

Ketchup: A Neuroadaptive Shape-Changing User Interface

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Abstract

Human-computer-interaction (HCI) has been subject to a rapid change over the past years. On one hand it is possible to control devices via a brain-computer-interface (BCI), on the other hand shape-changing interfaces (SCIs) enable the translation of information in movements and form change.

This work focuses on whether it is possible to connect these areas of research by using EEG data as input and therefore, as a control mechanism for shape-changing interfaces. To achieve this, we developed a prototype in form of a hedgehog that serves as a study companion.

The approach is rooted in the pomodoro study technique. The SCI receives data from the EEG about the cognitive load and engagement indices. This data is then transformed into a natural curling motion of the hedgehog. The state of the curl is an indication of the user's cognitive state and provides a guideline as to when to take a break.

We find that the combination of BCI (here: EEG) and SCI holds potential. For an real-life application, a more robust brain sensing technique to both movement and noise would be advantageous and more research to validate the estimation of a user's cognitive state is needed.

Überblick

Die Interaktion zwischen Mensch und Computer hat sich in den letzten Jahren rasant entwickelt und verändert. Auf der einen Seite kann Technik direkt über ein Brain-Computer-Interface gesteuert werden, auf der anderen ermöglichen Shape-Changing Interfaces die Übersetzung von Daten in Bewegung und Formveränderung.

In dieser Arbeit untersuchen wir, ob und wie die beiden Forschungsbereiche sich ergänzen können, d.h. wie die Steuerung eines Shape-Changing Interfaces durch die über ein EEG erhaltenen Daten eingesetzt werden kann. Dazu wurde ein Prototyp als Begleiter für Lernende in Form eines Igels entwickelt. Basierend auf dem Lernkonzept der Pomodoro-Technik soll das SCI die über das EEG erhaltenen, in Frequenzbänder übersetzten und als Cognitive Load und Engagement Index ausgewerteten Daten, in natürliche Bewegungen umsetzen. Dabei rollt sich der Igel angepasst an die Konzentration zusammen und streckt sich wieder. Damit wird über das SCI ein kontinuierliches Feedback über die Konzentration und Leistungsfähigkeit und eine Richtlinie für eine Pause gegeben.

Unsere Ergebnisse zeigen, dass sich durch die Kombination aus BCI (in unserem Prototypen EEG) und SCI interessante neue Möglichkeiten ergeben. Für eine weitere Entwicklung und Verbesserung wären jedoch gegenüber Störsignalen und Bewegung robustere Endverbrauchergeräte hilfreich und eine schärfere Definition der Begriffe zur Erfassung des mentalen Zustands nötig.

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Conventions

Throughout this thesis we use the following conventions:

- The thesis is written in American English.
- The first person is written in plural form.
- Unidentified third persons are described in plural form.

Short excursuses and important definitions are set off in colored boxes.

DEFINITION:

Definitions are set off in blue boxes.

EXCURSUS:

Excursuses are set off in orange boxes.

Where appropriate, paragraphs are summarized by one or two sentences that are positioned at the margin of the page.

This is a summary of a paragraph.

Chapter 1

Introduction

In the last decade, technology has become deeply interwoven into our daily lives. Thus, human-computer interaction (HCI) is shaping how we engage with the world around us from our daily routines to the way we work. Conventional graphical user interfaces (GUIs) usually represent information through virtual elements such as windows, icons, and menus. The interaction is often defined by the use of one time-multiplexed input device such as a mouse or keyboard [Fitzmaurice et al., 1995]. Therefore, the extent to which users can draw on their instinctive awareness of their surroundings and existing motor skills is limited [Alexander et al., 2018]. By incorporating physical form as an additional medium, shape-changing interfaces (SCIs) profit from our natural perception of physical objects and change the fundamental approach for interaction design [Alexander et al., 2018].

Interactive systems are evolving beyond traditional GUIs

SHAPE-CHANGING INTERFACES:

Alexander et al. [2018] define shape-changing interfaces as interactive or computationally controlled interfaces which employ a physical change of shape or change in materiality as input or output to convey information, meaning or affect. They can be self-actuated or user-actuated.

Definition:
*Shape-Changing
Interfaces*

Characteristics of SCIs
offer new input and
output possibilities

Shape-changing interfaces have given interactive systems a new form of expression through physical form, movement, texture, and material change [Alexander et al., 2018]. This added dimensionality allows for novel and rich ways of interaction and establishes new design spaces regarding both input and output possibilities in human-computer interaction (HCI) [Alexander et al., 2018; Rasmussen et al., 2012]. Therefore, current research explores the characteristics and the potential of SCIs in various areas of application [Sturdee and Alexander, 2018].

1.1 Shape-Changing Interfaces and their Application as Ambient Information Systems

As physical objects,
SCIs can be designed
to naturally fit into their
surroundings

As physical objects, SCIs provide both novel input and output modalities. Users can directly manipulate or physically interact with them, while the changes in shape, movement or other physical properties can represent information [Alexander et al., 2018]. This physicality not only allows for tangible interaction but also enables SCIs to integrate into their environment [Rasmussen et al., 2012], making them suitable as ambient information systems.

Definition:
*Ambient Information
Systems*

AMBIENT INFORMATION SYSTEMS:

Pousman and Stasko [2006] define ambient information systems (AIS) as a subset of peripheral displays, which present important but not critical information tangibly in the environment. They are designed to be aesthetically pleasing and fit naturally within their surroundings. While they mostly communicate through subtle, non-distracting changes in the periphery, they can also become more prominent when required.

By blending into their surroundings and communicating through subtle, non-disruptive movements, SCIs can function as AIS. This allows users to subconsciously process the stimuli produced by the interface without having to shift their attention away from the primary task [Juola, 2016].

Therefore, an ambient SCI should not require explicit user interaction but rather autonomously adapt to its context while remaining unobtrusive.

Current research primarily focuses on applications based on external context such as the environmental conditions, system states, or events [Daniel and Rivière, 2021; Lee et al., 2023]. However, the increasing use of brain sensing techniques in HCI research suggests moving beyond the external context towards an internal one such as the user's cognitive state [Tan and Nijholt, 2010].

SCIs can autonomously react to external context

1.2 Brain-Computer Interfaces as an Input for Shape-Changing Interfaces

BRAIN-COMPUTER INTERFACES:

Brain-computer interfaces (BCIs) are systems that establish a communication pathway between brain activity and an external device, enabling information extracted from neural activity to be translated into commands. They do not depend on peripheral nerves and muscles as an output pathway for the brain [adapted from McFarland and Wolpaw [2011]; Tan and Nijholt [2010]; Zander and Kothe [2011]].

