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RESEARCH

Reflection in Learning through a Self-monitoring Device: Design Research on EEG Self-Monitoring during a Study Session

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The increasing availability of self-monitoring technologies has created opportunities for gaining awareness about one's own behavior and reflecting on it. In teaching and learning, there is interest in using self-monitoring technologies, but very few studies have explored the possibilities. In this paper, we present a design study that investigates a technology (called Feeler) that guides students to follow a specific learning script, monitors changes in their electroencephalogram (EEG) while studying, and later provides visualization of the EEG data. The results are two-fold: (1) the hardware/software prototype and (2) the conclusions from the proof-of-concept research conducted with the prototype and six participants. In the research, we collected qualitative data from interviews to identify whether the prototype supported students to develop their reflective skills. The thematic analysis of the interviews showed that the Feeler's learning script and visualization of the EEG data supported greater levels of reflection by fostering students' curiosity, puzzlement, and personal inquiry. The proof-of-concept research also provided insights into several factors, such as the value of personal experience, the challenge of assumptions, and the contextualization of the data that trigger reflective thinking. The results validate the design concept and the role of the prototype in supporting awareness of and reflection about students' mental states when they perform academic tasks.

Keywords: reflection; awareness; design; self-monitoring; technology-enhanced learning

Introduction

The ability to reflect is considered a high-order thinking skill (Strampel & Oliver, 2007). According to Dewey (1933), reflection consists of active and careful thought about the assumptions that underlie any belief or form of knowledge, as well as the implications that these assumptions might have in the future. Whether reflection takes place during an action, as reflection-in-action (Schön, 1983), or after, as reflection-on-action (Kolb, 1984), reflection has been considered key for creating new understanding (Boud, Keogh & Walker, 1985), making sense of past experiences (Kolb, 1984; Boyd & Fales, 1983), making decisions (Pee et al., 2000), problem solving (Hmelo-Silver, 2004), and changing and transforming (Boud, Keogh & Walker, 1985; Mezirow, 1991). Specifically, in learning, reflective skills have been connected to self-knowledge and self-regulation (Zimmerman, 2002): The more students are aware of their acts and practices and understand why they do them, the more likely students are to make better decisions and control their learning process.

An emerging new media culture, in which ubiquitous information and communication technology surrounds us and provides continuous access to social media and social networking services, provides challenges to focused and reflective learning. The new forms of media, however, may offer opportunities for reflection. Due to the increasing availability of devices that automatically record everyday life events, people can collect various types of personal data and reflect about their behaviors. An example of this trend is the Quantified Self (QS) movement, whose followers engage in self-monitoring in order to increase their understanding of themselves.

In the literature, a growing number of scholars have emphasized that QS devices are powerful tools for engaging people in self-reflection and increasing their awareness (Li, Dey & Forlizzi, 2011; Rivera-Pelayo et al., 2012). Recently, wearable smart objects that automatically collect data have received interest among educators, as well as researchers in the field of teaching and learning. One of the challenges identified and discussed is what data should be collected and how they should be analyzed and used (Durall & Leinonen, 2015). For instance, Lee and Drake (2016) included QS tools to monitor pupils' physical activity and used this data to motivate students to learn about basic data analysis and statistics. In the

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StudentLife study, Wang et al. (2014) collected data with self-monitoring tools about different indicators, such as stress, sleep, activity, mood, sociability, mental well-being, and academic performance, in order to assess student well-being.

The increasing availability of devices that monitor brain activity, such as low-cost electroencephalogram (EEG), has renewed interest in the possibility of cognitive neuroscience to inform teaching and learning. For instance, in educational technology research, EEG has been used to track learners' emotions in distance education (Li et al., 2012), reading comprehension (Yuan et al., 2014), and cognitive workload (Galán & Beal, 2012). In most research of this kind, students are the subjects and are not given access to the EEG data. The data were then used to create models of the students, assess their performance, or advance a specific field of knowledge. In general, the adoption of EEG techniques in education has been marginal. One reason, as Ansari, Coch and de Smedt (2011) pointed out, is the gap between basic research and applied research, which complicates the exchange of communication and knowledge between education and cognitive neuroscience.

In this paper, we present design research that explores whether and how computer-mediated practices combined with self-monitoring brainwave activity augment awareness and reflection to contribute to students' self-knowing. The ultimate goal is to empower students by helping them gain more control of their behavior. The research results are two-fold: (1) a prototype called Feeler and (2) conclusions from the proof-of-concept research conducted with the Feeler prototype.

