Introducing Peripheral Awareness as a Neurological State for Human-Computer Integration

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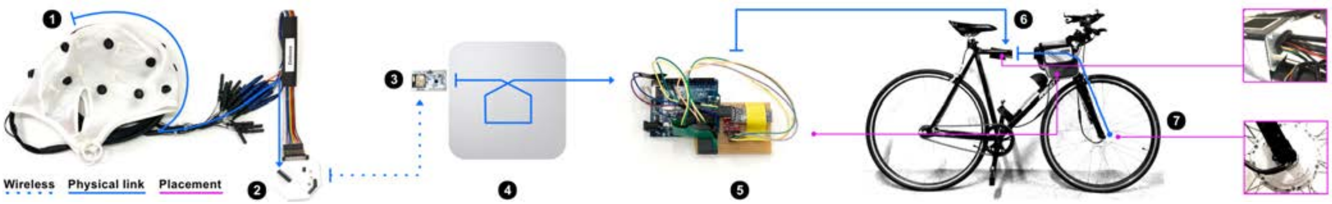

Figure 1. Changes in peripheral awareness in real-time regulate the eBike's engine. 1) Ag/AgCl coated electrode cap. 2) Cyton Board for EEG reading. 3) Bluetooth receiver. 4) Mac running OpenBCI for EEG classification. 5) Arduino converting Boolean to integer corresponding to whether the rider is peripherally aware or not. 6) eBike's engine controller to regulate engine support. 7) eBike's engine.

ABSTRACT

In this work we introduce peripheral awareness as a neurological state for real-time human-computer integration, where the human is assisted by a computer to interact with the world. Changes to the field of view in peripheral awareness have been linked with quality of human performance. This instinctive narrowing of vision that occurs as a threat is perceived has implications in activities that benefit from the user having a wide field of view, such as cycling to navigate the environment. We present "Ena", a novel EEG-eBike system that draws from the user's neural activity to determine when the user is in a state of peripheral awareness to regulate engine support. A study with 20 participants revealed various themes and tactics suggesting that peripheral awareness as a neurological state is viable to align human-machine integration with internal bodily processes. Ena suggests that our work facilitates a safe and enjoyable human-computer integration experience.

Author Keywords

Human-computer-Integration; human-system partnership; Inbodied interaction; peripheral awareness.

CSS Concepts

• **Human-centered computing** → Human computer interaction (HCI) → Interaction paradigms • Embedded and cyber-physical systems → Sensors and actuators

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INTRODUCTION

Recent HCI research has focused on better understanding internal bodily processes and how these can mediate our interactions with the world. This approach has been dubbed, "Inbodied Design" [2, 5, 15, 41, 49, 57], and proposes that if we design to support how we work internally as physiological and neurological systems, our designs will be more effective at supporting human performance. We take this approach in understanding what *peripheral awareness* is and how changes in the user's field of view can affect human performance [29, 44, 56], and, from this science, to design a human-computer integration system where changes in peripheral awareness in real-time regulate an electric bike's engine in order to support human performance (Figure 1).

Peripheral Awareness and Its Effects on the Body

The human visual system is composed of *central vision*, an area in the centre of the visual field that offers clear recognition of objects, and *peripheral vision*, which occurs around the central field of view and is responsible for the collection of peripheral visual information (Figure 2) [45, 53]. Sports scientists and neurologists have studied peripheral vision in relation to changes in neural activity using Electroencephalogram (EEG), revealing that peripheral awareness maps to the higher part of the alpha range 10-12Hz [44, 45]. Further work has shown that a relaxed and open mood can be conducive to widening our perceptual field to reach peripheral awareness [63]. This can result in being more coordinated and aware of the environment [29, 44]; as such, helping users to access peripheral awareness can benefit exertion experiences like cycling where the majority of accidents occur at intersection crossings [31, 50] where peripheral awareness is important. HCI has not yet explored peripheral awareness as a neurological state for human-computer integration, therefore this work offers an initial basis for such exploration.

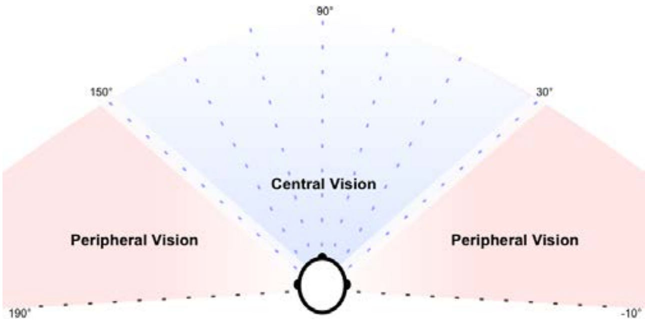

Figure 2. Illustration of central vision and peripheral vision.

Human-Computer Integration in an Exertion Context

Human-computer integration in an exertion context refers to the intersection between human-computer integration [22], where the user and computer co-operate in a partnership, and exertion support [40], where the user invests physical effort. This intersection is an emerging area in HCI. Due to advances such as artificial intelligence and the Internet of Things, systems can sense, interpret and automatically act on information without user input to participate alongside the user and support integration endeavours.