Definition:
Brain-Computer Interfaces

In contrast to conventional input modalities, which require physical actions or observable changes in the environment, BCIs can provide information about internal processes [Tan and Nijholt, 2010]. This makes BCIs a potentially interesting input for SCIs with passive BCIs being especially promising for ambient SCIs due to their lack of intentional control.

BCIs can provide information on the user's internal state

Our aim for this work is to address the potential of neuroadaptive SCIs, i.e., to gain a better understanding of whether and how SCIs can be combined with BCIs. We aim to explore this connection by building and evaluating an ambient SCI in the form of a hedgehog, which adapts to the user's cognitive state while studying. Instead of relying

We take a first step towards exploring the potential of neuroadaptive SCIs

on fixed time intervals or having to estimate a productive length for a task, study intervals could then be adapted on the basis of the user's current cognitive state. Which will be derived from electroencephalography (EEG) measurements and represented through the curl state of the hedgehog. This provides a foundation for future studies that can more directly evaluate the effects of adapting the physical interface to the user's cognitive state.

Overall, we found that the combination of EEG-based cognitive state estimation and shape-changing interfaces shows potential as a connection between a user's internal state and the physical interface behavior. However, the limited movements and practical constraints of EEG-based interaction still restricts the range of suitable applications. Furthermore, the interpretation of cognitive states remains a subject of ongoing discussions, making it challenging to establish unambiguous mappings between the states and interface behavior.

1.3 Outline

This thesis explores the potential of connecting SCIs with BCIs by building a neuroadaptive, ambient SCI.

We first provide the theoretical aspects of BCIs and EEG relevant to this thesis in Chapter 2 "Theoretical Background". Then, we discuss the existing work on ambient SCIs and already existing applications of BCIs to monitor live engagement or cognitive load in Chapter 3 "Related Work".

Chapter 4 "SCI Prototype Design" includes the design goals, concept development and final shape-changing prototype. The fabrication of the SCI is described in Chapter 5 "SCI Fabrication" and includes the used materials and methods for the construction of the prototype such as the actuation, curl mechanism and outer appearance. Followed by Chapter 6 "Connecting SCI and BCI", which presents the important aspects of the connection such as the interface and the logical mapping between the user's cognitive state and the movement of the SCI.

We discuss the prototype constraints and limitations based on an exploratory autobiographical design and concept evaluation in Chapter 7 “Evaluation”. Lastly, in Chapter 8.1 we conclude with a summary of this thesis and propose future work.

Chapter 2

Theoretical Background

In the following sections, we provide a foundation for the BCI and EEG aspects of this work.

2.1 Brain-Computer Interfaces

Brain-computer interfaces can be divided into three different types based on the user's involvement: active, reactive and passive BCI. While with an active BCI the application is directly and intentionally controlled by only the user through their brain activity, with a reactive BCI the user can indirectly modulate the output which is based on brain activity that occurs as a reaction to external stimuli. The output of a passive BCI is derived from arbitrary, continuous brain activity without any intentional control from the user [Zander and Kothe, 2011].

BCIs can be categorized in active, reactive and passive BCIs

All three types of BCIs roughly follow a sequence of five different stages. First, brain signals are acquired using a brain sensing technique, such as EEG. The acquired signals are then processed to improve the quality, before relevant characteristics can be extracted. The obtained features are then analyzed to identify specific patterns, which are associated with a particular state or intention. This is commonly done through classification or regression models.

Typical BCI pipelines consist of five stages

Lastly, the results are translated into an output or control signal for the target system [Nicolas-Alonso and Gomez-Gil, 2012; Salahuddin and Gao, 2021]. For passive BCIs in particular, the fourth step usually is a state estimation based on continuous brain activity, which is then given to the adaptive interface (see Figure 2.1).

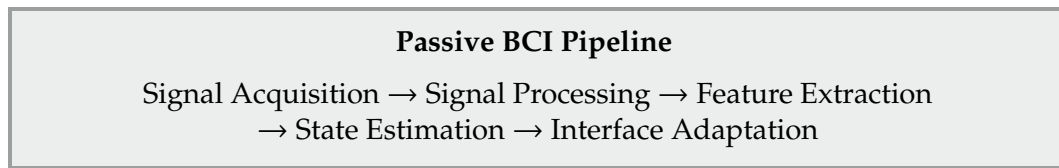


Figure 2.1: Typical processing pipeline of a passive EEG-based BCI (adapted from Salahuddin and Gao [2021]’s general BCI pipeline).

2.2 Electroencephalography EEG

EEG is a non-invasive
brain sensing
technology

Over the past years, brain sensing techniques developed fast and gained more relevance. This opens access to new consumer grade devices and their application in multiple research fields [Krigolson et al., 2017]. Tan and Nijholt [2010] divide these techniques into two classes: invasive and non-invasive technologies. Invasive sensing techniques use sensors which are implanted directly on or in the brain. These sensors cover small parts of the brain and enable a high temporal and spatial resolution. In contrast, non-invasive technologies operate using external sensors, which makes them better suitable for HCI research. Even though, there are many non-invasive technologies only EEG and functional near-infrared spectroscopy (fNIRS) fulfill important requirements for the HCI field like portability, safety, and affordability [Tan and Nijholt, 2010].

2.2.1 EEG Signal Acquisition

EEG measures the
electrical potentials
caused by large
populations of neurons

EEG recordings are typically obtained by measuring volt-

age differences between electrodes positioned at specific locations on the scalp. The recorded signal reflects changes in electrical potentials which are a result of synchronous activity of many neurons, i.e. the basic cells of the nervous system. Rather than measuring the activity of individual neurons, EEG recordings provide a summation of the potentials across large populations of them [Müller-Putz et al., 2015; Rao, 2013].

While EEG usually has a high temporal resolution, the spatial information is limited because the electrical signals are measured at the scalp after propagating through the brain and skull [Müller-Putz et al., 2015]. Additionally, the signals are susceptible to non-neural artifacts which include any kind of muscle movement and can also be caused by poor electrode contact. [Müller-Putz et al., 2015]. The usually low amount of electrodes in consumer grade devices can also impose limitations, because electrode placement and density influence the quality and range of the measurements [Putze et al., 2022]. While the limitations like a higher noise and movement sensitivity have to be carefully considered, the benefits of consumer grade devices seem to outweigh the disadvantages when used in an application. These benefits include the lower costs, a quick setup, higher comfort, and the lack of electrode gel [Putze et al., 2022].