In the following sections, we present the research design and the prototype we designed: a tool that guides students to follow a specific step-by-step study process that includes meditation, a study session, and reflection with self-monitored brainwave activity (see the Feeler Use Scenario). After presenting the prototype, we describe the results of the proof-of-concept research and identify the elements that support the behaviors related to awareness and reflection in learning.

Background

Reflection has been strongly linked to experience (Schön, 1983; Kolb, 1984; Boud, Keogh & Walker, 1985; Dewey, 1933; Sas & Dix, 2009). According to Boud, Keogh and Walker (1985: 19), reflection can be defined as a

> generic term for those intellectual and affective activities in which individuals engage to explore their experiences in order to lead to new understandings and appreciations. It may take place in isolation or in association with others. It can be done well or badly, successfully or unsuccessfully.

Despite ongoing debates about what can be considered reflection and where the boundaries are, research on reflection has recognized different levels of reflection. The seminal works of Kolb (1984), Mezirow (1991), Dewey (1933), Peltier, Hay and Drago (2005), and Kember et al. (2000) all indicate that the reflection process can be divided into awareness, critical analysis, and change. The first stage (awareness) refers to the process in which a person becomes conscious of a previous experience. Recalling actions and being able to describe them to justify certain decisions is characteristic of this stage. The next stage (critical analysis) requires identifying existing knowledge and finding possible alternatives for a specific situation. The cognitive processes involved in critical analysis include making relations, changing perspective, and creating hypotheses and different explanations. The third and last stage is change. The transformation of practices and beliefs is regarded as the consequence of awareness and critical analysis. To achieve this change, it is necessary to ask fundamental questions and challenge existing assumptions. Although in the research literature, different authors (Kolb, 1984; Mezirow 1991; Dewey, 1933; Peltier, Hay & Drago, 2005; Kember et al., 2000) describe different boundaries between the levels, all agree that there is a hierarchy, which means that each level builds on the previous one.

The tasks embedded in reflection consist of making inferences, generalizations, analogies, distinctions, and evaluations, as well as feeling, remembering, and solving problems (Mezirow, 1991). Acquiring reflective skills demands a lot of mental effort because many processes are involved. In addition, the sociocultural context in which we have developed and the learning environment in which we are studying can provide barriers to reflective learning. These barriers, however, can be overcame with critical reflection in which the barriers are recognized and accepted, named, and their origins are studied, and then strategies that can be confrontational or transformative are used (Boud & Walker, 1993).

Some education, as well as, interaction design scholars have recognized the potential of Information and Communication Technologies (ICT) to support reflection (Conole et al., 2004, Fleck and Fitzpatrick, 2010). In education, affordances have been connected to the 'characteristics of an artifact that determine if and how a particular learning behavior could possibly be enacted within a given context' (Kirschner, 2002, p. 19). The potential of QS tools for affording reflection is based on their ability to record data and experiences and revisit them to find patterns, to make relations and to develop new perspectives that can lead to a behavior change.

To the best of our knowledge, QS tools and practices have not been used in education to gather and analyze data to provide insights for students to reflect on and guide their own behavior. Although some students may already use QS tools to monitor everyday activities, such as sleeping and physical exercise, such monitoring does not mean that the students reflect on the activities or make connections to their academic activities. Moon (1999: 165) has pointed out that 'student reflection generally does not just "happen", but conditions can be structured to encourage it to happen'. In other words, if we want to foster students' reflective abilities, we need to design learning tools that support reflection.

Methodology and Research Design

Design process

In design research, theory and empirical research inform the design of new tools that are expected to introduce change that will improve human practices (Nelson & Stolterman, 2003). In this research, the aim is to influence current learning and teaching practices. Similar to design approaches that stress the importance of the artifacts produced, such as research-oriented design (Fallman, 2003), and in the model for interaction design proposed by Zimmerman et al. (2007), the final design of a tool is an important outcome of the research. By adopting this approach, we aim to create a well-informed design that includes the potential effects of the artifact on individuals' practices. Thus, design decisions about the prototype are based on research. With proof-of-concept research, we aim for evidence-based design.