To study peripheral awareness as a mechanism of integration between the user and the system we have chosen to use an electric bike (eBike). This is because the user needs to use their vision to navigate the environment and invest physical effort as part of the experience, while the eBike's engine support can be modified to respond to changes in the user's peripheral awareness. Moreover, the challenge with eBikes worldwide is that riders often misuse the eBike's acceleration and this has resulted in accidents and fatalities [50, 61]. As such, we consider this an interesting societal challenge for a human-computer integration design-intervention, where the system offers engine support only when the user is in a state of peripheral awareness, which affords them greater awareness of their surroundings [44, 45]. In order to use peripheral awareness directly from neurological activity we rely on indirect physiological signals as follows.

Peripheral Awareness via Indirect Physiological Signals

Indirect physiological signals resulting from a user's interactions with the environment are difficult to control, such as electroencephalogram (EEG) for neurological activity, galvanic skin response (GSR) for psychological arousal, and heart rate (HR) for HR changes indicative of emotional changes [37, 42]. We chose indirect physiological signals as these can reveal a user's state, in contrary to direct physiological signals which can be more easily manipulated by the user; these include respiration (RESP), via sensors placed around the user's chest to measure breathing, and electromyography (EMG) to sense muscle movement.

We hypothesized that changes in peripheral vision often occur due to instinctive reflexes [45], as such, these changes could be read from neurological activity via EEG—in order to explore changes to the user's field of view relating to peripheral awareness as a mechanism of integration. To explore this hypothesis we formulated the following research question: *Can we use peripheral awareness via EEG as part of an integration system to support user experiences?*

We built "Ena, the eBike", which reads in real-time the EEG signals of the rider for changes in neurological activity corresponding to whether or not the rider is in the peripheral awareness state. Ena automatically acts according to changes to this state to regulate engine support. 20 bike riders experienced Ena and were interviewed using the explicitation approach [64], the results were synthesized using thematic analysis [13], yielding the following results.

Main Contribution

Our work suggests that peripheral awareness as a neurological state for human-computer integration is viable, and it offers access to a user's pre-attentive processing state that the system can act upon to support the user experience.

Practical Contributions

- A detailed system implementation with reusable code.
- Study results from 20 bike riders using Ena.
- Themes to study peripheral awareness using EEG as a human-computer integration mechanism.
- Tactics as practical guidance to design human-computer integration systems using peripheral awareness via EEG.

These contributions are targeted to the agendas of *Human-Computer Integration* [21, 22] due to the insights resulting from studying peripheral awareness as a mechanism of integration; *Trustable and Explainable AI* [52], due to the tactics offered to promote trust when designing integration systems that can automatically act on the experience; and *Inbodied Design*, due to the focus on the internal bodily processes to inform HCI design [5, 57].

RELATED WORK

We summarize how peripheral vision has been used in HCI. We then describe the challenges resulting from eBike riders misusing the eBike's engine acceleration and how peripheral awareness as a mechanism for integration could contribute to this societal challenge. This is followed by prior work in human-computer integration in an exertion context. Finally, we describe the gap in knowledge that peripheral awareness as a neurological state can begin to fill in HCI.

Current Use of Peripheral Vision in HCI

HCI researchers have experimented primarily with peripheral vision for screen based and ambient technologies (e.g., [1, 7, 8, 58]), often within a predefined location, such as within the lab, home or office. These works have focused on the user experience of interactive systems that display digital information in our periphery and the resulting interactions afforded to users. A second use case is head mounted displays for augmented and virtual reality which have overlayed information from our periphery [48], and have even augmented our field of view by incorporating a 360º perspective [20] within the virtual environment. A third use case is eye tracking and gaze approaches (e.g., [24, 30, 36]) that have focused on using the eye as an input mechanism in physical and virtual environments while considering the user's periphery. These studies have examined the user experience and interactions resulting from various users' abilities, technologies and situations. It appears that the use of peripheral vision in HCI today has not considered monitoring the user's neural activity corresponding to peripheral awareness. This could facilitate HCI practitioners with opportunities to align our designs to how we work internally and it can also afford opportunities for human-computer integration in real-time according to the user's abilities, technologies and situation—including in the wild scenarios outside of the lab—in order to better understand users and the resulting experience.

eBike Riders Misusing Engine Support

eBikes are popular worldwide [23, 54] as they offer riders engine support to go further and faster. The challenge is that riders often misuse engine support to go too fast in inappropriate situations, and this has resulted in eBike riders becoming more prone to accidents than regular bike riders [23, 35, 50, 61]. This led us to consider that if integrated systems could be aware of the user's peripheral awareness, the system may be able to regulate when to offer engine support, probably resulting in a safer experience.

Designing Human-Computer Integration in an Exertion Context So Far

In this section we describe prior work in human-computer integration in an exertion context and highlight potential opportunities that our work can contribute to.

Integration Based on the User's Actions

FootStriker is a wearable running electrical muscle stimulation (EMS) device that actuates the calf muscles while running to control foot landing angle [26]. This facilitates participants to a decreased average heel striking rate for technique improvement. Another example is the eBike "Ava" [3] that acts on the user's posture to increase engine support as the user leans forward. These studies suggest that integration systems can act on, and react to, the user's bodily actions. In these works the user is responsible for monitoring aspects of the environment. However, in some cases the user could benefit from new knowledge derived by the system because the system could be better suited to monitoring and making decisions about certain aspects that the user cannot monitor easily, such as: finding the shortest route to a location, monitoring speed to inform the rider when going too fast, and monitoring air pollution. This notion has opened opportunities for integration systems as follows.