Characteristics of EEG signals

Benefits and disadvantages of consumer grade devices

Device Used in this Work: Muse

The headset device used in this work is the InteraXon Muse from 2016. As a consumer grade device it has a reference electrode located at FPz and four dry electrodes at TP9, TP10, AF7, and AF8 (see Figure 2.2) [Bangert, 2026; Krigolson et al., 2017]. While the temporal electrodes TP9 and TP10 are placed over scalp areas which are associated with memory and emotional processing, the frontal electrodes AF7 and AF8 cover scalp regions associated with attentional processes [Sawangjai et al., 2020]. The Muse supports data transmission via Bluetooth and has a sampling rate of 256Hz with a 12-bit resolution. It is limited in its signal quality and stability due to the use of dry electrodes

The Muse has four dry electrodes

The signal quality and stability are limited

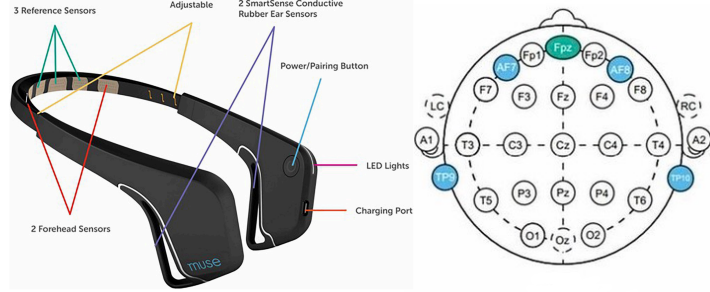


Figure 2.2: Muse device used in this work (left) and its electrode placement (right). Left picture taken from [Krigolson et al., 2021], right picture from [Sawan and Awad, 2023].

and a small number of channels [Bangert, 2026; Krigolson et al., 2017; Sawangjai et al., 2020].

2.2.2 EEG Signal Preprocessing

Raw EEG recordings contain not only neural activity but also unwanted signal components such as noise and artifacts [Müller-Putz et al., 2015]. Consequently, preprocessing is commonly applied with the aim to reduce these unwanted signal components and extract an EEG signal that is suitable for feature extraction. One common preprocessing method is filtering. While high-pass filters, which usually are between 0.1 Hz and 1 Hz, are applied to reduce slow signal drifts, low-pass filter, commonly between 30 Hz and 100 Hz, remove high-frequency noise which includes muscle movement and environmental influences [Bangert, 2026]. The choice of filter parameters represents a trade-off between suppressing unwanted signal components and preserving the relevant neural activity. Overly aggressive filtering can distort the signal while insufficient filtering may lead to unwanted components in the signal [Müller-Putz et al., 2015]. Furthermore, these filters can be applied to remove neural activity which is not of interest for the specific focus of research. For example, most components related to cognitive significant events are mostly in

a frequency range from 4 to 40 Hz [Müller-Putz et al., 2015]. As this thesis is focused on alpha, beta and theta activity, we apply a band-pass filter, i.e. a combination of high-pass and low-pass filters, at 4 Hz to 30 Hz.

Since our system is based on live feature extraction, the preprocessing is applied continuously to the incoming EEG data.

2.2.3 EEG Feature Extraction

After preprocessing, the EEG signal is transformed into specific features. While the EEG recording is initially a time-domain signal, transforming the signal into the frequency-domain offers new characteristics. A so called spectral estimation usually includes five steps: segmentation, Fast Fourier Transformation, power spectral density estimation, bandpower and feature calculation. It is used to determine how a signal's power is distributed across different frequencies. For a more detailed explanation of the first four steps refer to Bangert [2026]. The resulting spectral representation provides the basis for extracting the frequency band features used in our system. To establish the interpretation of the values in terms of cognitive states we summarize the different frequency bands and their associations. In general, changes in the bandpower have been associated with different internal states like attention, cognitive load, fatigue, and emotional engagement [Müller-Putz et al., 2015], but the boundaries vary across studies.

As our work builds on Bangert [2026]'s interface we use the following boundaries and meanings in line with the interface. The bandpower of theta (θ) is a reliable signifier for working memory demands, as it is associated with an increased mental effort and deep focus. Consequently, an increased theta power is used as an indicator of increased cognitive load. In contrast, alpha power (α) rises during a relaxed, but awake state and is usually low during demanding tasks. It is commonly applied in attention, alertness, and mental load estimation since an increased alpha power during a task has been linked with reduced concen-

Band	Frequency Range	Primary Functional Associations
Theta (θ)	4–8 Hz	Memory encoding, cognitive control, drowsiness, emotional processing
Alpha (α)	8–13 Hz	Relaxed wakefulness, attention, concentration, mental workload
Beta (β)	13–30 Hz	Active thinking, motor planning, focus, anxiety, cognitive processing

Table 2.3: The EEG frequency bands relevant to this work and their primary functional associations. Adapted from Bangert [2026].

tration and a rise in the amount of errors. Beta power (β) is applied as an indicator in research on visual attention and short-term memory. An increase is commonly interpreted as effortful attention [Bangert, 2026].

To apply the frequency bands and their associations, we will use ratios of the bandpowers through the cognitive load index and engagement index. While the formulations differ across studies and there is no universally accepted ratio index, we will use the following commonly used indices to stay in line with Bangert [2026]’s work.

The cognitive load index CLI is defined as:

$$CLI = \frac{\theta}{\alpha}$$

The engagement index ENG is defined as:

$$ENG = \frac{\beta}{\alpha + \theta}$$

Live Processing for Ratio Indices

For the shape-changing interface, the extracted features must be estimated continuously from the incoming EEG

data. The live processing uses a buffer containing 512 samples, corresponding to a 2 s window. Every new EEG sample is added to the buffer and every 64 new samples (250 ms) the spectral features and ratio indices are recalculated.

Before controlling the interface based on a combination of these ratio indices, the indices are processed separately. First, the indices are averaged over a one-second window, i.e. four values, to produce a 1 Hz signal. Then, the indices are each filtered using a rolling median over 10 s, this removes artifacts from muscle movement such as chewing. Afterwards, an exponentially-weighted moving average (EWMA) is applied to pick out general trends instead of the only momentarily changing indices. The smoothing factor of $c = 0.2$ places much weight on less recent data [Szafir and Mutlu, 2013].

Overall, this live processing transforms the acquired and preprocessed EEG signal into smoothed indices.