In this project, the design process follows research-based design methodology (Leinonen et al., 2008; Leinonen, 2010) in four phases: contextual inquiry, participatory design, product design, and prototype as a hypothesis. Iterations during the process are frequent, and therefore, the distinction between the different phases indicates the emphasis of the design activity, instead of viewing the process as a linear activity. The process borrows from participatory design and human-centered design traditions. Crucial is a close connection with the people who would benefit from the design. This way, design researchers try to ensure that the tools designed will truly meet the needs of the community (Robertson & Simonsen, 2013).

The contextual inquiry of Feeler research explored the socio-cultural context of the design (**Table 1**). The information gathered during this phase was used to recognize challenges, such as the impact of multitasking behaviors on students' ability to focus. On the other hand, from the literature review we noticed the difficulty to apply basic research findings on design solutions aiming to improve learning. With the contextual inquiry we recognized student's acknowledgement of the importance of self-awareness and their positive views on self-monitoring and meditation practices. These findings were used to define the first design concepts, which were discussed and further developed in the participatory design sessions with graduate students. The analysis of the data gathered during these sessions was the basis for the product design and the development of the prototype that was iterated and tested with users in several following participatory design sessions. **Table 1** shows the design research instruments used during the Feeler prototype design process.

The outcomes for the stages of research-based design process informed the actual product development. During the iterations, including the production of four prototypes, the requirements were revised and updated. The four key requirements were defined: (1) The tool enables reflection on (study) action, (2) the tool encourages users to recall and think about their personal impressions and feelings, (3) the tool helps users compare their own impressions with the data recorded, and (4) the tool does not provide explicit advice or suggestions for future actions by the users.

Research stage	Description	Main outcomes
Contextual Inquiry	6 semi-structured interviews with graduate students; 4 subject-expert interviews 4 days of observation and field note-taking in a university library environment Literature review 3 focus group interviews (n = 15) conducted with graduate students to explore the relation between learning, well-being, and physiological data Questionnaire distributed to 14 graduate students before and after the participatory design sessions	– Recognition of self-awareness and meditation as valuable skills in learning and well-being – Challenges in reflecting and focusing on the academic task due to constant access to social media – Gap between research and practice regarding the use of physiological data in learning – Positive attitudes regarding self-monitoring
Participatory Design	3 participatory design workshops (n = 14) with graduate students; a design game was created to improve communication with the participants and support the data collection 2 presentations and feedback sessions during the lab's open door event on the first 2 lightweight prototypes made out of cardboard and plywood	Participants' artifacts had a shared interest in proposing: – Design solutions that respect data ownership and privacy – Other forms of self-monitoring (emotions, time dedicated, etc.) – Reflection as a separate task at the end of the process
Product Design	Design studio work produced 4 prototypes, 2 of which are functional	– Personas – Scenarios with use cases – Feeler paper prototype – Feeler plywood prototype
Prototype as Hypothesis	Production of functional prototypes in a Fab Lab (hardware) and design studio (software)	– Feeler v.1.0 – Feeler v.2.0

Table 1: Research-based design process in the Feeler prototype design.

Proof-of-concept research

A functional prototype is a combination of role, look-and-feel, and implementation prototypes (Houde & Hill, 1997). The prototype was primarily designed and built to examine the possible benefits users would experience when they use it. To collect real data about the use of the prototype, the look-and-feel, user interface, and user experience were all carefully designed and implemented so that the tool would be functional and usable in real-life study situations.

The meaningfulness of the research, including the design and building of a prototype, is based on the prediction that in the near future the option to self-monitor one's EEG activity will be widely available to students. The specific motivation for building this prototype was to investigate how use of the tool could influence students' study habits and to assess the levels of reflection the prototype could support.

To understand the feasibility of the prototype, we conducted proof-of-concept research with six graduate students (MA and PhD candidates). All participants were heavy users of digital technologies in their everyday lives. The participants originally came from South America, Europe, Asia, and Australia and were fluent in English.

Individual testing of the prototype with the participants lasted 30 minutes. The testing included a simulation of an individual study session and consisted of three parts:

1. An approximate 5-minute meditation exercise
2. An approximate 15-minute study task consisting of reading a text and solving three-dimensional (3D) puzzles
3. An approximate 5-minute analysis of their experience by silently thinking about and answering three reflective questions.

The participants used the prototype to guide them through the three parts. The participants' EEG activity (a feature of the prototype) was monitored while they performed the tasks. After the third part of the test, the participants were given a visualization of the EEG data collected during the test.

The test was followed by a semi-structured interview, which started with the interviewees thinking aloud while they looked at the EEG data visualization. The participants were asked to express their thoughts and interpretations of the brainwave data visualization. Then, the interview focused on general aspects of the design, such as interaction, user experience, and usability.