Integration Based on the User's Environment

eBikes have been used to create systems that can act on, and react to, the user's environment, for example: De la Iglesia's et al.'s [18] system responds to the route's inclination, increasing the pedalling difficulty to incrementally challenge the rider towards improving fitness. Sweeney et al. [59] monitored pollutions levels ahead of the road so that their eBike could increase engine support and assist the rider with reducing their breathing rate to avoid breathing heavily polluted air. Andres et al. [4] used traffic light data to inform when the eBike should increase engine support to assist the rider to catch green traffic lights.

These studies show that human-computer integration in an exertion context has focused on systems that can react to the user's actions (focusing "*on*" the user's body – e.g., [3, 26]), and on the user's environment (focusing "*around*" the user's body – e.g., [4, 17, 59]), to support and facilitate new user experiences. What appears to be missing in this vibrant design space is systems that draw from the "*inside*" of the user's body to explore inner bodily processes as mechanisms of integration. As a result, we consider changes to the field of view relating to peripheral awareness as a valuable mechanism for integration between the user and the system as it is linked with human performance [32, 44, 45].

What is the Gap in Knowledge that Peripheral Awareness as a Neurological State Can Begin to Fill in HCI?

In sum, prior work in HCI has not yet studied peripheral awareness as a neurological state to understand and support an exertion experience. This is a limitation that hinders the experiences we craft, which in turn limits the benefits that our experiences can afford to people. To take the first step towards beginning to fill this gap in knowledge, we borrow from advances in sports and neurology science that teach a method to study changes in the user's field of view via EEG [44, 45]. This approach enables HCI practitioners to use a human-computer integration mechanism where the computer can react to the user's neurological activity in relation to peripheral awareness to support an exertion experience.

ENA, THE EBIKE

"Ena, the eBike" is a novel modified eBike connected to the EEG signals of the rider via an Ag/AgCl coated electrode cap. Continuous physical support is offered to the rider by the eBike's electrical engine when the EEG signals of the rider are between 0.76µV-1.19µV within the high alpha range of 10-12Hz. These figures correspond to the rider being in a state of peripheral awareness, which is known to facilitate better athletic performance, coordination, and higher awareness of the environment [32, 44, 45].

The eBike

We converted a regular bike into an eBike by installing a brushless DC engine in the front wheel, an 18V battery on the eBike's body, and an engine controller that is linked to an Arduino that can receive signals corresponding to the processed EEG to control the engine acceleration support.

The EEG System

To connect the participants' neural electrophysiological signal with Ena, we used an EEG system composed of an "OpenBCI Cyton" [9], and an Ag/AgCl coated electrode cap [10], using the 10/20 electrode placement. Electrodes O1 and O2, with AFz as ground and CPz as reference stream data (Figure 3), and electroconductive paste were used to improve contact between the participant's scalp and the electrodes. This electrode montage was validated by previous studies assessing peripheral awareness via EEG [32, 44, 45].

Figure 3. Ena in action (Left). Data is streamed via electrodes O1 and O2 (top), with AFz as ground & CPz as reference (bottom).

Deriving a Peripherally Aware State from EEG Data

The target values for determining peripheral awareness were established by taking the mean voltage values exhibited by individuals in a state of peripheral awareness in previous studies [44, 45] and creating a range of two standard deviations from the mean. The EEG raw data was collected from the participant's scalp at a sampling rate of 250Hz and streamed via Bluetooth to a small laptop placed in the eBike's pannier for signal processing using OpenBCI [47]. Fast Fourier Transforms (FFT) at a rate of 1,024/s were applied to the raw EEG data to translate the signal into the frequency domain. Furthermore, a bandpass filter of 7-13Hz was applied to the EEG stream to single out frequencies which have been demonstrated to be associated with peripheral awareness in the context of the electrode montage we have adopted. To assess the participants' engagement in peripheral awareness, the calculations were performed in real-time while the participant was riding Ena. When participants' values fall between 0.76μV-1.19μV within the high alpha range of 10-12Hz and 0μV-0.7μV within the beta range of 12-13Hz, the software infers that the participant is in a peripherally aware state. Values falling outside these parameters indicate that the participant is not peripherally aware (Figure 4). The addition of beta is used in reference to alpha to ensure signals that reached the desired alpha pattern were not a product of noise across all bandwidths. This was further complemented by the use of a mean smoothing filter to mitigate movement artefacts [6]. Lastly, the values were used to calculate an output Boolean of "true" when participants were peripherally aware, and "false" when participants were not.

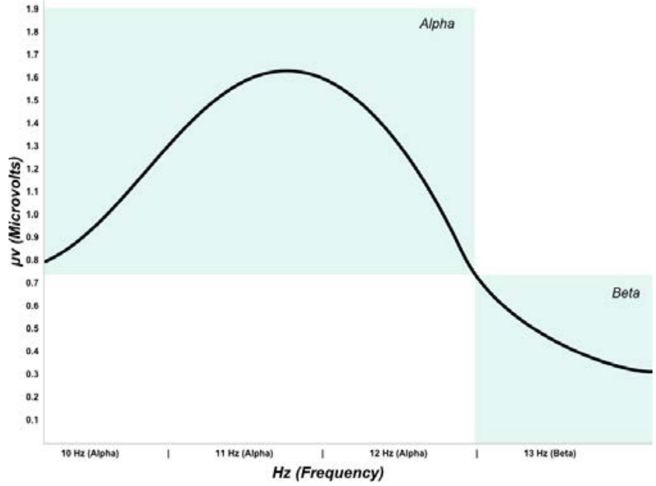

Figure 4. If the FFT above is in both the green zones, it suggests that the user is in a peripherally aware state.

