that may be applied across particular use situations and possibly even across application domains [34]. It is both a design element, which is a particular part of a design exemplar or prototype, and at the same time it is a concept that describes (and may explain) user behavior. Strong concepts, like patterns, are solution-oriented pieces of design knowledge. Strong concepts concern the dynamic gestalt of interaction and resulting behavior rather than static interface elements. In line with [17, 34], we envision that our strong concepts can be used to generate and refine new designs because they are ideas explained in words, illustrated with concrete elements of potential design solutions and provide guidance on how to create specific interactional behaviors.

Höök et al. summarize steps used to identify and validate a strong concept [33]. We present an adaptation of those steps here in the rough order in which they occurred in our derivation process, although many of the steps overlapped and/or were iterated.

1. Each concept was *identified*, sometimes during our first design process, and sometimes retrospectively. Articulation of each concept was refined retrospectively and iteratively throughout our derivation process.
2. Through the process of reflecting on our first design exemplar, we fleshed out each concept and *illustrated* it in specific use situations with elements from concrete *design exemplars*. We also demonstrate the *generative* properties of our concepts by describing how we used them to design two new design exemplars (prototypes) and three conceptual designs.
3. We *vertically grounded* each concept by referring to theories that explain how it might enable or support specific behavioral patterns that unfold over time, noting such behaviors where we observed them in our empirical evaluation of our first prototype.
4. We engaged in *horizontal grounding* in which we described relationships between each concept and related concepts that have been previously used within academe, highlighting canonical research prototypes that instantiated the predecessors of our concepts. When appropriate, we also analyzed instantiations of related concepts found in commercial products. In our description of the five strong concepts (below), we highlight how we have adapted ideas from other domains to this unique and emerging design space.
5. We identified expected *limitations* on the use or generalization of each concept.
6. Last, we refined the articulation of our concepts by applying Höök and Löwgren's three criteria for academic quality to our work [34].
   (a) First, is our strong concept framework *contestable*? That is, is the contribution unique and innovative in the CCI and/or BCI communities?
   (b) Second, is our framework *defensible*? That is, is the framework grounded theoretically, analytically, and empirically?
   (c) Third, is the contribution *substantive*? That is, is the framework relevant, useful and generative for those designing new instances of BCIs for children?

In summary, our strong concept framework emerged during our three-year BCI design program of research. The design of our Mind-Full (Nepal) BCI system began with the articulation of a set of challenges that we addressed to ensure that our BCI was usable and effective. During the design process and through post-design reflection, we identified five design concepts that we thought were fundamental to successfully addressing the five challenges. In our derivation process, we fleshed out each concept by abstracting it from, and yet grounding it in our concrete design exemplar. We identified when our concepts were grounded in theory that informed our design and provided understanding of how and why users might interact. The Nepal field evaluation results provide some evidence that our design problem framing (challenges) and solution were accurate and effective. That is, results verified that Mind-Full (Nepal) was a high-quality research instrument that was suitable to reflect on in order to identify the design concepts that made it successful. It also provided opportunities to observe interactional behaviors predicted by theory. We began to see the generative value of our concepts when we began to ideate and refine design solutions for two new projects (Indigenous and Urban, described below). During the generation of these two other design solutions and three new conceptual designs (selective attention, pain, sadness, described below), it became more apparent that our concepts were interrelated and thus formed a framework. As we worked to articulate the framework, we also completed our analysis for horizontal grounding, comparing, and contrasting our concepts to others in the literature, in other research prototypes, and in commercial products. Our last phase of the derivation process involved reviewing our framework and revising its articulation using the three criteria of contestability, defensibility, and substantiveness.

5 FIVE STRONG CONCEPTS FOR NF BCI'S FOR CHILDREN

We present our five strong concepts and note the inter-relationships between them. We formulated these concepts retrospectively, drawing on our experiences designing and evaluating a BCI for young children living with trauma in Nepal. For each concept, we identify the design challenge(s) that the concept addresses. We next describe the concept, vertically grounding it in theory that predicts interactional behaviors where relevant. We then describe the specific instantiation of the concept in our Mind-Full (Nepal) system including illustrating the concept with descriptions and diagrams of concrete design elements. Next, we horizontally ground our work by comparing it to the previous literature, research prototypes, and commercial products. Last, we discuss expected limitations of each concept. We address the three criteria for quality in our discussion.

5.1 Interaction Model: Body-Brain Embodied Metaphors

Our first challenge was how to teach children what they needed to do to interact with the system using their body and brain. For the Mind-Full (Nepal) BCI system, they needed to learn how to use their bodies to shift their current brain state to a more calm/relaxed or attentive state.

The strong concept we used in our interaction model was that of *embodied metaphors*. An embodied metaphor links experiences we have in our bodies with ideas or concepts we have in our brains [8, 37, 40]. For example, we have all experienced moving up with our bodies. We stand up. We fall down. Repeated patterns of bodily experience create embodied (image) schemas, which are neural patterns in our brains. Early in life we unconsciously extend the body schema of "up" to metaphorically understand precepts (UP IS LOUDER), concrete concepts (UP IS MORE), and abstract concepts, such as affective states (UP IS HAPPY). We also express these body-concept metaphors in language. For example, when we are happy we might say, "I'm so *up* today." In this way, embodied metaphors provide a link between source domain, which are familiar bodily experiences, and a target domain, which is our understanding of perceptions and concepts. We adapt this idea to BCIs by basing our interaction model on the link between body experiences and affective or cognitive states rather than precepts or concepts. We link a source domain, which is a body state, to a target domain, which is a brain state. The body state forms the target basis for the metaphor that structures how we understand and experience the desired brain state.

In our Mind-Full system, for each game we identified an interaction model that we structured based on a body-brain embodied metaphor. We embedded these body-brain mappings into a familiar activity that would prompt a child to enact the desired body state. For example, we designed the Pinwheel game based on the embodied metaphor BREATH IS CALM. For example, we might say, "There was not a *breath* of wind in the sky" meaning the wind was calm. This metaphor was instantiated in the familiar activity of blowing on a pinwheel. Breathing can both help a child understand the meaning of calm but also attain a calmer brain state. When breathing stops, a child's brain state becomes less calm, and the digital pinwheel stops spinning, as it would in real life. We designed the Paraglider game based on the embodied metaphor STILL IS CALM. For example, we might say, "The ocean was *still*" meaning that the ocean was in a calm rather than stormy state. This metaphor is instantiated in the familiar activity of lying in a field watching a paraglider slowly glide down to the earth and land. The Paraglider game also utilizes the metaphor that DOWN IS CALM, and so landing the paraglider occurs when a child is calm. We designed the Stones game based on the embodied metaphor SEEING IS ATTENDING. For example, a teacher or parent might say to a child, "*Look* at me" meaning pay attention to what I am saying. This metaphor is instantiated in the familiar activity of watching stones pile up as building materials. Attending to the stones focuses the child's attention and as the child attends to the stones, one by one they build up a composite form, a stone sculpture. In this way, we built each of our games around a body-brain metaphor embedded in a familiar activity. A child can see how to enact the desired body state, which will in turn alter their brain state, which acts an input. In response, the system causes an effect in the activity. The effect represents the child's current brain state. In each case, we chose metaphors in which we could represent body-causes and brain-effects in ways that children would understand based on their lived experiences.