The proof-of-concept prototype tests and the interviews were video- and audio-recorded, and a qualitative analysis was performed using qualitative data analysis software (ATLAS.ti). To study how the participants assessed the prototype's support for reflective practice, a thematic analysis of the interviews was carried out. Thematic analysis is a suitable method as this approach is oriented to the identification, analysis, and reporting of patterns (themes/categories) present in research data (Braun & Clarke, 2006).

To interpret the interview data, we adopted a hybrid process that combined inductive and deductive thematic analysis (Fereday & Muir-Cochrane, 2008). The analysis followed an inductive approach. We created codes by carefully analyzing the discussions between the interviewer and the users and assigned the codes to fragments of the audio that revealed particular speech patterns related to reflection. We then revised and refined the codes several times in order to detect recurring categories. Once a more stable version of the codes was generated, it was contrasted with the research literature on levels of awareness and reflection in learning (Kolb, 1984; Mezirow, 1991; Dewey, 1933; Peltier, Hay & Drago 2005; Kember et al., 2000). Then, we generated another coding scheme and applied it again to the interview data.

To determine the applicability of the coding scheme, we invited a researcher who was not involved in the process but who was familiar with the literature to code the raw data again with the coding template (**Table 2**). The categories and the codes were found to be applicable, although some behavior found in the data was analyzed more closely and discussed among the researchers in order to make a decision about the final codes.

The codes were grouped under three categories: C1/Non-Reflection, C2/Recognition, and C3/Reflection. These categories were defined and organized according to the hierarchical levels of reflection described in the literature (Peltier, Hay & Drago, 2005; Kember et al., 2000). In this hierarchy, different levels are distinguished according to the cognitive effort involved in the task. Thus, C1 (Non-Reflection) involves very little effort, whereas C3 (Reflection) demands higher learning skills.

C1/Non-Reflection refers to situations in which the user expresses not having any particular interest on the brainwave (EEG) data or is not able to create meaning or a hypothesis out of the data visualized. The codes included under these categories are No Expectations and Not Understanding.

The category labeled C2/Recognition includes quotes that suggest the user understands the data but acknowledges only what was expressed in the visualization. Integration and Curiosity are the codes grouped under this category, which connect to Boud, Keogh and Walker's (1985) claim about the key role of emotions in reflection. Curiosity can be a necessary emotion, although it is not strong enough to ensure that reflection happens.

The category C3/Reflection refers to behaviors clearly associated with reflection, such as Puzzlement, Appropriation, and Transformation. Feeling puzzled is connected to the states of perplexity and doubt noted by Dewey (1933). People experience these states when their data do not correspond to their assumptions. Puzzlement also indicates a strong emotion (Boud, Keogh & Walker, 1985) as the person feels her or his assumptions are challenged but lacks the resources to explain why things are the way they are. Appropriation indicates that the person interprets the data and makes connections to her or his personal experience (Kolb, 1984). The term Transformation alludes to perspective transformation (Mezirow, 1991) in which, as a result of reflection, the individual changes her or his beliefs and/or modifies her or his behavior.

C1/Non-Reflection	
C1a: No Expectations	The person does not express a particular interest, question, or expectation about the prototype or the EEG data.
C1b: Not Understanding	The person cannot make sense of the EEG values or the way these data are visualized.
C2/Recognition	
C2a: Integration	The user relates the data to what is already known. The user seeks relations among the data.
C2b: Curiosity	The person expresses interest in the data or in how certain activities affect her or his mental states. The person formulates questions and identifies aspects she or he would like to know more about.
C3/Reflection	
C3a: Puzzlement	The participant feels surprised when he or she discovers values that do not correspond to her or his previous assumptions. The participant is unable to explain why the data monitored by the system differ from what she or he experienced during the session.
C3b: Appropriation	The person interprets the data (makes inferences) and builds her or his explanation for how the raw data connects to her or his experiences. The person identifies how the prototype might benefit her or his learning process. The person also determines the authenticity of the ideas and feelings that resulted during the session.
C3c: Transformation	The user's views about how his or her brain activity affects her or his study activity have changed. This new understanding motivates the user to make a change in her or his study habits or practices.

Table 2: Coding template used to analyze the qualitative data collected from the prototype testing.