2.2.4 EEG State Estimation

Lastly, the smoothed indices are normalized before being combined and used as an input. While the method was proposed by Hassib et al. [2017] to normalize the engagement index, it can be applied to the cognitive load index as well since both indices are ratios derived from alpha, beta, and theta power. The normalized indices I are each calculated using:

$$I_{norm} = \frac{I_{smoothed} - I_{min}}{I_{max} - I_{min}}$$

While $I_{smoothed}$ refers to the smoothed indices which result from the live processing, the minimum and maximum values are acquired due to calibration recordings since the values differ heavily between users [Hassib et al., 2017]. The minimum is derived by taking the minimal smoothed index from a baseline recording with closed eyes and minimal movement while the maximum is derived by taking the maximal smoothed index from a *high-load* record-

ing. Basing the minimum and maximum on the smoothed data avoids choosing outliers for thresholds. The *high-load* recording includes solving arithmetic problems to achieve a high cognitive load [Chikhi et al., 2022]. While the recording for the maximum is focused on the cognitive load index, the engagement index is likely to be high as well. However, since the thresholds are continuously adapted if over or underscored during the study process, the engagement threshold is adapted throughout the later application if the upper threshold is too low after the calibration task.

Overall, the normalized indices provide the foundation to map the movements of the SCI to the cognitive state of the user.

Chapter 3

Related Work

This Chapter further reviews the research introduced in Chapter 1 and additional subfields relevant to designing a neuroadaptive shape-changing interface. It is divided into two main sections.

The first main section focusses on ambient SCIs and introduces the different levels of disruptions caused by alerts. Finally, it discusses different input modalities for ambient SCIs. Together, these fields provide the basis for the SCI design developed in Chapter 4.

Then, the second section introduces EEG as an input modality and summarizes prior research on adaptive learning approaches using brain-computer interfaces. It includes both approaches based on the cognitive load index and engagement index. This provides the basis to utilize EEG as an input modality for the SCI and for the adaptation of the EEG interface. Overall, these areas lay the foundation for the connection of the SCI with the BCI in Chapter 6.

3.1 Shape-Changing Interfaces

3.1.1 SCIs as Ambient Information Systems

In a time, in which everyone is always available and every-

The physicality of SCIs
leads to advantages



Figure 3.1: The CairnForm axissymmetric shape-change display (left) and the flat screen (right) which were compared in a user study. Pictures taken from [Daniel et al., 2019].

thing sends a notification, the physicality of SCIs poses a significant advantage. A study shows that users rarely disable alerts entirely even though conventional notifications commonly require them to shift their visual attention towards a display [Iqbal and Horvitz, 2007; Jones et al., 2017]. The disruption often causes them to switch tasks. Still, many users choose to stay informed rather than focussed [Iqbal and Horvitz, 2007]. Physical objects like SCIs which already exist in the user's environment offer an alternative solution. As they can communicate through subtle movements they can be applied as ambient systems. Research on focus and attention suggests that there is a peripheral awareness which allows users to subconsciously process peripheral stimuli, even if their attention is dedicated to a central task [Juola, 2016]. This allows SCIs to add dynamic information into the environment without becoming the primary task [Jones et al., 2017; Juola, 2016].

SCIs enable
non-disruptive alerts

SCIs are deployed as
ambient information
communication systems

One example for such an ambient SCI is CairnForm, an axissymmetric display that notifies users about the availability of renewable energy [Daniel et al., 2019]. Its cylindrical form enables users to read the information from 360° around the y-axis. While an initial study already showed a suitability for public spaces and work places, Daniel and Rivière [2021] further explored its allure and suitability as an ambient display in a two month follow-up study. The field study included six Ph.D students from their own lab-



Figure 3.2: The drop motion of an shape-changing interface mimicking plants designed to convey notification of health goals and cause different levels of disruption. Picture taken from [Lee et al., 2023].

oratory which were tasked to optimize their renewable energy consumption in the work place by shifting the charging of laptops to the hours with much renewable energy sources. To analyze the effects of an ambient display on users, the participants were split into two groups. One group worked near the CairnForm SCI while the other group received the same forecast on a flat-screen (see Figure 3.1). While the practice performance was affected by a lack of reliability in the forecast, the study still provided interesting insights about the effects of SCIs applied as ambient information communication systems for an extended period of time. The participants showed an initial struggle to apply the information received from both interfaces, especially the SCI, but both artifacts showed an increase in the pragmatic quality over time. Furthermore, the CairnForm achieved an equal pragmatic quality as the flat-screen over the course of the study, signifying a stronger learning effect. While the SCI's hedonic quality increased throughout the study, the flat-screen's decreased. This shows that the initial fascination SCIs elicit, can last over longer time frames as well. Whereas the CairnForm is similar to our SCI in its ambient quality and its ability to continuously communicate information, our system additionally works as a notification system.

Lee et al. [2023] created a plant-mimicking SCI in a Research through Design (RTD) approach, which can not only serve as an ambient SCI but adapts the disruption level of a movement based on the urgency of a notification. This approach is called abruptive technology and aims to find

Ambient SCIs still elicit a fascination in users after an increased exposure

The design of the motions can add different disruption levels

Variations in speed,
range, timing, and
direction of movements
can influence the
perceived intensity of a
disruption

a balance between keeping the user updated on important information and not overloading them with notifications. Two plant-mimicking artifacts with different motions were used in the study. The first artifact was designed to shake its leaves. Two control parameters influence the shake and can be used to adjust the level of disruptiveness and the speed of a back and forth movement. The second artifact was designed as a plant with drooping leaves (see Figure 3.2). The control parameters dictating the droop-artifact are again the distance and the speed. Additionally, the timing and direction of the movement can be controlled. In the study, the droop artifact was presented with basic up and down movement at various speeds as well as some movement sequences such as a down state which is interrupted by a sudden up and down movement (hiccup).

Subtle, slow, small and
smooth movements are
perceived as suitable
for ambient systems

The movements of the artifacts were presented in short videos and then discussed in online interviews. The focus was on the participants' reactions to different motions and on how they perceived each motion both in regard to disruptiveness and in comparison to other movements. The study suggests that smooth movements and ones with a small range are perceived as appropriate for ambient notifications, while larger and faster movements in general are perceived as more disruptive. For example, hiccup with a large range was interpreted as a good option for an escalated attempt of disruption. Furthermore, Lee et al. [2023] found that the acceptance of different levels of disruptiveness heavily depended on what was interrupted and on the importance of the notification. Participants seemed to approve of heavier disruptions in regard to immediate health problems. In contrast, health problems as a long term effect were prioritized lower. The estimated recovery time for a notification also influenced the acceptance. Notifications for quick or easy tasks such as taking a break were seen as more tolerable.