Regulating the eBike's Engine Support

The output Boolean is then sent to the Arduino board over a wired serial connection at a baud rate of 56,700b/s. The Arduino interfaces with the eBike's engine via a digital-to-analogue-converter. Once the Arduino finds the Boolean to be "true", it outputs a command to activate engine support; when the Boolean is "false", it outputs a command to terminate (if it was applied) engine support.

Safety Considerations

To lower potential risks we took the following measures: 1) when the user engages the brakes, the eBike's engine is cut off regardless of EEG state; 2) Ena offers engine support gradually, as an aggressive increase could be perceived by the rider as threat and affect their field of view by narrowing it; and 3) we only recruited experienced bike riders.

STUDY

We built Ena to study peripheral awareness as a neurological state for human-computer integration in an exertion context.

Participants

Ena was studied with 20 bike riders (F=8, M=12), between the ages of 24 and 58 years (M=39.8, SD=10.5), recruited via advertisement and word of mouth. Our inclusion criteria were: a) participants had to know how to cycle so that cycling risk could be reduced, b) they cycle a minimum of once a week, so that they had recent cycling experiences to compare with their experiences using our system. Seven participants had previous experience cycling eBikes, ranging from 2 weeks to 4 years.

Setting

The study lasted three months and it took place in mild weather, without rain, in the afternoon on a suburban street. The road used was straight, flat, about 1.5 kilometres in length and it did not have traffic lights. We selected this road as riders could cycle continuously without stopping, and it often had bikes, pedestrians and vehicles to offer a realistic setting. It took participants approximately seven minutes to cycle from the start to the end and return to the starting point.

Procedure

Each participant was invited individually to the location to receive a briefing about the study and safety procedures.

Study Setup: Peripheral Training and Feedback

We started with a sports science video exercise that guided the participant to practice reaching peripheral awareness [16]. The video invited the participant to stand up straight, fix their gaze to a point in the distance, breathing in and out slowly a few times to relax (extending their arms to the sides, and bending their hands forward to move their fingers until their peripheral view caught on to the finger movement). Participants gradually adjusted how extended their arms were to test their peripheral vision detecting the finger movement while their gaze remained fixed in front. This was followed by the researchers placing the Ag/AgCl coated electrode cap on the participant and connecting the system. The participant then cycled the course twice while trying to access their peripheral awareness. Upon returning to the starting point we asked participants if they had experienced the system increasing engine support, and we also reviewed the collected EEG data to see if, and for how long, they had reached peripheral awareness. When a participant did not reach peripheral awareness, we invited them to watch the video again and practice cycling a few times. All the participants were able to reach peripheral awareness for different lengths of time while cycling before proceeding with the study.

Study Procedure

After the study set up, which included adjusting the system for comfort, the participant proceeded to cycle the course a minimum of six laps as this would offer us approximately 40 minutes of total cycling time. In between laps we conducted five 10-minute interviews.

Data Collection

We collected EEG data for all participants that showed when and for how long they had reached peripheral awareness, and this data was accessible to the participants during interviews. Every participant was interviewed every time they returned to the starting point, each interview lasted approximately 10 minutes, resulting in each participant being interviewed for approximately 50 minutes. To draw from the participants' experience we used the explicitation approach [46, 64], to capture first-person in-situ observations. We chose this approach as it provided participants with a way to tell us "what happened" throughout key moments of the experience with high detail from their perspective.

Data Analysis

We used an inductive thematic analysis approach to the data [13]. Two of the authors individually coded the interview transcripts using Nvivo software and over several meetings discussed them and converged them into themes. The themes including the participants' quotes and our experience in designing the system served as the foundation to develop design tactics phrased as practical takeaways [11].

RESULTS

We present the results in the form of themes with a total of 292 units coded. The results are organised to reflect how the user experience unfolded.

Theme 1: Participants' User Experience Highlights

This theme describes 51 units and it has three sub-themes.

T1.1: The System Is Integrated with My Brain and It Can React Before I Do (24 units)

Participants shared their reflections in relation to interacting with the system, for example, *"It is directly from my brain wave, there's no need to think about what kind of function I need to do or how to raise attention to pass information"*. It was particularly interesting to hear about participants' experiences when navigating the environment and encountering obstacles. One participant said: *"There's a minor moment of panic where you realize, 'Hey, I need to quickly find a way to avoid this incoming thing [referring to other bikes, pedestrian or vehicles that may obstruct the way if they continue ahead]', that is when the bike slows down and it gives you time to think"*, and "*The bike is actually responding before I'm capable of, that's really powerful"*. In occurrences like these the system responded to the situation by stopping the engine support before the rider could reach the breaks, resulting in the eBike going slower. This occurred as the rider perceived the oncoming obstacle as "the threat", narrowing down their field of view and resulting in EEG signal changes that terminated the eBike's engine support.

T1.2: The World Became a Video Game (9 units)

Participants engaged with other riders and pedestrians to negotiate and navigate the environment. One participant stated: *"I felt like I was participating in the environment to negotiate where I was going, this clarity of knowing where I was going, triggered the acceleration and it made it feel like a game"*. This appears to have resulted from riders finding out that once they had no oncoming obstacles and a way in mind to go ahead this could trigger the system's engine support. When the rider looked away to focus on a potential obstacle, such as another bike passing by or a pedestrian, this resulted in changes to the EEG signal and therefore the system stopped offering engine support. One participant said: *"In an action-adventure game there are non-playing characters, you can choose to interact with them or not, in this case those characters were the other riders and pedestrians because I could choose to negotiate a way with them to go through – my goal was to get rid of the obstacles so that I could get the system to accelerate again"*.