Results

The research results consist of (1) the Feeler prototype, a tool designed to help students focus and reflect on their work in individual study situations, and (2) the results obtained from the proof-of-concept research that helps us understand use of the prototype, the learning experience the tool enables, and how it supports awareness and reflection and has a positive impact on students' behavior. In the following section, we present the Feeler prototype and the findings from the proof-of-concept research.

Feeler prototype

The Feeler prototype guides students in self-study, which starts with meditation and ends with self-analysis. During the sessions, students self-monitor their brain activity through EEG. The EEG data are used after the self-analysis stage, to foster students' metacognitive skills by triggering questions about the mental state of studying and then improving it. With Feeler, reflection is expected to happen during the revision and interpretation of the EEG data visualization.

The prototype is composed of the following elements (see **Figure 1**): three smart objects with which the user physically interacts (the blocks), an EEG monitoring device, and Feeler software running on a laptop.

With Feeler, students are guided to follow a script while they perform an academic task, such as studying, reviewing literature, or reading materials to prepare for an exam. The script structures the session in three parts; each part is associated with one of the smart objects, the blocks (see **Figure 2**):

1. Meditation: The first block guides the user's breathing rhythm with a slowly pulsating LED light. When the meditation period is over, the block vibrates and asks the student to move on and use the second block.
2. Study: The block is a timer that provides subtle visual information about the passing time with a grid of LED lights. The time can be set to 20 minutes, for example. When the study period is over, the block vibrates and asks the student to move on and use the third block.
3. Self-analysis: The third block activates questions displayed on the blocks. Each question is illuminated for 1 minute. The questions are as follows:
   - o How did you feel during the session?
   - o What do you expect from the EEG data?
   - o What would you change for the next session?

Inside the blocks are Arduino microcontroller boards with sensors, magnets, a vibrator, Bluetooth components, and LED lights. The blocks communicate the script to users, and very little external instruction is needed to use the blocks. The tangible interaction, playing a little with the blocks, dim lights, and gentle vibrations, is expected to be non-disruptive but still engaging for users.

The data visualized with the software include brainwave frequencies corresponding to delta, theta, alpha, beta, and gamma waves (expressed in Hertz) and attention, meditation, and blink-rate values, which are defined in percentages. The software shows each wave in one color gradation, where the transparency varies according to the value of the frequency in each brainwave (see **Figure 3**). For instance, if alpha brainwaves include values from 8 to 12 Hz, the color is more intense when the values are close to 12 Hz. If the value is near the lower limit, such as around 8 Hz, then the transparency level is almost 100%.

All the data about brain activity were exported directly from the EEG monitoring device as raw data. The prototype did not filter or clean the data but provided a

Figure 1: Feeler blocks, digital app, and EEG monitoring device.

Figure 2: To connect the Feeler smart objects, the user needs to place them next to each other.

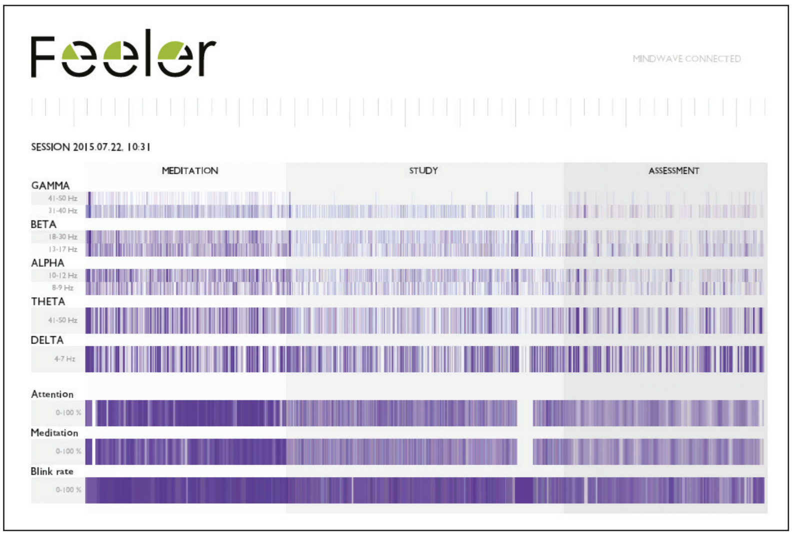

Figure 3: Screen capture of the data visualization for one session.

visualization of the raw data that is expected to be analyzed by the users by comparing, making connections, triggering questions, and creating a hypothesis. Rather than showing empirical evidence about reflection, the visualization of the EEG data in Feeler aims to engage students in reflection by practicing key reflective skills, such as making relations, questioning, and creating explanations. To provide an easy-to-read overview of the entire process, color scale visualization was used instead of waves (common in EEG). It was expected that the visualization would help students identify which brain waves (frequencies) were dominant in each moment. For simplicity, the duration of the stages was the same.