We ground the concept of using embodied metaphors to structure an interaction model by discussing its occurrence in the previous HCI literature. This concept was first explicitly explored through design research by Hurtienne's group at the University of Berlin [36] and by Antle's group at Simon Fraser University, Canada [2]. Hurtienne's group applied it to user interface elements (e.g., big is important) for adults to improve accessibility. In our own work with children in whole body and tangible environments we investigated how we could structure interaction models using embodied metaphors to improve usability and bootstrap learning [6, 9]. The interaction model provides the mapping(s) between input actions and system responses. For example, in SoundMaker (interactive environment) and MoSo Tangibles, the interaction model is structured using the embodied metaphor UP IS LOUDER [8, 10]. When children enact upward actions, each system produces louder sounds. In Springboard (interactive environment), the interaction model is structured using the embodied metaphor BALANCE IS JUSTICE [7]. When users enact a state of bodily imbalance, the system responds with representations in which social justice is out of balance (e.g., luxury homes juxtaposed with hovels). We have adapted the concept of using embodied metaphors to structure interaction models to BCI design. We used embodied metaphors to structure the interactional mapping between body-brain states. We expect that when children enact the target body state it will both help them understand the desired brain state and will also likely cause the desired brain state. This is, in part, because the same neural patterns are triggered for these linked body (motor, perceptual) and brain (cognitive, affective) states. We also embedded each metaphor in a familiar activity that would elicit the enactment of the desired body state, and resulting shift in brain state. Our approach is unique compared to previous usages of embodied metaphors that focused on using them to design UI elements, input controls, or to link input actions to perceptual or abstract concepts.

One limit on the application of this concept is that large or fast body movements may create noisy EEG data, and may have an unpredictable effect on desired brain states. In addition, research has shown that metaphors may have multiple interpretations [10]. Embedding them in frames (familiar contexts) as we have done may improve interpretation [19]. Future work should explore the interpretability of a wider range of body states metaphorically linked to a range of brain states (e.g., pain, positive affect, working memory load). We begin this work in our conceptual designs, described in Section 6.5.

5.2 Feedback: Dynamic, Iconic Representations of Body-Brain Cause and Effect

Our second challenge after showing children how to use their bodies to change their brain state was to provide feedback that they had successfully (or not) shifted their brain state toward calmer or more attentive states. If they had not correctly shifted their brain state, then feedback must be corrective (i.e., provide some guidance on how to successfully shift body-brain state).

The strong concept we used to design feedback was to provide feedback using *dynamic icons* that were culturally specific and represented the cause and effect model of each metaphor-based familiar activity (described above). Icons are pictorial images that depict simplified versions of actions, objects, and concepts. In our design, we used culturally familiar iconic pictures to depict changes in each activity that reflect the child's current brain state. We based this form of representation, in part, based on Bruner's theory of development. He proposed by about 5 or 6 years of age, children can understand both enactive representations (action-based) and iconic representations (image-based) [18]. We used both enactive and iconic representations and linked them through metaphors embedded in familiar childhood activities.

In designing Mind-Full, we chose animated iconic objects taken from each metaphoric activity to represent the current body-brain state. We introduced the feedback model by first presenting an animation of a child enacting the desired body state (see Figure 2(a) above) and causing the iconic object to change state. This showed the child the cause and effect between the child's enactment and effect on an iconic object in the activity, reflecting the cause and effect between body and brain. We then presented the same scene with the iconic object but without the animated child—giving the real child a turn to try. We used icons based on children's culturally specific experiences. We did this through site visits, which were photographed and detailed in rich observational notes. For example, the pinwheel is an iconic representation that most if not all children in Pokhara (the town in Nepal in which we worked) immediately recognize. When it spins, it suggests the enactment of breathing or blowing (or wind) to cause the movement. When it is still, it suggests that the child must blow on it to cause it to spin. The pinwheel spins when the brain is calm, reflecting the act of deep breathing or blowing, which calms the brain. These brain wave-controlled iconic visual elements provided visual feedback to the children about their relaxed or attentive states, depending on the game, and provided guidance and motivation to change their brain states. We also use iconic, culturally specific representations in our interface to show progress, another form of feedback (e.g., glass jars as collection of tokens) and to support navigation (e.g., tap pinwheel icon to play game).

There has been previous literature on iconic interfaces and accompanying metaphors. Uden and Dix were some of the first researchers to explore iconic interfaces with children [63]. In a study of iconic internet search interfaces, they found that children's understanding of icons was dependent on using icons that reflected children's background knowledge, which was culturally specific. Children preferred animated icons because they depicted function and were more alive. Although this study showed that not all children understood all icons, the authors suggested that if the children's background knowledge and cultural context were taken into consideration, then most children would understand the icons.

We see this concept frequently used in pictorial iconic representations found in young children's educational software menus where children navigate by selecting iconic representations of characters or objects related to content or controls (e.g., Sesame Street, Lego, Leapfrog interfaces). This design practice is based largely on understanding of children's cognitive development [55] and as such it likely generalizes to new platforms as long as there is a visual display. For BCIs, we use dynamic iconic representations to show cause-effect metaphors that depict body-brain states, shown to the child first in an animated sequence, and then as the core game mechanic, that the child uses to learn and practice altering their brain states.

One limit on the use of animated iconic representations may be for cases where there are no culturally specific activities that link body movement to effects on iconic objects that we can use to represent brain state. There may also be situations where it is difficult to show the animated nature of the body-brain link without annotation (e.g., using symbols) or explanation (e.g., using audio).

5.3 Input: Brain-Free Actions

Our third challenge was to provide a way for children to interact with and navigate through the application and access features including game progress and signal quality, in ways that did not detract from the specific brain states they were trying to achieve. With young children, we cannot assume either computer or language competence. Their fine motor skills are also limited. Any input actions that are required must be simple to learn so the children can automate them almost immediately to avoid distractions that change brain states or require significant motor-cognitive resources.

We call the strong concept we use *brain-free input actions*. It builds on the previous two concepts plus the simplest gesture available for direct manipulation interfaces, a single tap. Previous work has shown that a single tap on an appropriately sized target is the most intuitive and foundational form of touch interaction for young children [1]. In terms of representation, even young children can understand that tapping on an object may trigger an action involving that object [64]. While interacting with a NF BCI often occurs through the EEG headband, there are likely other input actions required. For example, navigation, starting games, checking progress and history. These should be relatively brain-free (easy to learn, remember and enact). One approach is that to navigate a child simply taps on an icon that fits with the metaphoric activity (for starting games) or that represents the function they want to use (for other features). A child can easily learn this form of navigation and it requires almost no cognitive resources to execute once automated [1]. Our approach was to reduce cognitive load by creating brain-free interactions that could be quickly automated, minimizing distraction from body-brain training games. While this may seem obvious, we see many BCI games that involve complex menu structures, resulting in an interruption of mental state and flow (e.g., ZenZone Kids Super Power[6]) or that have graphical elements that are distracting (e.g., Muse App[7] has a checker-patterned background that is distracting in the attention task, which involves attending to float fruit!).