T1.3: The Experience can be Elating, Dramatic and Surreal (18 units)

Participants described a variety of emotions in relation to their experience. One participant stated: *"You get a mini high when it starts going"*, and *"You feel like a kid again"*. In another case, a participant reached out after the session to tell us: *"I just felt that same feeling I had today when the bike pushed me […] when you drive for hours and your feet still feel the vibration from the accelerator, this shared control of* *the acceleration makes it a rather dramatic experience".* This echoed the experience that other participants (7 units) also had in relation to trying to master controlling the engine support but were unable to do so immediately. Lastly, participants (5 units) commented about how they needed to be in sync with their inner body to get the system to provide engine support. One participant said: *"It feels a bit surreal because you need to be in sync with your body to get the bike to accelerate, and it then stops accelerating before I realise that is what I wanted to do*", *"it accelerates more when I'm more relaxed"*, and *"if you are uncertain and you start to look around, the bike would not go"*.

Theme 2: The User Experience of Peripheral Awareness as a Mechanism for Integration

This theme describes 88 units and it has four sub-themes.

T2.1: The System Responded to How I was Seeing the World (9 units)

Participants mentioned that they focused less on how they spent their energy according to the upcoming road, and instead focused on navigating the environment: *"The bike gives you acceleration when not much attention is required on the road, and it stops giving you acceleration when you need to pay attention to the road, that's a good thing, as you need to engage with people"*, and *"You're focusing only on the environment and not on any physical effort, so it's a different sensation"*. Participants then commented on the link between how they were interacting with their surroundings and how the system responded: *"It felt like the bike was drawing upon my perception of how safe the way ahead was"*, and *"I could see pedestrians and because I was trying to avoid them, you could feel that the bike was responding to how I was seeing the world"*.

T2.2: Strategies for Reaching Peripheral Awareness (20 units)

Participants described various strategies they engaged in to increase their peripheral awareness: *"You're trying to learn how to control that part of your mind, like learning how to flex a muscle that you're unaware of, so you got to try lots of different things until you start to figure it out"*. Some participants experimented with widening their field of view: *"When I'm looking at a nice view, I broaden my view to take it all in", "The system works when I dial into the peripheral awareness, I look ahead and embrace the horizon"*. Others focused on their breathing patterns: *"I stared into the distance while breathing in a controlled manner, and the system accelerated intermittently, then after I got my breathing under control it was continuous"*. Participants played with their field of view focus and commented that: *"It felt like a mind game, trying to control my focus until the system responded"*. Finally, participants commented that they were not thinking about increasing peripheral awareness but were rather being decisive: *"You'd identified a way to go head, you ahead, and people around you just disappeared to the side, because you've made a decision and once you have that focus, that's when the bike moves forward"*.

T2.3: In-Sync Control Between the Rider and the System (27 units)

We asked participants: *"Who was controlling the engine support was it you or was it the ebike?"*, one participant said: *"It felt like it was a combination of me, the bike and the environment. I noticed when I was riding that when you are decisive, when you feel clear in your mind as to where you are going that's when you increase the speed"*. Interestingly, others drew comparisons to the system as a partner: *"If I'm comparing it with a partner, I wouldn't use the word control, we just have to be in sync without speaking with each other"*. Participants in some cases controlled the engine support; this also depended on *"what the environment served you each time"* as commented by some (Units 5).

T2.4: Reflections on Controlling the System's Engine Support Using Peripheral Awareness (32 units)

Participants described the user experience of using their field of view relating to reaching peripheral awareness to increase the engine's support: *"'Yes I did it!': then also it was a bit unnerving because it's out of your control? Well, of course, it's technically in your control because you made it happen by broadening your vision, I think. It feels like it's out of your control because it just fades all the same"*. Participants reflected on the ambiguous qualities it offered: *"That's the thing about these sorts of things you're not aware of, to me it's an ambiguous feeling, I don't have a direct switch to say to the system 'go'"*, and a participant stated that: *"I'm affecting the system, but the system is having control over me completely because the system has more information about what's happening than me, which makes me think the system has maybe more control over what's happening than I do"*.

Theme 3: Internal Bodily Signals Observed by Users

This theme describes 24 units and it has two sub-themes.

T3.1: I Had to be In Sync with Myself Before I Could be In Sync with The System (16 units)

Participants shared observations in relation to bodily processes that they observed. One participant said, *"It's quite exciting, because it feels as though all of a sudden that you've activated a different part of one of your senses, of your vision that you didn't know you had access to. It's like you've gotten access to it all of a sudden. That's pretty cool!"* Another participant said, *"Whenever the system accelerates, my heartbeat goes up"*. Comments like these suggest that participants became aware of what they were doing and how their bodies and the system were responding to one another, facilitating a space to experiment with by being in sync with themselves and the system. One participant said: *"All that the bike is doing is trying to ensure that I'm in sync with myself and my own thoughts, using my signals. I think the reason why I was disappointed is that it was me who made the system stop accelerating"*. For other participants, how their body reacted was a mystery: *"The system is reacting to something in my body. How aware I am as to what my body actually did, I don't know"*. It appears that tuning in and observing bodily processes in relation to the system's reaction can be intriguing for some participants.