The use of Feeler and a practical use case are described in the following scenario.

Feeler Use Scenario

Timo is a second-year university student in chemistry. He is preparing the final assignment for his Inorganic Chemistry course, which consists of a paper about a specific topic chosen by the student. Timo knows that focusing on studying is difficult for him. Somehow, studying without looking every 5 minutes at what is happening on social media has become very hard. In this study task, he needs to review recent academic publications, define a research question, and design an experiment to test his hypothesis. Timo, in general, is not very familiar with academic research, and each task requires a significant effort. He found that working at home is too distracting, so he prefers to work on his final assignment at the University Learning Center. At the learning service desk, Timo finds Feeler, a tool that supports students to stay focused when working on academic tasks. He feels that this tool could be what he needs and decides to use it while researching and writing his final assignment.

To use Feeler, Timo has to follow a specific script guided by smart blocks and wear a headset that monitors his brain activity. The first task consists of a short meditation exercise. Timo has never meditated before. He tries to sync his breath to the lights of the first Feeler block. When the block vibrates, indicating the end of the meditation period, Timo feels in the right mood to read the literature and to start writing notes. He connects the second Feeler block and starts working on searching for research articles and slowly drafting some text on the computer. After 45 minutes, another vibration tells him to move to the next task, which consists of briefly analyzing his experience by answering three questions. Timo silently answers the questions shown on the blocks.

Then, he checks the Feeler software to access his brain activity data. The visualization of the data surprises him. Apparently, he was more attentive while meditating and not as much when studying. He is curious and spends a bit more time searching for information about how the different brain waves correlate to his mental activity. Over the following days, he keeps using Feeler while testing different hypotheses. For instance, he realizes that multitasking decreases his attention and relaxation and that doing physical activity in the morning works better for improving his attention span than drinking coffee. After several months of using Feeler, Timo feels he knows himself better. The feedback provided by the Feeler software has helped Timo reflect on and modify some of his study habits. For instance, every time Timo needs to work on demanding tasks, he logs out from his social media accounts and sets a time limit before he goes online again. Thanks to these behavior changes, Timo is able to focus and avoid multitasking when he studies for longer periods.

Proof-of-concept

To validate the Feeler prototype, we conducted proof-of-concept research with six graduate students. By analyzing the qualitative data (6 × 1.25 hours of audio and video recordings), we aimed to understand the prototype in use, the learning experiences the prototype facilitated, and specifically how it supported awareness and reflection in relation to helping students become more focused.

Qualitative results

In the first phase of interviews, the interpretation of the EEG visualization was discussed. The visualization presented the data in different color gradients that represented the participant's brain waves recorded during the session. During the interviews, two participants did not understand the EEG visualization. One clearly expressed a lack of understanding of the visualization: 'I don't know [. . .] I don't know how to interpret it. I mean, because here it is dark in the meditation and then is less (referring to the color intensity differences of the visualization)' (user 6).

In the research data, this and similar comments were coded as Not Understanding, which could be explained by the lack of basic information on how to interpret the visualizations. It seemed that the visualization was not easy to read. However, participants who were able to get over their initial confusion soon showed signs of Integration, by comparing and relating information in the graph to their prior understanding of brainwaves and mental states. One participant stated:

> So, technically I have no idea how you can translate this data, but I'm guessing that it's just a, these different brain types are related to different brain activity, considerably relating to study or focusing and this data can be used to understand which part of the brain or what kind of brain activity was happening during different kind of tasks. (user 2)

The participant missed some background information about brainwaves but still made guesses and interpretations regardless of a lack of technical knowledge. The participant was also already showing some signs of integration. The same participant stated the following, a good example of this effort for making relations among the data:

> I think that there was more brain activity during study and assessment. I think study is the most crowded phase or active. I'm basing this solely on the visualization, it's like there are more frequent colors, and there are frequent changes between them. (user 2)

Expressions of Curiosity were heard in many participants' comments. The data visualizations sparked the participants' interest regarding what type of activity they were engaged in at specific times: 'It would be great if you could, somehow, know at what point I was having that thought' (user 3).