In Mind-Full, besides controlling the games with their brain, children must also interact with the touch tablet to navigate through the application. We designed a simple interface flow in which children began their sessions by tapping on a photo of themselves. The first game, Pinwheel, was automatically loaded. Once a child had achieved five tokens in Pinwheel, they could tap on the jar of pinwheel tokens (Figure 2(a)) to go to the game selection and progress screen (Figure 4(b)). There they could choose any of the three games by tapping on the icon for that game. The jars on the shelf (Figure 4(b)) showed their most current session progress in each game. Tapping on any of the jars took the user to a history page where they see past sessions (Figure 4(c)). In addition, they could adjust their challenge level by tapping on one of five sections of a bar for any game, colored light to dark for easier to harder (not shown). Our site visits also provided inspiration for many of these elements. For example, we noticed that children in our population often asked tourists to take their photo and then show it to them. We inferred that most children understood the camera roll metaphor and would be able to find and then tap their own photos to begin their session. Logging in is relatively brain-free and does not require literacy (e.g., to type in a user name). Similarly, to start each game, a child simply taps the iconic game object. Progress is shown using a series of glass jars that fill with tokens. In our site visits, we noted that in many homes, a variety of objects were stored in glass jars on wooden shelves. We use this imagery and the metaphor COLLECTION IS PROGRESS. Tapping a jar shows progress in the corresponding game; tapping a shelf of jars shows history.

Previous pioneering work by Druin et al. advocated the use of graphical direct manipulation web interfaces for young children (e.g., in their Digital Libraries project) [26]. For their Digital Library project they used the navigational interface metaphor that searching for books is like going on a journey. This enabled them to help the children understand a digital library is not a collection of books but a place to search for information. For children, interface and control function metaphors need to be relatively simple, which removes some of the challenges associated with more complex

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[6] http://www.zenzoneinteractive.com/apps-learning/.

[7] http://www.choosemuse.com.

metaphors (or blends) like the desktop. More recently, we have seen metaphoric and iconic touch-based interface investigated in mobile phone design for children (e.g., [41]) as well as commercial products (e.g., Osmo, Crazy Gears). In all these successful products, we see the key components are that the metaphor that links action to function is simple and familiar; the pictorial representation is meaningful to the child in terms of both what the object is and how it will function; and that a child can trigger the function through a simple gesture like tap or drag. In terms of generalizability, our work has shown us that this approach is understandable for illiterate young children using a touch screen device [4], and it is therefore likely understandable to more computationally literate children as well.

One limit of our approach is the caution raised by Blackwell who suggested that all control and interface metaphors (just like interactional metaphors) need to be tested to determine the limits on their interpretation because multiple interpretations are possible [15].

5.4 Customization: Real-Time Distributed Adaptation

Our fourth challenge was how to accommodate developmental and other individual differences between children as well as daily variations in children's brain EEG activity without extensive calibration or training. The exact brain wave frequency that corresponds to "relaxed" for one child may be different from another and brain waves can vary slightly from one day to the next. Most EEG systems accommodate this through calibration (to an individual) and training (to account for variations). We need to find the right parameter values for each child on any given day so that the difficulty of each game is just right for the child.

The strong concept we use here is customization through *real-time distributed adaptation*, which enables another person (rather than an algorithm) to adapt the system in real time to fit the child. Over time, the child and the system can be co-adapted to fit each other and provide optimal challenge level as the child moves along what is likely a non-linear trajectory of learning. In order to avoid interrupting the child while they are focusing on their body-brain state (see brain free navigation above) changes must occur unobtrusively in real time.

The Mind-Full system enables real-time distributed adaptation of the child's learning environment. The system is distributed across two applications on two connected devices: Games and Calibrate. The Calibrate application enables a second person (e.g., counselor, teacher) to monitor and customize game parameters. Each game had a preset default R (relaxation) or A (attention) threshold (40/100) and a default "hold time" value (e.g., 5 seconds in Pinwheel). These parameters values were determined during previous testing with young children (some with ADHD) in Canada. However, each parameter can be adjusted in real time using the Calibrate application. For example, in the Nepal study, a counselor monitored each child's R/A values and game progress in real time (scenario in Figure 3, UI in Figure 4(a)). The counselor was able to adapt the child's learning environment in real-time based on that child's brain states and game performance. Initial calibration took less than 5 minutes. By asking each child to blow on the digital pinwheel, they relaxed a little, and the corresponding R value was visible in the Calibration interface. During subsequent sessions even if a child could not calm down or focus, default values could be set so they could make some progress, which may encourage continued practice. Since we worked with children with large behavioral challenges, we also found adaptation useful to support a child when they were experiencing difficulty. We also used adaptation to increase the challenge of games unobtrusively as children improved their ability to self-regulate their relaxation and attention levels.

Previously we see the concept of real-time co-adaptation of external environments and internal states in the theory of distributed cognition [32], which suggests that cognition is distributed between external resources (e.g., computer systems) and one or more internal minds (people). Specifically, the distributed learning theory of mutual adaptation posits that young children learn more effectively when using a physical environment that adapts in real time to their ideas [48]. Optimal learning happens when both the environment and children's ideas co-evolve. We adapt this idea from learning concepts to learning self-regulation. Through feedback in the learning environment (game), children learn to modify their actions (body) and as they do this, they modify their internal (brain) state, which is reflected in the game environment. The second person can be viewed as part of this distributed learning system; as they adapt variables in the game (environment) in response to the child's brain states, the child's ability to regulate their body-brain states and the game co-evolve. We have seen this concept implemented in adaptive learning algorithms for educational software (e.g., [29, 56]) and advocated for in other products (e.g., LinguaBytes); however, implementation can be complex because it often involves machine learning [11].

One limit of our non-machine learning approach is that changing parameters in real time without distracting a child requires a second device and a user who can adjust the default values. While having a "coach" present is helpful for self-regulation learning, children can easily practice on their own once default values are set. They can also adapt the games by tapping a new challenge level on the history page when an adult is not present. However, this requires navigating out of the game to the history page and then tapping the challenge bar and returning to the game (total of four taps). It remains to be determined how "brain-free" this is. Likely it is distracting, but it also promotes autonomy. There is a trade-off here between providing real time customization and autonomy during game play. Likely, both modes are necessary for optimal progress.

5.5 Sensing: Design for Imprecision

Our fifth challenge was that while cost-effective and widely accessible, consumer grade headsets produce noisy data and the signal quality can be variable.

The strong concept we use to deal with sensed data is *design for imprecision*; that is, design strategies that take into account this imprecision. Unlike using a mouse or video game controller, interaction (input) by changing brain states is invisible, gradual, and may be non-linear. Commercial headset data may be noisy and of variable quality. We suggest the following design strategies to design for imprecision:

1. Use a smoothing filter since precision is not critical (i.e., a typical relaxed state can be within R the range of values 40–100);
2. Choose activities in which it makes sense that continuous body actions will slowly cause changes in feedback (e.g., blowing slowly starts pinwheel spinning) versus discrete actions, like a button press;
3. Choose activities in which variation in feedback makes sense (e.g., paraglider decent speed varies);
4. Use an unobtrusive game element to represent signal quality.

In our system, the NeuroSky headset monitored the child's brain wave activity and provided a value between 0 and 100 for relaxation (R) or attention (A). We took a moving average of these values to help smooth noisy data. Since noise tended to be of short duration (e.g., less than the hold time to earn a token), we set our moving average to be just below the hold time duration. These smoothed R/A values controlled world state changes in the game, typically of visual elements such as appearance or movement of objects (e.g., spin pinwheel). Our game mechanisms accommodate imprecise data. For example, a pinwheel slows down gradually when not blown on or a paraglider ascends slowly on a thermal back to the top of the mountain. Our design embraces imprecision. This approach ensured that short spans of noisy data or poor signal quality were not disruptive. We also integrated signal quality information into the interface. Each child's photograph (their ID) was shown on every screen. A graphical picture frame and headset was overlaid on the photograph and showed a signal quality of green, yellow, or red (Figure 2(c)), which is very simple to interpret.