T3.2: It's the Relaxed State Not the Focus State (8 units)

Participants reflected on their emotional state and the influence that this had on the system and the experience. One participant stated: *"In other sports its similar, you want to make good decisions and you need to control things like fear, so you do deep breathing. There's a similar sort of thing of trying to control your emotional state here"*. Another participant said: *"I notice it's the relaxed state not the focus state that triggers the acceleration, if you're going along smoothly, you're relaxed and there's no panic or danger. It [the system] speeds up"*. Participants became aware of their emotional state and the influence it had on the experience.

Theme 4: Human-System Symbiotic Relationship

This theme describes 43 units and it has two sub-themes.

T4.1: Using Information Directly From The User's Brain Was Scary For Some Users And Also Interesting (27 units)

Participants expressed their opinion in relation to a future where interactive systems were able to read indirect physiological signals and automatically act on such information as our system did. Participants described (8 units) such a future as "scary" and they were wary of large technology companies misusing their indirect physiological signal readings. On the other hand, participants also endorsed such a future and wished to be more deeply integrated with technology due to the possible benefits. A participant stated, *"It was coming from my brain wave, but the system could slow down before I could react to 'hit the breaks', it was uncanny but useful",* while another participant mentioned, *"the bike was using my brain signal to control itself according to where I was looking at".* These observations suggest that the user and the system were leveraging each other's skills in a symbiotic relationship to navigate the environment.

T4.2: The System Kept Me Safe (16)

Participants described their experience in relation to the system stopping the engine support due to changes in the rider's EEG readings caused by obstacles or distractions that resulted in the user narrowing their field of view. One participant said, *"There was no acceleration as soon as I saw the pedestrian starting to cross, […] a few extra seconds with less acceleration can result in avoiding collision",* and another stated, "*I felt like the system was cycling with me and slowed us down when the situation ahead changed"*. This was particularly interesting as the rider was not accustomed to the system acting on information, especially since the system stopping the engine support resulted often in a bit of extra time that allowed the rider to scan the environment and find an alternative way around an obstacle. The system appeared to facilitate a form of mutual collaboration to navigate the environment.

Theme 5: Explainability And Trust To Support Human-Computer Interaction

This theme describes 64 units and it has three sub-themes.

T5.1: The System was Intuitive for Most Users (20 units)

Participants described their experience in relation to controlling an understanding of how to use the system, *"It was a little bit uncertain, but that was only for a second, then I think I was surprised at how intuitive it was", "When the eBike stopped going, it didn't take long to look at how to reset myself to make it start again because you have to refocus and you start to know what to do to get the bike to go forward, I don't know how it happens but it just happens pretty easy".* It appears that some participants (11 units) could more easily get the engine support to trigger, while others utilised different thinking patterns that reminded them of other experiences. One participant said: *"When I played skittles it takes a lot of concentration and you are trying to work on a specific technique".* Another said: *"I don't know whether it's the sensor or whether my brain is momentarily offline"*. In cases like this, it appeared that participants struggled to get the system going continuously as they were focused on one specific aspect which affected the width of the field of view and made it difficult to reach peripheral awareness.

T5.2: I Trusted the System Once I Realised it was Helping me to be Safe (24 units)

Participants reported developing trust in the system over time, especially, when they realised that the system could react before they could in a situation that required slowing down to scan the environment and think about where to go. This earned the rider extra time to react and it was translated by one participant as: *"the system is helping me to be safe",* another said: *"the bike is trying to keep you and other people safe from crashing"*. Another said: *"A system that enables people to focus on the activity and enables them to avoid making mistakes"*. It appears that experiencing the system acting before the rider can to slow down offered riders a sense of having a safety net.

T5.3: Participants Describe In Their Own Words What The System Does (20 units)

We invited participants to describe what the system does as a form of retrospective enquiry [27, 38] to elicit descriptions about their mental models and understanding of the system and their interaction with the system. Participants commented that the system supports their experience. One said: *"It understands that I don't see any threat on the road; this makes me relaxed and it accelerates".* Others commented on technical aspects of the system, one participant said: *"It's looking at your brainwaves and based on a specific classification of the high alpha range it triggers the engine"*. Participants commented on the importance of knowing that what they think, and do, can result in different signals which the system may act upon. One participant said: *"It's very exciting, but I think it will need to be very carefully calibrated so that people understand the relationship between what they are doing or feeling or thinking with their senses and what effect that has on the given system."*

Theme 6: Participant Suggestions

This theme describes 22 units and it has two sub-themes.

T6.1: Participants Made Suggestion To Combine Inside Of The Body Data With Computer Functions (12 units)

Participants suggestions included: *"Combining EEG with heart rate to offer more support to the rider"*, or *"Sensing sweat through the handle to help you be calm"*. There may be additional opportunities when it comes to focusing on the inside of the body to facilitate human-computer integration.

T6.2: Participants Wished Initially for More Feedback Via Other Sensory Channels (10 units)

Participants wished for more feedback via other channels such as, *"One thing that would help greatly would be a little coloured LED that glowed, that you could keep in your peripheral vision, that either changed colour of changed brightness depending on how close you are from reaching peripheral awareness"*. Another took this idea to the extreme, *"I'd like it to show me, A, everything is working as expected. B, here's your value and C, is your threshold"*. We chose not to use other forms for feedback so the rider could focus on the experience, and as such tune in to their body to receive kinetic feedback via sensory receptors in the muscle, skin, and joints [60].