In other cases, participants made hypotheses and expressed curiosity about testing whether their impressions were valid: ‘I think I was more focused when starting to read this after the meditation, but that's my feeling. It would be actually be nice to test how this it affects’ (user 1).

The participants clearly were interested in different aspects of the data and expressed their wish to know more. The participants also described various scenarios for how they could use the data and hypothesized how it could benefit them. One interviewee noted:

> Actually I would be interested how my brain activity works when I'm reading, because you know when I'm doing a task like, practical task. . . I feel that I'm concentrated. . . but while I'm reading sometimes it's really hard for me to concentrate. Sometimes my brain starts to wonder on different things and I'm reading, but I'm actually not understanding anything, so I have to read it again (user 2).

The participants were surprised by some of the conclusions they reached after they interpreted the session data. In some cases, this reaction was explicitly connected to learning. A participant stated: ‘I learned that during the meditation all the waves were stronger than in any other task, which is new thing. I didn't actually know that, and I think it's super interesting because in the end you are not doing anything new, you are just breathing’ (user 1).

Later in the test sessions, when the participants were familiar with the visualization, they started to associate it with their mental states, activities, and feelings. These expressions were marked with the code Appropriation. For instance, participants made assumptions about the visualization and its significance related to their mental states: ‘Based on my assumptions about the purple color, it seems I was more engaged in the meditation part, although I feel I was more engaged in the study part’ (user 4).

These examples are clear signs of reflection, and some are more toward Transformation, in which the participants show an interest in changing their habits and practices. Some participants also discussed the difficulty of changing their habits: ‘Yeah, I would (meditate). And as I told you, I tried once and . . . it's just—it's hard. Not hard—it just takes time to create the habit’ (user 5).

Another participant explained that she used to take the time to meditate, but she had never meditated before studying. She also expressed a real interest in making meditation before studying a practice: ‘Of course, concentrating a while and breathing, but not that really sort of thinking: now I focus on meditating [for] 15 minutes, and then I start reading. I don't know why that hadn't occurred to me [before], but maybe I should try [it]’ (user 1).

Each comment was assigned to a specific coding category. However, in some cases, the comments were ambiguous. For instance, some comments coded primarily under Curiosity could also be interpreted as including signs of Appropriation. Some of these cases dealt with participants' expressions of surprise in response to unexpected results that contradicted the participants' assumptions. A participant stated: ‘I would like to know why my attention was poor when I was in the study mode because somehow, consciously I felt that it . . . that was the time I mostly—I was the most concentrated’ (user 2).

This expression of curiosity indicates a certain level of reflection as the participant was interpreting the experience. Despite this, in the analysis, these comments were coded as part of Curiosity because the participants were curious about validating their hypotheses.

In general, participants were positive about the Feeler user experience. They enjoyed the interaction with the physical objects and the feelings that use of the prototype provoked, such as surprise, curiosity, and absorption. The following quotations show the participants' attitudes when they were asked about the boxes: ‘I like the simplicity of the interface and the idea that everything is happening inside my brain’ (user 2) and ‘They are nice boxes, I like them, I like the boxy shape’ (user 4).

Regarding the script, participants recognized that the highest levels of engagement happened while they were meditating and studying. Most participants were pleasantly surprised by the effect that meditation had on them: ‘I feel relaxed, so the meditation kind of worked for me’ (user 5).

Quantitative results

To get an idea what behaviors and interactions dominated the use of the prototype, we performed a quantitative analysis of the distribution of the codes (n = 228) among the categories (see **Table 3**). The codes assigned to the first category, C1/Non-Reflective, were very rare

Category	Code	Number of codes	Percentage
C1/Non-Reflective	No Expectations	5	2%
	Not Understanding	15	7%
C2/Recognition	Curiosity	71	31%
	Integration	48	21%
C3/Reflection	Appropriation	69	30%
	Puzzlement	13	6%
	Transformation	7	3%

Table 3: Distribution of codes found during the proof-of-concept analysis of the Feeler prototype.

(only 9% of the total): No Expectations totaled 2% and Not Understanding 7%. The codes in the second category, C2/Recognition, accounted for 52%, and included Curiosity (31%) and Integration (21%). The percentage of codes assigned to the third category, C3/Reflection, was also high (39%) and included Appropriation (30%), Puzzlement (6%), and Transformation (3%).