Previous researchers have embraced uncertainty in sensed data through the concept of seamfulness [12], designing for uncertainty [28, 13], and slow technology [52]. For example, in location-based games (e.g., Can you see me now? [11]), seams are areas in building shadows where satellite sensors cannot collect data. Players embraced this uncertainty and developed offline strategies where they could slow down to rest or hide while remaining creatively engaged in game play. Similarly, advocates of design for appropriation (e.g., [25]) suggest that children may find their own ways to deal with noisy, imprecise data. Slow technology advocates for latency or imprecision between inputs and responses. We need further research here. In our studies, we noticed children patiently adjusting headsets, having an adult do so, or simply waiting, creating a calm, attentive brain state while the technology recovered.

This limitation of BCIs will likely be reduced over time as quality improves; however, this process may not be linear. For now, we suggest that designers design for imprecision when working with commercial grade EEG headsets.

6 USING STRONG CONCEPTS TO GENERATE NEW NF BCI'S

6.1 Variations of Mind-Full NF BCI

After the Nepal Mind-Full field study was complete and we had received some media coverage we were approached by two communities who were interested in being research sites for this project. One was an indigenous group with a culture that included fishing practices located in an ocean and forest environment. The other was an urban school district in a city that was close to nature and farming districts. We refer to these as Indigenous and Urban. Each project had similar learning goals around teaching children self-regulation of attention and anxiety. As team lead, I formed a new team that had a different project manager, artist, and UI designer but same programmer (mostly due to people's availability). We began this phase of the project by envisioning that we would create a single new application based on the nature theme that would work for both populations. It turned out that this was not feasible, and we will address this below.

Design Generation: Ideation and Refinement. We began our design research process by reviewing the five challenges and then brainstorming different cultural themes that might be familiar to the children in our Indigenous and Urban group. Some of our early thematic explorations include agriculture and farming, beekeeping, hiking trails, birds of prey, indigenous mythologies, rivers and tides, sprouting seeds, and the forest. As we explored these themes, we addressed how children would know what to do and how to do it using our first concept (*body-brain metaphor*) to focus and structure ideation on suitable interaction models. Within each cultural theme, we tried to identify child-centric activities that contained embodied body-brain state metaphors related to relaxation and attentiveness. Conversely, we also brainstormed body-brain links that were viable to enact wearing a headset and interacting with a mobile device and then ideated child-centric activities that might contain such links. In this way, the body-brain metaphor concept helped us generate ideas for games while at the same time helped us quickly discard ideas that would not work. Our next step was to work our broad set of game ideas and apply other concepts. For each activity that we generated we asked questions like: Can we easily represent on a mobile device the body state enactment required? Is there a form of feedback in which an iconic object can be acted upon using input body state? Can we design feedback based on the gradual change of some characteristics of an object to reflect different brain states? Does the core mechanism of the activity "make sense" as feedback of brain state? In embodied interaction design, Antle suggests that design must take into account three kinds of mapping between physical/body and digital space:

perceptual (typically visual), that is how things appear versus how they respond; behavioral, that is how input actions relate to digital effects or controls; and semantic, that is what things mean in the physical world versus digital aspects of the system [2]. Such mapping can be literal, isomorphic, or metaphorical [45]. For children, any form of mapping that is abstract must be grounded in their concrete experiences to be understandable (without instruction) [2]. Is the action-effect in the activity literal, isomorphic or metaphoric in a way that lends itself to an effect a child can understand? Is the visual representation of the effect understandable? Does feedback guide corrective action? Does the activity lend itself to different brain wave thresholds and difficulty levels that can be adapted in real time using our second Calibrate application? Can a child move between different activities in ways that do not detract from desired brain states? Can the object effect accommodate noisy data? We used the challenges we identified to create questions that helped us quickly discard many ideas. We used the concepts to elaborate and flesh out on remaining ideas that addressed the design challenges.

For example in our farming theme, we ideated relaxation activities including softly blowing on a dandelion (flower) to spread its seeds and blowing on a toy boat to send it across a lake or tide pool. Both of these ideas are consistent with a BREATH IS CALM metaphor, which utilizes an object that can be represented iconically and dynamically. We ruled out activities that did not fit our criteria. For example, we had ideas around planting seeds but could not generate an appropriate body-brain metaphor related to calmness. We envisioned a hybrid calm and attentive activity in which a child would softly blow on seeds to distribute them and then attend to them to make them grow. However, in this activity the link to everyday life seemed a stretch since *a watched seed never grows* is a common saying!

In the forest theme, we brainstormed several ideas around watching animals in the forest all of which required being still and hidden (STILL IS CALM). Because a large proportion of our target population was young boys with attentional challenges, we wanted to ensure that our themes and activities were appealing to them. As a result, we also played with ideas from TV shows and movies. We riffed off pop culture activities including the idea of hiding from zombies in the forest (e.g., TV show *Walking Dead*) and causing mishap to an obsessive character (e.g., Wyle E. Coyote in the TV show *Road Runner Hour*, nut-obsessed squirrel in the movie *Ice Age*). Again, our first two concepts helped us generate, refine, and converge on feasible solutions because they provided both inspiration (e.g., ideating around different embodied metaphors) and constraints (e.g., the need to fit the metaphor into culturally familiar activities with an iconic object that can be used to represent NF). For visual attention, we came up with ideas such as watching sequences of creatures or visually steering a canoe down a river. We played with the idea of watching and catching fish in the river where users have to tilt the tablet to catch the fish, but this broke away from our brain-free navigation strategy, and we realized the input action was incompatible with the desired brain state because it would be distracting.

We also used the concepts to create “classes” of design ideas. For example, we realized that embodied metaphors for relaxation formed a subset in which the body movement had to be slow, small and subtle, and had to lead to a calm or relaxed brain state. Thus, the idea of hiding in the forest to avoid zombies was ruled out because even though the input activity of being still and quiet worked, we envisioned that the resulting brain state might be heightened anxiety due to fear of zombies or heightened arousal due to anticipation of zombies.

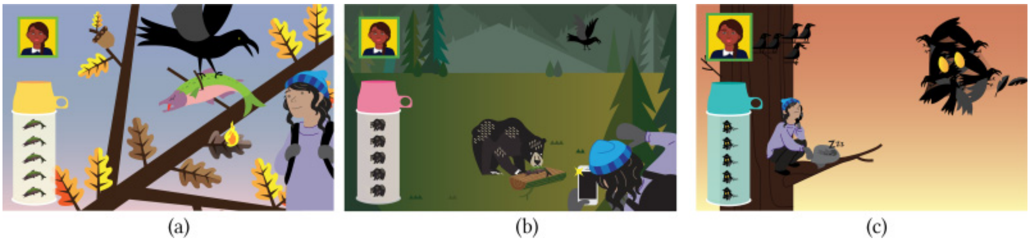
Communicative Value. As we brainstormed ideas and reflected on these early body-brain metaphors and culturally specific activity ideas it became clear that having new team members was of benefit because the project lead (Antle) needed to explain the core concepts to them in ways that were concise and clear. Thus, another benefit of using our concepts was that referring to them enabled the team lead to educate the team by providing the rationale for including or excluding design ideas. Antle quickly saw that team members started to apply these concepts themselves in order to support or discard ideas. In this way, the concepts had not only generative value but also communicative value, providing a common language and information.