The acceptance of
disruptiveness heavily
depends on the timing,
context and the
personal prioritization of
the message

Even though the concept of abruptive technology and the artifact were designed with health notifications in mind, the ideas can be beneficial for various areas of SCI applications. While our SCI is mainly an ambient SCI, the design recommendations for disruptive motions can still be applied to

avoid unintentionally alerting the users and reducing their focus.

3.1.2 Mimicking Living Beings

As SCIs draw from contextuality, it comes in handy when their appearance is already connected to its purpose. Metaphors are known as a valuable design choice as they help to convey new concepts to users by building on their already existing knowledge [Yao, 2024]. An interface metaphor, which serves as a natural model, can elevate a system and provide realistic expectations about the result of an action [Erickson, 1995] or about the conveyed information [Yao, 2024].

Metaphors help convey new concepts to users

A metaphor often applied in SCIs for information communication are plants [Degraen et al., 2019; Lee et al., 2023; Yao, 2024]. Lee et al. [2023] used plant-mimicking SCIs because plants have been associated with health throughout history and science. In the study, participants interpreted the artifacts motions based on there existing knowledge about plants and how to care for them.

Plants are often used as a metaphors for SCIs

Info-Motion, a project about interfaces based on soft robotics technology, uses a different approach when mimicking plants. Instead of using the metaphor to give context to motions, Yao [2024]’s work is focused on mimicking the natural motions of the plant with more abstractly designed SCIs (see Figure 3.3).

Similarities to familiar biological movements can guide the user even with an abstract form

The models based on this approach were able to evoke associations with plants through their movements in most participants. This suggest that humans project meaning onto familiar biological movements, even if the overall shape is just an abstract representation of the object.

Eliciting Emotional Engagement

In addition to providing context, using familiar motions

Well-known motions can cause empathy



Figure 3.3: The different abstract SCIs which mimic plant-motions. Picture taken from [Yao, 2024].

can also evoke emotional engagement. Reynolds and Reason [2018] propose the concept of kinesthetic empathy, which demonstrates that humans have empathy for anthropic objects, i.e. objects with similar structures to humans themselves. Miyoshi [2018] suggests that this empathy extends to moving objects that do not have this structure but which motions are well known by the user. This experience with a motion can either stem from observations or embodied experience. Info-Motion is an implementation of this idea because humans regularly observe plants' motions [Yao, 2024]. The extended concept of kinesthetic empathy applies to our hedgehog-mimicking SCI since knowledge of animal movements can be acquired through observation.

Softness and a cuddly form support emotional engagement

The stiffness and feeling of materials is another design choice that can contribute to this empathy and even lead to an emotional bond. The physical resistance of a material effects how an interface is perceived and influences the mental model a user forms. Studies show that users interact with hard and soft materials in different ways. People can be positively affected by soft objects since they provide comfort. Therefore, characteristics like softness and a cuddly form can not only lead to the acceptance of an interface but also increase the emotional and physical engagement [Sugiura et al., 2016]. For stuffed toys especially, the effect of the softness is supported by a positive association stemming from most people's childhoods [Sugiura et al., 2012].

The use of an stuffed toy hedgehog as a shell for the SCI follows the same principle.

Degraen et al. [2019] suggest using a plant SCI as an avatar for the user based on an empathetic connection. This could raise awareness of the user's self and their behavior. While Degraen et al. [2019] propose to connect this idea to tracking apps such as food or movement tracker, our SCI applies this concept based on the user's mental state instead of the physical one.

A SCI as an avatar of the user

Lee et al. [2023]'s artifacts elicited not only empathy in participants but a feeling of responsibility as a caretaker for the plant. The droop artifact, as previously described, was interpreted as an unhealthy or dying plant which evoked strong negative emotions in some participants. These emotions overshadowed the conveyed information and combined with a complex or time-consuming task to reverse the effect or no way to reverse it, discouraged some participants from using such a system. This suggests that SCIs which evoke empathy in users need to be considered carefully in terms of emotions they might evoke. As our work could elicit a similar caretaker bond in users, avoiding movements that could trigger unintended emotional responses represents an important design consideration.

A user's empathy for an SCI can lead to unintended emotional responses

3.1.3 Input Modalities

The reviewed ambient shape-changing interfaces employ different input modalities to determine how and when the interface should move. CairnForm acted as an renewable-energy availability forecast in the study [Daniel et al., 2019] and therefore, reacts to system or environmental context. Lee et al. [2023]'s plant-mimicking artifacts change based on health-related notifications. Even though a health related information can influence the users state, the plants do not react to the user's health state directly. Instead, they function as reminders for predefined health-related reminders. While these modalities allow SCIs to dynamically respond to their users and the context, they primarily pro-

Ambient shape-changing interfaces respond to different input modalities

vide information about externally observable interactions or environmental conditions. Consequently, they do not directly account for the user's internal context such as the mental state. Our neuroadaptive SCI explores this opportunity by reacting to the users cognitive state derived from the cognitive load and engagement in real time.

3.2 Brain-Computer Interfaces

3.2.1 EEG as an Input Modality

EEG is the most prevalent method in HCI research

EEG is the most commonly used method in HCI research [Putze et al., 2022]. In addition to the development of consumer grade devices, recent research lowers the entry barrier by reducing the amount of interdisciplinary knowledge needed to use EEG devices. One example for this is the development of an EEG recording and analysis interface for HCI researchers, which enables objective feedback in HCI research based on continuous monitoring [Bangert, 2026]. This thesis builds upon the work of Bangert [2026] and utilizes the tools and framework provided as a foundation for the implementation of this EEG-based work. Therefore, we use the following concepts and definitions to stay consistent with Bangert's work:

Definition:
Cognitive Load Index

COGNITIVE LOAD INDEX:

The term cognitive load refers to the amount of cognitive capacity required to meet the demands imposed by a task. A high cognitive load index (CLI) signifies an elevated mental effort and increased task demands [Bangert, 2026; Paas et al., 2003].

Definition:
Engagement Index

ENGAGEMENT INDEX:

A high engagement index (ENG) indicates an elevated attentional focus and engagement [Bangert, 2026].

3.2.2 Monitoring Engagement or Cognitive Load

Monitoring the cognitive state of users during learning tasks has been investigated as a means of understanding and supporting the learning process. The approaches vary between EEG and fNIRS based systems and use either the engagement or the cognitive load as a foundation for the user's cognitive state.