The distribution of the codes confirms the hierarchical relation of the behaviors linked to reflection. The distribution also demonstrates that the participants moved from C2/Recognition to C3/Reflection. The high number of comments that were coded as Integration (21%) suggests that the initial reading and interpretation of the visualization were crucial in raising awareness of and interest in the user's own cognitive processes. In connection with the latter, Curiosity about specific points in the visualization led to Appropriation after a period during which the users figured out possible connections between their state of mind, their feelings, and the activities they performed.

As the participants analyzed the visualization, awareness of their cognitive activity rose, and they were able to reflect on changing their practices and routines. By taking the percentages as a reference point, once a user reaches higher levels of C3/Reflection, the behaviors labeled C1/Non-Reflection and C2/Recognition decrease. This trend implies that it is highly unlikely that users engage in higher levels of reflection if they do not first understand and contextualize the visualization.

The number of behaviors coded as Curiosity (31%), Appropriation (30%), and Puzzlement (6%) indicates that the Feeler prototype facilitates reflection about mental states while the user is performing an academic task, such as studying alone, reviewing literature, or reading materials to prepare for an exam. The most relevant behaviors were those where the participants made a connection to their personal experiences (coded as part of Appropriation) and the cognitive disequilibrium that arises when assumptions were challenged (coded as part of Puzzlement). The difficulty in understanding the data monitored by Feeler and the inability to elucidate why the data visualization conflicted with the participants' personal perceptions explain the high levels of Curiosity (31%) shown by participants. These findings suggest that Feeler facilitates inquiry about mental states. The participants were very interested in understanding how different study practices affected their brainwave data.

The results indicate that the Feeler prototype may also support transformation and change. Although the number of behaviors coded as Transformation (3%) was low, its presence suggests that Feeler had an impact on participants' prior perceptions and assumptions about their mental states when the users performed the tasks. During the interviews, most participants recognized they had learned something about their mental activity through use of the prototype. Feeler enabled participants to reach a new understanding of studying, which, in some cases, may also lead to a long-term behavior change. The difficulty in conclusively assessing whether the participants are really planning to change their practices and whether the participants are really able to do so, however, requires longitudinal research.

Conclusion

In this research, we explored potential uses of self-monitoring technology and practices, especially EEG, to support students in acquiring high-order thinking skills, such as awareness and reflection. The design objective was to design and develop a prototype that presents and frames one approach, view, and functionality in which a learning script is combined with self-monitoring of brain activity. The research question for the proof-of-concept research was, how did the prototype support students (or not)?

In evaluating the first part of the results (the prototype), the nature of this study should be kept in mind. In design research, the prototype is considered a result and should be critically discussed by evaluating the concept and its implementation. A meaningful question to ask is whether the prototype solves the challenge (lack of awareness and reflection) in a creative way. The proof-of-concept research aimed to provide insights into the same issue with a traditional qualitative research approach.

The results validated the design concept, as well as the role of the prototype in supporting awareness and reflection about students' mental states when the students perform academic tasks. The participants recognized that the prototype helped them gain a new understanding about themselves and that it led to new questions about how their brain functions when they perform cognitive demanding tasks. Surprise and curiosity were among the most common reactions observed among the participants, which connects to middle and higher levels of reflection. The aspect that was most highly valued in the use of the Feeler prototype was the meditation phase. Participants reported a positive user experience during the meditation phase that in some cases led them to reconsider their study habits. The test also helped us identify aspects that required further improvement, such as the visualization of the brainwave data and the reflective questions included in the last box.

With the study, we also found technological and pedagogical affordances specifically related to awareness and reflection in learning. The script and the prototype introduced students to sense making, inquiry, and reflective practices and then more likely equipped the students with these skills. More research using controlled trials is needed to validate these results.

A limitation of this study is that the use of the smart objects, EEG monitoring, and software might have increased the users' awareness of the situation and reflection on their mental states (similar to the Hawthorne effect). To confirm the results, additional studies with additional subjects and control groups in real-life environments should be conducted.

Finally, the proof-of-concept research also provided valuable insights into specific aspects that influence reflection, such as the focus on personal experiences, the challenge of personal impressions, and the contextualization of the data. Therefore, future versions of the Feeler prototype will reinforce these aspects to help students increase their awareness of and reflection on different behaviors that affect their ability to stay focused. In future pilot tests conducted in real-life situations, we expect to find to what extent the Feeler prototype helps students self-regulate their attention and relaxation.

Competing Interests

The authors have no competing interests to declare.

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