Inter-relationships between Strong Concepts. During this design process, it also became very clear that we had to tackle our concepts together; they formed a framework. For example, we had to embed the core interaction model relating body-brain into a culturally themed and familiar activity, in which NF could be represented with an iconic object that changed its state dynamically with a continuous, graduated effect. This core cause and effect in the activity had to accommodate different difficulty levels that could be set on the fly, without distracting the user, as well as accommodate noisy data in a way that made sense for the activity (e.g., pinwheel slowing down gradually). No interaction with the device should distract a child from achieving the target brain state even when moving between activities or checking progress.

We decided to implement the same customization module based on the concept of real time dynamic adaption. As a result, we used similar system components (EEG headset, Android tablets running Unity 3D) and system configuration (two connected tablets). From a design perspective, this enabled us to address the need for real time calibration and customization. From a research perspective, it enabled us to focus on determining if our other four concepts were useful in the generation of new design solutions rather than developing new technical solutions in our design research process. We did upgrade our software to incorporate Unity's new libraries and revised the calibration interface to make it easier to understand and use for adult users, but these steps are unrelated to the use of our five core concepts.

Preliminary Designs. At the conclusion of our second design process, we had three new games. In the first game, a lightning strike caused dry leaves to smolder, which startled a squirrel trying to grab a nut from a tree. By blowing on the smoldering leaves, a child created a small fire under the squirrel who runs off. The act of softly blowing on an ember may create a calmer brain state. In the sustained relaxation game, a child hid in the forest waiting for a Sasquatch (an indigenous creature of myth) to emerge and fall into a leaf trap. The act of being still and hiding may help sustain a relaxed state. In the visual attention game, we had a child sitting in a tree watching a flight of birds fly across the sky into their nest. Visually attending to the birds may help focus attention.

Refinement with Stakeholders. At this point in our project, we were asked to visit the village site of the Indigenous band and we had the opportunity to show our early ideas to several healthcare workers involved in the Indigenous community as well as meet with elders (stakeholders). The healthcare providers immediately expressed a sensitivity to games that riffed on mischievous TV themes. They told us these were inappropriate for this particular population, citing examples such as some of the young boys in this community had been known to start fires as acts of defiance and so the idea of playfully startling a squirrel in a cartoonlike manner was deemed inappropriate. They also described how children in the community experienced inter-generational violence and thus often had to hide from perpetrators. Our stakeholders told us that idea of a child hiding in a forest was anxiety provoking (rather than an opportunity to practice stillness). We brainstormed with some of the stakeholders and came up with the guiding principle that we should base our activities on the mythology of this Indigenous group and that the core of each activity was positive and proactive in ways that we could align with the culture's values. Our framework facilitated efficiency in our revision process and we quickly ideated variations of activities and icons but kept similar body-brain metaphors. For example, in this culture's mythology the bear is a power animal.



(a)
(b)
(c)

Fig. 5. (a) Indigenous relaxation warm-up. (b) Indigenous sustained relaxation game. (c) Urban attention game.

By relaxing and remaining still, children can capture a picture of the Bear in an iPhone photograph and in doing so can be imagined to regain some of their own inner power.

An important part of using our concepts to generate and refine design ideas was to embed this design process with key stakeholders who play a major part in providing feedback on early design ideas working with us within our framework. The framework gave us the structure and language to use during brainstorming and then as we refined our games during this stakeholder-informed part of our design process. The framework provided boundaries and scaffolding within which to generate and refine our ideas.

We next describe the games for the Indigenous group. We found that some of our early ideas were suitable with some variation for the Urban group and describe them in the following section. Because we did not need to redesign our real-time calibration module, we do not describe it below.

6.2 Indigenous NF BCI Prototype

The Indigenous theme was a forested, coastal wilderness. We created games based on the familiar cultural icons taken from the site visit and our own knowledge of this environment and culture (raven, fish, bear, stars, constellations); and embedded these icons in the metaphorical activities that used body-brain links for interaction. In the warm-up relaxation game, a lightning strike starts a flame smoldering and a gender-neutral indigenous child blows softly on the flame to increase the fire and smoke a salmon (positive feedback), which is then scooped up by a hungry raven (mythology: raven = trickster). The embodied metaphor is again BREATH IS CALM. If the R value drops below threshold the fire goes out (negative feedback). If data is noisy or the headset signal quality is low for longer than the time to earn a token, then the fire can flicker without disrupting a child's flow. Once the salmon is smoked, a raven swoops down and takes the fish, triggering a new round of the activity (Figure 5(a)). The salmon token appears in a thermos (i.e., container for hot drinks often used in forest hikes).

In the sustained relaxation game, the raven drops the stolen salmon on a log in the forest. This attracts the attention of a bear. The same gender neutral iconic child is shown staying still, hiding behind a tree until the bear is close enough to the log to be captured in a photo on an iPhone, symbolizing bringing power into oneself by learning to stay calm (Figure 5(b)). The embodied metaphor is STILL IS CALM. If the R value drops below threshold the tree shakes, the bear retreats and the iPhone picture will not show the bear. If data is noisy, the tree gently shakes and the bear may pause but not retreat all the way back into the forest. A bear token is earned when relaxation is sustained above threshold for 11 seconds (can be adjusted) and stored in the thermos container.

In the attention game, the iconic child is camped with a fire at night. The child visually attends (SEEING IS ATTENDING) to a series of five shooting stars as they one by one cross the sky and form a bear head constellation, a reward for sustained attention. Each star reveals another part of the constellation. If the *A* value drops below threshold or data is noisy then the star will shimmer and/or disappear before reaching the constellation. A star token is earned for sustaining attention long enough to form the five-star constellation. A child can switch between the games on the progress and game selection page by tapping salmon, bear or constellation icons, providing brain-free navigation. We used a small headset icon in the top right, no longer overlaid on the user's photo, to be consistent with other EEG apps (not shown in figures).

6.3 Urban NF BCI Prototype

The Urban population theme involved TV cartoon-like characters in a forested park. We created games based on the familiar icons taken from our own culture (squirrel, monster, crows); and embedded these icons in humorous metaphorical activities that used body-brain links for interaction. In the warm-up relaxation game, a lightning strike starts a flame smoldering and a gender-neutral urban child blows softly on the flame to increase the fire and scorch a squirrel's tail, as the squirrel reaches for a nut (positive feedback). If successful, the squirrel jumps into a ball, makes a humorous shocked face and races off, abandoning the nut. The embodied metaphor is again BREATH IS CALM. If the *R* value drops below threshold, the fire goes out (negative feedback). If data is noisy or the headset signal quality is low for longer than the time to earn a token, then the fire can flicker without disrupting a child's flow. Once the flame remains long enough to spook the squirrel, a squirrel token appears in a thermos (i.e., container for hot drinks).

In the sustained relaxation game, a clumsy monster is chasing the squirrel through the forest towards a leaf pit trap, presumably set by the child. The same gender-neutral iconic child is shown staying still, hiding behind a tree until the squirrel and monster cross the trap and the monster falls in. The embodied metaphor is again STILL IS CALM. If the *R* value drops below threshold, the tree shakes, and the monster and squirrel retreat into the forest. If data is noisy, the tree gently shakes and the squirrel and monster may pause but do not retreat all the way back into the forest. A monster token is earned when relaxation is sustained above threshold for 11 seconds (can be adjusted) and stored in the thermos container.