DESIGN TACTICS

We now present six design tactics emerging from our experience in building and studying the system in use.

Tactic 1: Use Peripheral Awareness as a Neurological State to Study Human Performance During Interactions

From: T1.1, T4.2, T5.1

Prior work in HCI revealed a gap in knowledge in terms of aligning our designs with how we work internally when it comes to using peripheral awareness. In this article we borrow a validated approach from sports science to study peripheral awareness as a neurological state to create a novel prototype and study the user experience.

Take away: HCI Practitioners can re-use the implementation description and the code offered along with the equipment listed to study changes in the user's field of view via EEG in real-time during interaction. This is important, as changes to our field of view affects how much we see, and can influence thinking processes that enhance or hinder creativity [25, 34] and affect human performance [14, 29]. As such, we invite HCI practitioners to use peripheral awareness as a neurological state to better understand how we can support human performance in other areas within HCI, such as: health and wellbeing, critical systems, sports, and creative and collaborative work, to name just a few.

Tactic 2: Use Peripheral Awareness as a Neurological State for Integration Experiences

From: T1.1, T4.2, T5.1

Prior work in human-computer integration showed works focusing on "*on*" the user's body [3, 26], to react to bodily actions, and "*around*" the user's body [4, 18, 59], to react to external data to support human performance. In this article we explored a new mechanism for integration focusing on "*inside*" the user's body to design an integration system that reacts to changes in the user's peripheral awareness.

Take away: Our work suggests that HCI practitioners can use changes in a user's field of view relating to peripheral awareness as a mechanism for integration. We suggest that they should consider how the integration system extends the user's abilities in the contexts of the experience. Using EEG to monitor neural activity can offer access to a user's pre-attentive processing state, resulting in possibilities for integration where the system responds to a situation "before" the user can with their body. This offers design alternatives relating to the user and the system using their sensing capabilities to complement each other.

Tactic 3: Use Peripheral Awareness Integration with Kinetic Feedback to Facilitate User's to Develop Connectedness with Their Body and the System

From: T3.1, T2.4, T2.3

We chose kinetic feedback [12, 60], as this would keep the user's eye sight free so they could focus on experiencing the system, their body and the surroundings. This enabled users to concentrate on the sensation afforded by reaching peripheral awareness, which made the eBike go faster and resulted in a kinetic feedback loop.

Take away: Our work suggests that HCI practitioners can use kinetic feedback for peripheral awareness integration over mechanisms such as screen notifications, sounds, and haptics, because the user can remain attentive to the experience, rather than having to switch their attention to receive feedback via other sensory inputs, which, in turn, could affect the integration experience. This approach invites users to tune in to their body, contrasting many current technology-driven exertion experiences that take the role of sensing and offering feedback to the user via digits, graphs and tables [51]. Here we eliminated screens and focused on making the physical world the place where the interaction occurs between the user and the system.

Tactic 4: Use Peripheral Awareness Integration to Offer User's Opportunities for Mastery

From: T3.2, T1.3, T1.2, T2.1

In our study participants practiced reaching peripheral awareness to gain engine support to go faster as a "fun reward", making the experience of being "in sync" with themselves and the system "worth it". One of the opportunities of using indirect physiological signals, such as EEG is that these are difficult to control [37, 42] and therefore offer a challenge for mastery.

Take away: Our work suggests that HCI practitioners can design integration experiences by considering the following: 1) the system uses a feedback mechanism that does not take the user's attention away from what they are doing (see tactic 3), as this facilitates time for the user to focus on mastering and "tuning in" to their inner bodily processes; 2) the system offers feedback in a way that is rewarding to the user, such as increasing engine support; and 3) game theory such as "flow" [43] in relation to reactions between the user and the system during integration could be used to dynamically adjust difficulty towards achievement of mastery.

Tactic 5: Use Peripheral Awareness Integration in Real-time to Create Symbiotic Like Experiences

From: T4.1, T2.3

Challenges that limit designing for symbiotic-like experiences were quoted by Licklider [33], such as "the speed mismatch between humans and computers", where real-time computing was expensive and equipment heavy back then. This reporting of this challenge was followed by "the problem of language" where users had to communicate in computer language. Today, home and smartphone assistants require the user to learn commands to raise the system's attention and to instruct the system. With these challenges in mind, our work suggests an implementation where the system can gain access to a user's pre-attentive processing state in real-time in order to automatically act on this pre-attentive processing state before the user is able to.

Take away: Our work suggests that HCI practitioners could address "the speed mismatch challenge" by studying changes in the neural activity of the user corresponding to peripheral awareness via EEG in order to access a user's pre-attentive processing state for symbiotic-like experiences. Using the same approach, it seems that HCI practitioners could address "the problem of language" by considering neural activity changes in relation to peripheral awareness over longer periods of time to collect a time-series data set. This data set could offer user interaction and neural activity changes in relation to peripheral awareness, resulting in opportunities to tailor a system's reaction based on the user's performance, and removing potential language barriers between the user and the system for symbiotic-like experiences.

Tactic 6: Use Peripheral Awareness Integration to Promote User's Trust in the System

From: T2.4, T5.2, T5.3

Most participants realised that the system stopped offering engine support as soon as a "threat" was perceived. This often led them to feel more safe, accompanied, and secure as they had more time to react to the situation. In retrospect, participants required practice to reach peripheral awareness and gain engine support; however, once they mastered it, it afforded them a powerful feedback loop that made them feel in sync with the system. By getting to know their own signals through this feedback loop, it appears that users developed confidence in tuning in to their body, which translated to efficiently interacting with the system and a safer and enjoyable experience.