ARTFUL is an adaptive review technology based on the user's engagement. Szafir and Mutlu [2013] used a consumer grade EEG device to monitor the attention of participants during online lectures in a flipped classroom concept. The information recall, i.e. the percentage of correct answers in the evaluation quiz, and the learning effect, i.e. the normalized percentage difference between the results of the initial and evaluation quizzes, were compared across four different review types to explore the effects low engagement has on learning. While the *maladaptive review* group received a review based on contents with the highest average engagement scores during the initial lecture, the *adaptive review* group reviewed the contents with the lowest initial average engagement. Additionally, there were a *no review* group and *full review* group which reviewed no or all the contents. While both the *full review* and *adaptive review* groups outperformed the *no review* group in the evaluation quiz, the *adaptive review* group additionally was able to achieve equivalent results to the *full review* group with only 25% of the review time and content. The *maladaptive review* showed no better than *no review*. These results, show an effect of attention levels on learning tasks and suggest that a low engagement during a task negatively effects the results.

Low engagement can negatively effect learning

EngageMeter is another EEG-based monitoring system. It is designed to monitor the audience's engagement during presentations and provide both real time and post-hoc feedback for the presenter [Hassib et al., 2017]. While some presenters in a real-world evaluation study were to engaged in their task to incorporate the live feedback, others perceived the feedback as very helpful especially to estimate the perceived complexity and adjust there explanations ac-

Engagement monitoring can be applied live

cordingly. The presenters saw a potential application in re-occurring and consequently familiar presentation context such as lectures and expressed an interest in experimenting with different presentation approaches based on the live feedback. All three presenters saw potential in the the post-hoc feedback and could see themselves adjusting their presentations overtime based on it. These results show that engagement monitoring can be applied in live settings and offers the users an opportunity to improve their own performance in real time. As our work, includes both real time feedback and a post-hoc review, this can help users notice when a task is not contributing to their learning and adjust it accordingly and overall evaluate their approach.

Adapting the task
difficulty based on the
user's cognitive load
can improve learning

Yuksel et al. [2016] based BACH, their real time adaptive learning system, on the cognitive workload of the user and adjusted the task difficulty while learning to play the piano. Unlike the ARTFUL and EngageMeter systems, their approach uses fNIRS as playing the piano involves frequent muscle movement. In a study, participants learned to play different piano pieces by either learning as they normally would or using the adaptive interface, which divides the piece into sections and autonomously moves on to new lines when the participant's cognitive workload fell under a predetermined threshold. The study showed improvements in both the playing speed and performance accuracy when using the adaptive learning system. This demonstrates that adapting the learning difficulty based on a continuously monitored cognitive load can improve the learning performance.

Overall, the reviewed literature demonstrates the potential of both shape-changing interfaces and passive BCIs to provide adaptive interactions. Existing ambient SCIs primarily adapt their physical form based on external information, environmental conditions, or predefined events, while research on cognitive state monitoring indicates that the user's internal state can be continuously estimated and may provide useful information for adaption. However, these approaches have largely been researched separately. This gap motivates our exploration of neuroadaptive SCIs in this thesis.

Chapter 4

SCI Prototype Design

In this chapter, we present the design of our shape-changing prototype. First, we establish a context to ground the development in. Then, we formulate the design goals and how the concept is influenced by the insight gained in Chapter 3 “Related Work”. Lastly, we present our final design of the SCI.

4.1 Establishing a Context: Studying

The context chosen to investigate this question is grounded in the study technique pomodoro.

A productivity system provides a suitable context, as studying or working at a desk represents a familiar everyday activity for many people. The clear structure of a pomodoro-based system in particular with its distinct temporal phases can be represented through a SCI. At the same time, such a system provides a context in which the cognitive state becomes relevant. Instead of relying on fixed time intervals or having to estimate a productive length for a task like the original method intends [Cirillo, 2007], in a neuroadaptive version the intervals could be adapted based on the user’s current cognitive state derived from the ratio indices CLI and ENG.

A pomodoro-based system makes a suitable context for this work

Excursus:
*The Pomodoro
 Technique*

THE POMODORO TECHNIQUE:

The pomodoro technique is a productivity system with set work and break times. It aims to keep motivation high and constant, improve the study or work process, and enhance concentration.

At the start of the day, the user plans their tasks or activities. Then a so called "pomodoro" is started, which consists of a 25 min time interval spent on one task followed by a three to five-min break. Every four "pomodoros" the short break gets replaced by a longer 15-30 min break.

The time intervals are fixed and should not be changed, even if a task is nearly finished. Additionally, it is advised to not engage in activities which induce a significant mental effort in the break intervals [adapted from Cirillo [2007]]

4.2 Design Goals

The aim for the SCI is
 to transfer information,
 while being
 non-disruptive

With our prototype, we aim for a SCI that can transfer information, while being non-disruptive. As the chosen context is studying, the prototype should fit into the a typical learning environment and subtly communicate the users cognitive state to not disrupt the user's primary task. Consequently, the size and range of movement have to be suitable for a desk area and designed for the peripheral view. The information should be presented in a way so that it can be easily understood without needing much time or thought. Since both the cognitive load and engagement are continuous values the prototype should mirror this continuous progression. To support the general principle of the pomodoro technique, the SCI needs a state to clearly indicate the need of a break. While the primary goal of the prototype is to explore the potential of BCIs as an input modality for SCIs, the prototype is intended to act as an ambient information communication system and represent the continuous changes in the user's internal state physically.

The prototype should meet the following requirements to fulfill this goal:

1. **AMBIENT SCI:**
Communicate subtly, in the periphery, and without unnecessary disruptions.
2. **POSITIVE ASSOCIATION:**
Evoke a positive or at least neutral association through the physical behavior.
3. **APPLICATION CONTEXT:**
Function as an adaptive information communication system using the estimated cognitive state as an input to determine its physical behavior.

Design requirements
based on the goal of an
ambient and
neuroadaptive
information
communication SCI

These requirements defined the prototype's form, motions, and materials.

4.3 Concept Development

In this section, the prototype's overall form and the underlying concepts are described.

Based on the design goals, the SCIs form was developed around a hedgehog-inspired shape. The choice of an animal was motivated by the potential of soft, organic and lifelike forms and movements, which can support safer and more intuitive interaction [Brocker et al., 2026]. The hedgehog and its curling motion can be connected to the cognitive state of the user. A central element of the metaphor is the hedgehog's characteristic curling behavior, which happens in natural states as hibernation or sleep but can also be a defensive response in times of a threat. This provides a basis for the curling motion to be perceived as a movement towards rest. In the context of the user's mental state a sustained curling can represent a prolonged high cognitive load which is associated with excessive mental demands and potential cognitive overload. *noch nicht in rw!!!* Therefore, the curling metaphor provides an intuitive basis

The hedgehog shape
provides a natural
context for the
interpretation of the
motion

for communicating increasing cognitive effort up to a strain through a gradual transition towards a curled state.