In the attention game, the iconic child is sitting on a thick tree branch beside a nest with a sleeping squirrel (presumably exhausted from its run-in with flames and monsters). Above the child is a nest of black crows. The child visually attends (SEEING IS ATTENDING) to a series of five crows as they one by one leave the nest and cross the sky, a familiar scene in the Urban area. Once there are five crows, they morph into a monster head, which awakens and spooks the sleeping squirrel (Figure 5(c)), who again runs off. Each crow reveals another part of the monster head, which the game reveals one crow at a time. If the *A* value drops below threshold or data is noisy then the crow will fly erratically and/or fly back to the nest. A crow token is earned for sustaining attention long enough to form the five-crow monster head. A child can switch between the games on the progress and game selection page by tapping squirrel, monster or crow icons, again providing brain-free navigation. The thematic overlap between Indigenous and Urban is intentional because the familiar environments of these children also overlap. We have found it easy to think of new games for different environments and cultures, in particular after site visits. In Urban, we added a playful "cartoon" element to appeal to the large portion of young boys with attentional challenges in our population.

One of the things to notice is that we ended up using the same body-brain metaphors for each game in all three systems. Once we zeroed in on the appropriate metaphor, it was easy to use it in a variety of activities and game designs. This efficiency may be one of the strengths of our approach. It also means that once children have used one of our applications, they could potentially also use others even though the culturally specific activities might not resonate as strongly. For example, in a second field evaluation that included in its population sample 7–8 year old urban boys with attentional challenges, we elected to use all three applications in order to maintain their interest long enough to complete 18 sessions over 6 weeks. Based on our design process and evaluations, we suggest that our framework enables designers to create an initial application, and then quickly "skin" it to create variations. However, in terms of our work present in this article, using the same body-brain metaphors limits any claims we can make about generalization. We address this in the next section by presenting three new conceptual designs, which involve different metaphors, self-regulation goals, and end-user populations.

6.4 Prototype Evaluation: Usable and Effective?

We have currently just completed a 14-week field experiment with 28 young children in two urban schools using a similar protocol as the Nepal evaluation. We ran an *a priori* power analysis on our main survey measures and determined we need at least 26 children to detect a moderate effect. Counselors and teachers identified 32 children aged 5 to 8 who had severe anxiety and/or attentional challenges. We received parental consent for 28 children. We used both Urban and Indigenous NF BCIs with this population over a four-month period. Pre-post and follow-up measures included open interviews with teachers; 5-point ratings by teachers and parents on validated survey instruments for assessing anxiety, attention, hyperactivity and depression (BASC-3); salivary cortisol tests (for stress/anxiety); tests of executive functioning (EF) (including attention); brain wave and game performance measures and observational notes by trained social workers who facilitated the sessions. Observational notes of the early sessions revealed no usability issues with the systems for any of the 14 children in the intervention group. Observational notes reveal that all children were quickly able to learn to self-regulate at a level sufficient to receive tokens. The ability to transfer self-regulation skills learned from the games into the classroom is a better indication of effectiveness than game performance. Post-test analysis of interviews indicated that most (9/13) children showed improved ability to self-regulate in classroom settings when prompted by teachers (e.g., "Can you take some pinwheel breaths to calm down?"). Observational notes provided further qualitative evidence of positive impact with the intervention group. Preliminary inferential tests of quantitative measures between groups (surveys, cortisol and EF tests), have all shown evidence of effectiveness, largely within groups due to between group pre-test differences in all measures except surveys. Preliminary qualitative and quantitative evidence suggests that our new systems are viable (children were able to complete the intervention) and effective (evidence of both transfer and maintenance). We will report on these findings in detail in a subsequent article.

6.5 Conceptual Designs: Self-Regulating Selective Attention, Pain and Sadness

So far, we have demonstrated how our framework helped us generate and refine prototype designs for the same two self-regulation goals: reducing anxiety and focusing attention. To show the versatility of our framework, we next show how we use our framework to create conceptual designs for NF BCIs for different self-regulation goals: improving selective attention and working memory, coping with body pain, and reducing feelings of sadness.

Selective Attention. A large proportion of our Urban population is young boys with EF challenges including attention and working memory. We quickly sketched out a selective attention game, in which children must focus their attention on a set of objects while ignoring distractors. Rather than start from scratch, we envisioned a version of our Urban Crows game to improve selection attention and working memory. We added a feature to the game where children first attend to two kinds of birds crossing the sky (say crows and sparrows). Rules dictate the direction that the birds fly. The sparrows appear and quickly fly across the sky to the safety of their nest (crows eat sparrows). The crows, being mischievous and possibly hungry, appear on one side of the screen but then fly across the screen from the other direction, acting as a distraction to the sparrows and the child. Playing the game requires the child to tap (brain free) on one side to release sparrows and the opposite side to release crows. Outcomes are based on successfully remembering and applying these incongruent rules that dictate if the birds will be released across the sky, similar to the hearts and flowers task [24]. Again, the body-brain metaphor of SEEING IS ATTENDING, now within the context of a game with rules that must be remembered (working memory) and executed in a brain-free way (tapping). If a child's attention drops below threshold or the data is noisy, then the speed the birds fly at can change (e.g., slower). Another option consistent with the seeing-is-attending metaphor is that the birds slowly disappear or fade as attention drops. If attention is above threshold and the child selects the correct side of the device, then the program releases a sparrow or crow. Sustained attention ensures the birds cross the screen. One successful outcome might be getting the sparrows successfully across the screen to their nest without being eaten by crows. More morbidly, correctly releasing the birds could result in their paths crossing, and crows eating sparrows when they are flying in opposite directions. In this scenario, if the wrong side is selected then the crow or sparrow could stay in its nest (e.g., to avoid being eaten). This form of feedback may appeal to our audience who may enjoy improving their selective and sustained attention as well as working memory to trying to get more crows to eat sparrows. Working within our framework we can brainstorm many feedback scenarios that will make sense to children and provide corrective feedback as needed.

Pain. For pain management in hospital or clinical settings (e.g., for repeated painful procedures), we ideated several body-brain metaphors including reducing pain as removing resistance to pain, spiraling into or falling into pain or moving closer to pain. These all build on the body-brain mechanism that focusing in on pain may reduce it, and trying to move away from or struggle against pain intensifies the sensations. We used this core relationship to ideate activities based on the metaphor of MOVING DOWN IS FOCUSING. For example, an animation could display a body outline. The child taps on the painful area to highlight the area in the animation, and then visually and mentally focuses their attention on that part of their body. We could embed this in an activity that equates successfully focusing in on a painful body area as the body outline moving down (DOWN IS LESS) into a substance that provides relief. For example, one metaphor we worked with was that focusing on pain is like diving into a cold substance, a variation of a common metaphor used in VR pain management [51]. The ability to self-regulate by focusing on pain, metaphorically diving into coldness, may eventually reduce pain sensations compared to struggling against pain. Here, the metaphorical activity of falling down, or diving into lent itself to a variety of activities that are familiar to our urban population, such as diving into a cool swimming pool on a hot day; snowboarding, skiing, or sledding down a cool snowy slope; or even something more fun, like falling into a giant-sized bowl of ice-cream. Again, we used the body-brain metaphor to both generate and later discard ideas for activities (e.g., if input action could not be easily enacted with the tablet). For this self-regulation goal, the interaction with the device is again minimal; but the animations show the child what to do (tap and then focus in on painful body part) in order to cause the body on screen to dive down into a substance that reduces pain. In terms of accommodating noisy data or poor signal quality in our feedback design, we ideated ripples on the pool, or stalling during the dive; bumpy snow slowing down the snow boarder or sled; and melting ice-cream or a slower descent into it. Sometimes the need for a continuous graduated effect response ruled out a design idea. For example, having brain wave data dictate the speed and direction of a dive could result in feedback that seems unrealistic and even jarring, so we discarded the idea. Instead, we designed corrective feedback to show the child's body outline slowing down in its descent into the substance and the painful area glowing brighter red, attracting the child's attention to try to

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dive back into the substance and/or refocus on that part of themselves to move down into and reduce pain. We arrived at this preliminary conceptual design in only a few hours, building our ideas out on the framework. There may be good design solutions we missed due to the constraints of the framework. However, the framework enabled us to quickly generate and refine (or discard) conceptual designs that are likely feasible for children to learn to use quickly and easily.