Take away: Our work suggests that HCI practitioners could consider the associated emotions elicited from the user when the integration system participates in the experience, and focus on eliciting emotions with positive valence like "joy" and "delight" as these can afford the user an opportunity to develop trust [19]. In our case the system often elicited joy when it offered engine support and it also afforded the user time to think when a threat was perceived, resulting in experiencing the system as helpful.

REFLECTIONS

We reflect on our work and highlight future considerations.

Why *Integration* and not *Interaction* or *Augmentation*? We draw from the general HCI understanding of interaction [28], which tells us that interaction happens between two entities that determine each other's behaviour, such as between a human and a machine where the human goals determine the interaction; for example, this quote from our study depicts this situation: *"My goal was to get rid of the obstacles so that I could get the system to accelerate again."* This suggests that users were initially interacting with the system. We now draw from augmentation [55] with its goal to create human-machine technologies that provide us with an extension of our own abilities. This quote from our study depicts this situation: *"It feels as all of a sudden that you've activated a different part of your senses, of your vision, that you didn't know you had access to."* This suggests that the user's abilities were augmented through our system. Finally, we draw from integration [21], which implies that both, human and machine, can draw meaning around each other's actions to work in a partnership. This quote from our study depicts this situation: *"I felt like the system was cycling with me and slowed us down when the situation ahead changed."* This suggests that it was perceived as if the user and the system were working in a partnership. In summary, it appears that users progressed from *interaction* to *augmentation* as steps on a continuum towards reaching a partnership state of human-machine *integration* rather than simply reaching a state of integration from the start.

Considerations relating to "control" when designing human-machine integration: By using peripheral vision as a binary engine controller in our prototype, we placed the user in a situation where controlling engine support was at times ambiguous. While our system only offered engine support when the rider was in a peripherally aware state to better navigate the environment; HCI practitioners should consider the users "adjustment curve" when working with integration machines that participate in the experience, as it affects the user's experience of "control" over the system.

Inquiry into the effects of our systems beyond the user: With Theme 1.2, "The World Became a Video Game", we depict how the user was moving through the environment at increased speed in a peripherally aware state while seeing the public as part of an adventure game. When designing these types of experiences, designers need to carefully consider the effects of systems not only on the user but also on nearby people, including social dynamics that may emerge between them.

Neurological states as a commodity: It is important to reflect on the implications of this technology and how it could be misused. For example, as new neurological states that map to specific states of our sensorial realm, as peripheral awareness is mapped to a specific EEG range, in the future these mappings could be commodified, and external entities could plug into. As such, we may need to begin defining what are our "inner bodily data boundaries" in order to promote our bodily data privacy.

LIMITATIONS

We acknowledge that our work could be improved, for example by deploying the system for everyday use, cycling longer distances, in different traffic conditions and environments and at night with low visibility. This could all yield additional insights. Furthermore, as part of the study setup participants practiced accessing their peripheral awareness via the sports science video in order to gain feedback on what it feels like. While in this study we do not report on peripheral awareness changes during interaction to study the user's health, we imagine that for such cases the pre-training would need to be removed or coordinated in a way that offers investigators a baseline for the user.

FUTURE WORK

This work demonstrates that peripheral awareness can be read as a neurological state in the design of integration experiences to support human performance. Future work can explore how this approach can support other domain experiences, for examples users accessing a narrow field of view for focused attention, such as a football striker selecting a target when about to score a goal, a doctor performing a precise medical procedure, or a patient interacting with a medical device for self-assessment. Interaction data in relation to changes in the user's field of view reveal opportunities into the user's pre-attentive processing state for future interventions ranging from personal health to physical-cognitive performance. To underline a few near-term opportunities, we offer the following examples based on the presented design tactics:

- Use tactic 1 to integrate peripheral awareness as a neurological state with exercises that study changes in Alzheimer's Disease sufferers' field of view [62].
- Use tactic 3 for bodily movement experiences, such as dance, martial arts and play [39], to inform the design of integration experiences that allow the user to tune in to their body for improved technique and performance.
- Use tactic 4 for emergency response operations or team sports to facilitate individuals' greater awareness of their team and of their environment.

CONCLUSION

Prior work in HCI has not yet studied changes to the user's field of view in relation to peripheral awareness via the user's neural activity. Peripheral awareness can influence how much we see, our thinking processes that hinder or support creativity, human performance and the resulting decisions we make. As such, this link between peripheral awareness and our interactions with the world is of paramount importance to the HCI community. To take the first steps to begin filling this gap in knowledge and further our field, we orchestrated and studied a system outside of the lab, in a real world setting, using *peripheral awareness* as neurological state via EEG in real-time—the changes in the user's field of view were used to create an integration between the user and an electric bike, which regulated engine support according to whether or not the user was in a state of peripheral awareness. By drawing directly from the user's neurological activity while navigating the environment, our system was able to access and react to the user's pre-attentive processing state to support the user experience.

In this first-of-a-kind approach in HCI, we offer a detailed system implementation description, including reusable code, practical themes and tactics resulting from a study with 20 bike riders to study and design integration experiences that use peripheral awareness as a neurological state. Potential future work includes an invitation for the field to explore aligning interactive experiences with internal bodily processes, such as peripheral awareness, to inform, design and afford a greater benefit to people.

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