Excursus:
Hedgehogs

HEDGEHOGS:

Hedgehogs are mammals with the ability to curl up into a ball due to their flexible spine and their specialized muscles. This skill helps protecting hedgehogs from predators and additionally increases the spines' ability to absorb the impact force of a fall. But the curled state does not only shield the animal from potential threats, moreover it helps with hibernation as it minimizes the surface to retain body heat. All the reasons above lead to hedgehogs adapting a more or less curled state while sleeping [Drol et al., 2019].

The design supports
emotional engagement

The use of familiar and biological motion also supports emotional engagement. As discussed in Chapter 3, familiar animal movements can elicit empathy towards the SCI [Miyoshi, 2018; Yao, 2024]. The form of a hedgehog combines a recognizable animal form with soft materials and a stuffed toy as an outer shell. These characteristics are intended to present approachability and create acceptance [Sugiura et al., 2016]. As the interface represents the user's own internal state, the hedgehog can be seen as a companion or a physical representation, or avatar, of the user [Degraen et al., 2019]. Its state and behavior reflect the user's current cognitive condition, creating a connection between the user's internal state and the physical state of the hedgehog.

Negative associations
are avoided

Furthermore, the design deliberately avoids motions and states which could be perceived as sickness or death. This decision was informed by the findings from the droop plant-mimicking artifact discussed in Chapter 3. As the artifact's movement was associated with an unhealthy plant, it evoked strong negative emotional responses which discouraged some participants [Lee et al., 2023]. Since our hedgehog-mimicking SCI is intended to establish a positive relationship with the user, the design is instead based on a curling and relaxing motion to represent changes of the internal state. This allows the interface to communicate potentially undesirable states, such as an overwhelmed one,

without visually representing the user or artifact as unhealthy.

The shape-changing motion is designed to be subtle to not disrupt the user in their primary task. However, as the motion progresses with the user's cognitive state, the speed is mostly defined by the change of the cognitive load and engagement. As both indices commonly fluctuate during learning processes [Yang et al., 2025; Yuksel et al., 2016], the changes are first smoothed using a EWMA with a smoothing factor of $c = 0.1$, which places much less weight on recent data and takes a long memory window into account. This leads to an overall slower response to recent data changes and to slower movements with smaller ranges at a time. As a heavy drop in the engagement suggests that the learning effect will be reduced as described in Chapter 3, quicker movements are allowed to signal an increased urgency for action. However, the motion should still lean to the side of ambient rather than disruptive alerts, since long term health effects were prioritized lower in appropriate disruptiveness [Lee et al., 2023]. In contrast, the low complexity of the implied action and low initial hurdle of starting lead to a higher acceptance with or more disruptive alert for a break. Additionally, the stuffed toy was chosen to have an overall simple form and color design, to better blend into the user's surroundings and is sat on a wooden box which includes foam to reduce noise caused by the motor.

The motion is designed to be ambient but can increase the level of disruption

The box also serves as a foundation and therefore, allows for a defined position of the SCI by anchoring the hedgehog in a vertical position. While the horizontal position is intended to give the user a a three-quarter view of the SCI, the angle can be adjusted depending on the user's preferences. As a frontal view lets the motion seem less-prominent and a side view emphasizes the curl state, the adjustment of the angle allows the user to customize the intensity of the information display.

The intensity can be customized through the hedgehog's position

The hedgehog's structure is composed of two main parts: the outer shell and a spine, which consists of 11 individual vertebrae. This modular structure was chosen to support both the repairability and adjustability of the proto-

The SCI is designed for repairability and adjustability

type. During the design process individual vertebra can be removed, replaced or modified to fit another outer shell without needing to redesign the entire spine.

4.4 Final Prototype Design

4.4.1 Appearance

The outer appearance
and the position of the
SCI

The final prototype (see Figure 4.1) is an ambient SCI in the form of a hedgehog. It is intended to sit in the user's study environment such as the desk and act in the peripheral vision. The outer shell is a stuffed toy made of a soft fabric to imitate the belly and a fluffy one for the spikes on the back. The chosen commercially available stuffed animal is designed to be held in a curl state by a hook-and-loop fastener, to make sure the overall stiffness and form can be bent. While the overall form of the animal is simple, the hedgehog's nose is uptilted which serves as a good indicator of the curl state. The hedgehog sits on a wooden box to hide the technical components of the prototype. With a height of 21 cm, it is easily visible while still fitting into its surroundings.

4.4.2 Shape-Change Mechanism and State Design

The hedgehog's curling
represents the user's
cognitive state

The shape-change mechanism features a curl motion that continuously adapts to the user's cognitive state. The mechanism ranges from the *no curl* state, which refers to the upright position of the hedgehog, to the *full curl* state (see Figure 4.2), that refers to the hedgehog curled nearly into a ball. The *curling motion*, i.e. the movement from the *no curl* state towards the *full curl* state, indicates an generally increasing cognitive load and decreasing engagement index. During this process the hedgehog's back becomes rounded and the nose is drawn towards the belly. Therefore, the *curling* motion represents the progression towards a recommended break, whilst the *uncurling*, i.e. the progression from the *full curl* to the *no curl* state generally stands for



Figure 4.1: Ketchup: Our final SCI prototype.



Figure 4.2: The hedgehog in its *no curl* state from the frontal perspective (left) compared to its *full curl* state (right).

a cognitive regeneration. During this process, the hedgehog raises its nose and return to its upright posture, by reversing the curls movement. The movement is calm and inspired by the curling of real hedgehogs.

Chapter 5

SCI Fabrication

In this chapter, we present the fabrication of our shape-changing prototype. We give an overview over the spine construction, the realization of the curl movement and the outer appearance. The implementation process was aimed at achieving the design goals postulated in Chapter 4 “SCI Prototype Design”.

5.1 Spine Construction

The construction of the spine is oriented towards a mammalian spine to enable natural movement. To allow the curling motion, the links of the spine are alternating compressible and firm to imitate spinal disks and vertebral bodies. Both types of links are designed as prisms and stacked atop each other with the firm parts pointing in one direction and the compressible ones being oriented the opposite way. For stability the hedgehog’s spine is set on a base element which is mounted on a wooden box. The box was cut with a laser cutter and contains the technical components (see Figure 5.2).

The SCIs spine is designed like an mammalian spine

To account for the natural initial form of hedgehogs, one spinal disk is missing in the middle of the constructed spine, leading to a slightly curved spine (see Figure 5.1).