Future design concepts based on recent studies on NF and pain management have also shown that adult patients may be able to learn to reduce neural activation in specific brain regions related to endogenous pain modulatory systems [23]. Currently, learning to self-regulate pain using this approach involves fMRI-based NF because pinpointing activation in localized brain areas is beyond the capability of commercially available EEG headsets. However, in the future, teaching children to deactivate specific brain areas is an intriguing possibility that raises new research questions and open the door for using our framework in a slightly different context.

Sadness. For reducing sadness, we identified several body-brain linkages that might be effective starting points for our game design. For example, we could structure games on the embodied metaphor of HAPPY IS UP. Upwards actions may increase positive valence and arousal. Another option, based on EEG NF research on alpha asymmetry training protocol for depression in adults, is the mapping of left (prefrontal alpha activation) to happy and right to sad [44]. Another option is the direct relationship between smiling and positive affect. Next, we came up with interaction ideas using each embodied metaphor to generate ideas for input actions, vetting each idea against what is feasible to enact with a mobile device and EEG headset. We also used each metaphor as ideation cues for child-centered activities, looking for those that could encompass the body-brain metaphor. We pruned ideas by only keeping those that involved a cause-effect relationship of body action to some change in the components of the activity that we could use iconically to represent the changes in brain state in ways children could relate to and understand. One conceptual design we finalized involved both smiling (captured on the device camera) and imagining body lightness (LIGHT IS UP) in order to release balloons. Another design we came up with involved either motioning upwards with the device and/or dragging objects upwards and/or to release them. In this design, we linked upward input actions to positive events displayed on the system. The upward dragging interaction is unlikely to interfere with positive feelings, so it is aligned with our brain-free input actions concept. However, we were concerned that these simple upwards body actions alone may be insufficient to trigger positive feelings, which is why we added smiling as a second form of interaction. We would need to prototype this idea and test it. If successful, we can turn to refining activities that utilize these *up* gestural and facial patterns. These include conducting music, climbing up a play structure, moving up towards a warm sun, or climbing up a tree after an annoying squirrel! For this design case, our framework again provided a generative starting point for ideation (metaphor/activity) as well as being useful for discarding and/or refining conceptual designs.

Future design concepts based on recent studies of NF with fMRI have also shown that adults can learn to “up-regulate” or activate specific areas of the pre-frontal cortex correlated to positive affect [44]. Since commercial headsets tend to sense brain wave activity in the pre-frontal cortex, we may soon be able to use this information to provide NF that helps children learn to up-regulate their emotional state. Again, these ideas raise interesting research questions for future work.

7 DISCUSSION

We identified five design challenges and then derived and grounded five strong concepts from our design and evaluation research with NF BCIs for children. Guided by our design research, and the existing literature on NF BCI’s, we identified a number of design challenges. Other challenges emerged, but the solutions were either not at all novel (e.g., addressing motivation, which we did through progress tokens) or they were too specific. For example, Gruzelier's system required participant's eyes to remain closed throughout NF training to encourage stimulation of particular brain states, leading to a unique design challenge: *feedback must not be visual* [30]. However, this challenge is not broadly applicable, and although feedback was visual in all our systems, it need not always be this way since audio could be used to provide salient and understandable feedback. The result of our derivation process was the final five concepts we describe above. These strong concepts and their inter-relationships form a novel conceptual framework for this new and emerging design space. In this discussion, we first address the three criteria for assessing the quality of our strong concept framework, followed by a discussion of limitations of our work and how we expect others will use our framework.

7.1 Is the NF BCI Strong Concept Framework Contestable?

Although the five concepts we have presented here have appeared in the HCI literature for other platforms, we argue that our framework is contestable; that is, our contribution is both innovative and uniquely adapted to the design space of BCIs for children and self-regulation training. In particular, the adaptation of embodied metaphor theory to structure the body-brain interaction model is novel and unique. It provides a starting point for designs, and predicts subsequent user behavior and related brain states. In addition, as all our descriptions of design exemplars show, we recommend that designers consider the concepts together, as a framework. The way we combine the concepts into a framework and work with them together provides unique and innovative design guidance for this new and emerging design space. However, it may be that designers can also benefit from using one or more concepts individually in the context of their own design processes. Either way, our work is unique, at this point in time. There is no other design research available at this time that might guide design. Ours is a step toward better understanding and designing to support children learning and practicing self-regulation. Taken together, these three elements of our contribution provide evidence that it is both innovative (in particular our use of embodied metaphor) and unique (the whole framework).

7.2 Is the NF BCI Strong Concept Framework Defensible?

We defend our framework by showing that our derivation methodology was more than reflective. We linked each concept to theory, which predicts interactional behaviors; grounded each concept in previous academic work; and described examples in which these concepts were instantiated in other systems. This form of vertical and horizontal grounding suggests that our concepts already have validity in the design field and our contribution has been to identify them, and explain how we extend, adapt, and apply them to generate, inform, and refine NF BCIs designs for children and self-regulation. For example, our first concept is based on embodied metaphor theory [40], which has been applied in interface design [36], interaction design of interactive environments and tangibles [6, 10] and we now extend to body-brain interaction design for BCIs. The theory provides guidance on how to select body-brain interaction models that predict user behavior through enactment and resulting brain state changes. We empirically validated this predicted behavior in our Nepal evaluation, seeing evidence of predicted interactional behaviors as well as self-regulatory behaviors both with and without our system (e.g., in the classroom). We continue to defend this new strong concept, which is foundational and the most innovate element of our framework, in our investigation of our new systems. Similarly, the rest of the concepts were explored individually in our Nepal field study (e.g., children understood feedback; children navigated without detracting from brain task; continuous, graduated object effects masked noisy data). The overall Nepal evaluation results and preliminary qualitative pre- and post-test results from our Urban evaluation suggest that our framework-based design process resulted in three new NF BCIs that were not only usable but may be effective in helping children learn to self-regulate.

7.3 Is the NF BCI Strong Concept Framework Substantive?

Our strong concept design framework opens up the design space of BCIs for children to the CCI (or IDC) community, who likely are novices in this space. We showed how our concepts provide guidance to address the key design challenges we have identified for this design space. We showed how it enabled us to create usable and effective design solutions in three different (yet similar) design situations and quickly ideate conceptual designs for three new types of self-regulation learning. The framework has generative power. It suggests where to begin and how to progress with design and game ideas. It suggests how to think about core body-brain linkages and how to build these mechanisms into games in which children will know what they need to do to change their brain state, how to do it, if they are doing it right, and how to correct body-brain states if necessary. The framework also enabled us quickly to discard ideas that did not fit the five concepts. During training of new team members, it provided a common language to describe, discuss, and discard ideas. Even more importantly, the framework provided a cohesive conceptual structure that we worked with during our initial and iterative design processes. For example, when working with non-designer stakeholders in the value-sensitive Indigenous design process, it provided a structure within which we quickly revised ideas based on key stakeholder input. Rather than going back to scratch, we used the existing conceptual structure of our designs as scaffolding to quickly ideate variations of games that conformed to the same conceptual structure yet involved different activities and themes. There was an efficiency to our revision process; the structure quickly enabled us to dismiss or expand upon suitable ideas. This allowed us to present stakeholders with our new ideas before we left the site, confident that they would be usable and likely effective once implemented. To date, we have used our framework to inspire and inform design, generate new ideas, educate team members, serve as a common language, and provide a conceptual structure within which we quickly created and refined new solutions with and without stakeholders. Last, we briefly explored advances in other forms of brain sensing (fMRI) and used the framework to generate research questions about how different forms of brain sensing might be used to create NF BCIs. We imagine we will find new ways that the framework is substantive as we continue our evaluations of the current systems and create new ones.

7.4 Limitations and Usage

We identified design challenges, framed from the perspective of what children must be able to do and understand. They were gathered from our literature review of how and why NF BCIs are usable, feasible, and/or effective or not; built on our past design experiments with NF and BF (which largely informed our technical understanding of the design space); and empirically grounded in our long history of working with children. These are, however, only one set of challenges. There may be other challenges we have not identified, and there are certainly more requirements that we did not focus on. For example, the need for repetitive self-regulation practice means that game challenge level, motivation, and hedonic elements must work together for a particular population to encourage practice. The role of the facilitator who shows a child how to use a NF BCI and coaches a subset of subsequent sessions is also critical. While the intervention deployment is not within the scope of this article, the interface of a NF BCI (both game and customization apps) must be usable and understandable to a non-technical facilitator, such as a counselor or social worker. Last, we grounded our design process in site visits before and during development. Many of our activity ideas came from observations of children or interviews with their caretakers on site visits. We revised our designs iteratively with input from key stakeholders who provided guidance on appropriateness of themes and activities, cultural characteristics of iconic representations and alerted us to value sensitivities. We have not included these aspects in our challenges, largely because they are not specific to this design space. However, they are critical to successful systems design and deployment.

It is important to point out that even with careful use of our concepts, a BCI will likely be usable but may not be effective. Effectiveness depends on having the right fit between the brain state goal and the familiar, everyday activity, the body-brain link it relies on, and the way it is represented to the child. All of these design decisions must be well thought through, and there is no substitute for stakeholder feedback and early user testing.

Our framework is a response to these challenges. It represents only one solution space for this complex and multi-faceted design space. Within this solution space, researchers and designers can use the framework directly, as is, making design decisions using the strong concepts as actionable guidelines to create usable NF BCIs. This is the most direct use of the framework. It can also serve as a conceptual structure to inspire, ideate, and inform other solutions to the five challenges. This may lead to the emergence of other strong concepts that extend the framework. New concepts may require trade-offs in design if they conflict with the suggested approach. This type of work is expected and important because it opens up the design space more fully. Other researchers may also expand or adapt the challenges themselves as they work through the design problem, in a manner similar to Schön's reflective conversation with the design materials [57]. The challenges and framework are design materials for others to use in this design space. That is their main contribution—they open up this design space by providing scaffolding for design and grist for reflective conversations between the materials and between researchers. It is possible there are other strong concepts that we have not seen in our own work or that will emerge in work of others. Conceptual frameworks are meant to be iteratively refined, and we have no doubt that ours will go through similar processes as the field matures.

8 CONCLUSION

Our contribution includes several forms of new knowledge in the design space of NF BCIs for children and self-regulation: the five challenges that must be addressed to create usable and effective NF BCIs; the responding framework of five strong concepts and last, the three fully functional design exemplars (prototypes) and three conceptual designs within this new design space. These contributions will be of benefit to the CCI and BCI research communities and industry partners. Our work also makes a methodological contribution; it is one of the first examples of a rigorous methodology for deriving strong concepts from design research. In doing so, it illustrates how strong concepts can be derived from scholarship and design practice, and how the resulting concepts can be applied in design research for a class of similar artifacts. As such, the work may benefit all design researchers working to derive intermediate level design knowledge in the form of strong concepts.

In summary, we contribute five design challenges. First, children must know *what to do* to interact with the BCI and *how to do it*; that is, how to change their brain state to achieve this interaction. Second, they must get *feedback* related to that brain state that shows them in a way they understand that they have done it right and if they have not done it right; they need feedback on how to do it right (i.e., corrective feedback). Third, they must be able to interact in ways that do not *detract* significantly from the brain state they are trying to achieve. Fourth, the system must be *customizable* in real time in order to not require lengthy calibration procedures and adapt to the child's current performance level. And fifth, in order to use commercially available headsets the system must function reliably even when signal quality is poor or there is *noise* in the data. In response to these challenges we present one solution space—five inter-related strong concepts, adapted from other classes of artifacts, applied to NF BCI design for children, and applicable to a range of self-regulatory processes. The concepts inform the design of interaction models, feedback, input actions, customization and sensing. They are body-brain embodied metaphors (interaction model); iconic, dynamic representations of body-brain cause and effects (feedback); brain-free input actions (input actions, e.g., for navigation); dynamic real-time adaptation (customization) and design for imprecision (sensing). The concepts should be considered together, beginning with the core interaction model embedded in a culturally familiar activity that can be used to show children body-brain causes and effects. Then designers can explore how these effects can be represented as state changes to one or more iconic objects taken from that child-centric and culturally specific activity. State changes should be continuous and gradual to reflect changes in brain state(s) and to accommodate customized changes for calibration or challenge level adjustment and noisy headset data. Input actions, when required, must not detract from achieving desired brain states. It is a lot to think about and our framework will ensure researchers and designers new to this space have handholds to guide their design efforts.

In terms of generalization, we propose that there are many more use situations (e.g., different types of self-regulation) that our framework can be used to design. We have shown the versatility of our framework through our descriptions of using it to generate designs for self-regulatory processes including sustained attention, anxiety, selective attention, pain, and sadness. We present this work in the hopes that others will be inspired and informed by our framework, using it as a tool to understand the core challenges of designing NF BCIs to teach children to self-regulate processes related to learning as well as emotional development and mental health. The framework forms one set of solutions to the design challenges we identified. There may be variations or other solutions. As the field matures, we look forward to discussing variations and seeing other solution spaces. We also envision that our framework can be used to identify potentially interesting avenues for further research investigations in the design space of NF BCIs. We identified possible research avenues for self-regulation of pain and depression once the technology can accommodate location-specific EEG sensing. Our framework may be applicable beyond the specifics of helping children learn and practice of regulation. Others may extend our framework for this design space to other applications of BCIs for other populations. However, one-step at a time. In presenting this work, we envision that our contribution is the first step in opening up the vast potential of this design space for the development of BCIs that improve learning, mental health, and other developmental outcomes using newly available technology on a platform that millions of children already use.

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