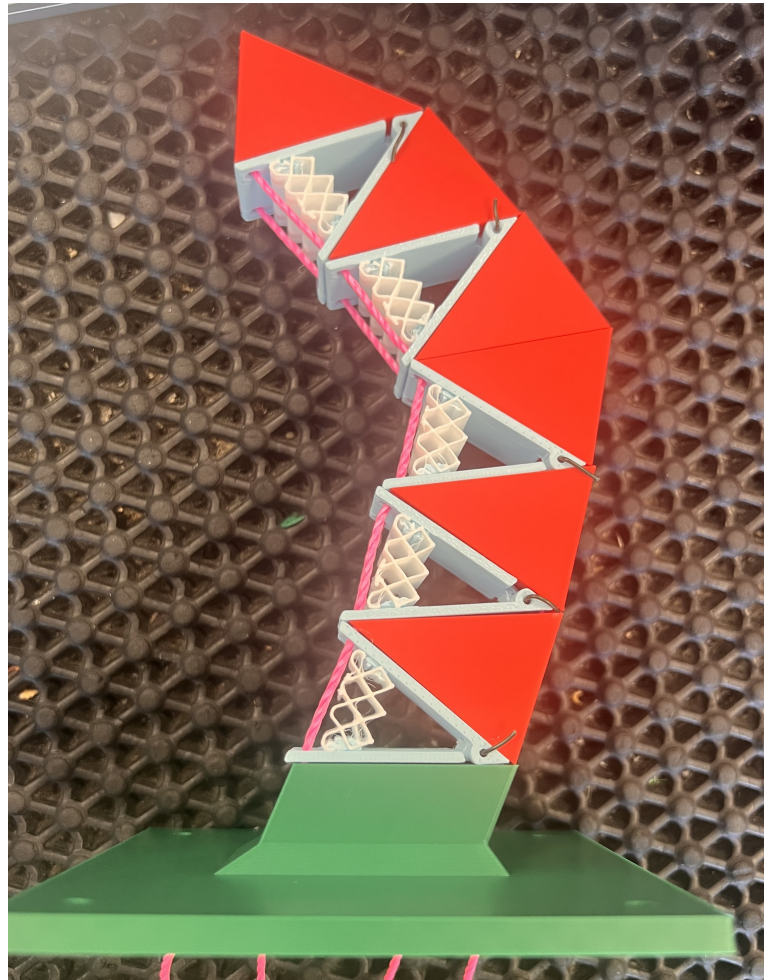


Figure 5.1: The spine construction is anchored on a base (green) and consists of firm *vertebrae* (red) and flexible *spinal disks* (light blue).

Construction of the firm
vertebrae and
spring-like
compressible parts of
the spine

Whilst the firm vertebral parts are made from TPU (see red elements in Figure 5.1), the compressible parts consist of two 3D-printed rectangles made from PLA and a bouncy structure made of TPU A90. To create the spring-like structure for the compressible parts, the TPU A90 parts were printed with an rectangular infill of 20% and no walls (see Figure 5.3). To account for the pressure put at the tip of the structure, a hinge was added. Additionally, every part of the spine has four holes to later tie them together and to activate the curl mechanism.

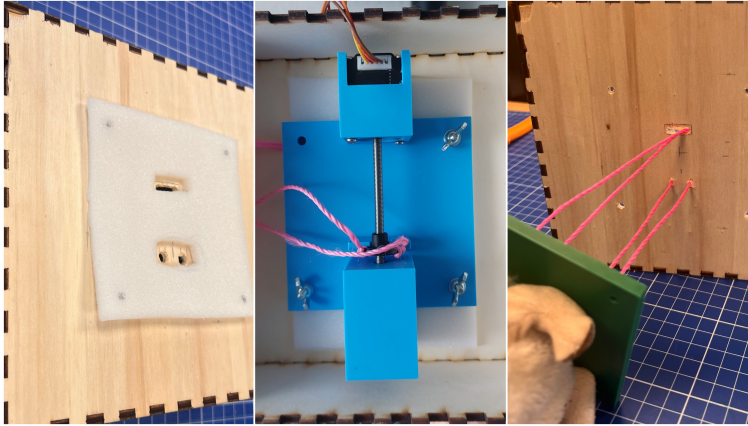


Figure 5.2: The wooden box serves as base element and contains the technical components.

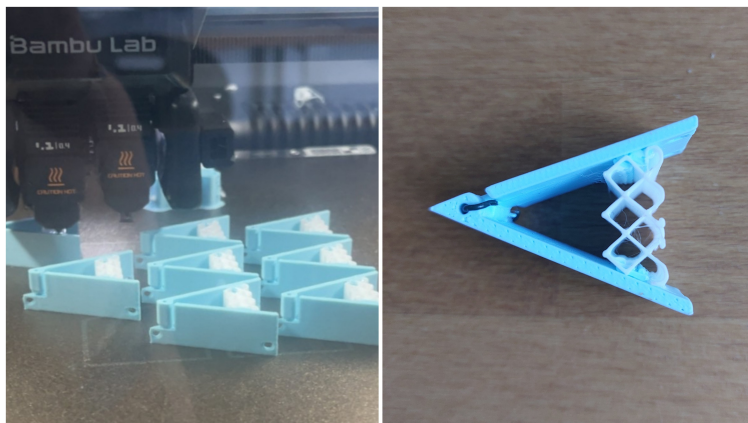


Figure 5.3: The 3D-printed intervertebral disks are a main component of the curl mechanism.

The spine is enwrapped in a protective layer of fabric, to separate the spine from the cotton wool and ensure unhindered movement (see Figure 5.4).

5.2 Curl Mechanism

The curl mechanism is rooted in a strap (PP Nylon) which

The curl mechanism is
string actuated



Figure 5.4: The protective layer for the spine is attached to the outer shell.

is pulled through the spine parts from the base to the top of the spine and back down again as can be seen in Figure 5.1. The range of motion spans from an almost upright position to a curled position that almost resemble a ball. The source of motion is a step motor from the type Nema 11 and the driver is of the type tmc2209. The driver receives a value between 0 and 100 and translates this into steps. This set-up makes it possible to access all states between the *no curl* and *full curl* state continuously.

Chapter 6

Connecting SCI and BCI

In this chapter, we explain how the final SCI prototype is controlled by the BCI. First, we will give an overview of the general connection. Then, the interface workflow is described and lastly the mapping is discussed.

Overall, the connection consists of two main parts: the software, which derives important features from the EEG data as described in the pipeline in Chapter 2 and the logical mapping, which translates the different cognitive states into movements. The software includes a user interface which is based on the EEG data analysis interface by Bangert [2026] and enables an easier access to EEG recordings for non-expert users. For this, it provides a calibration, live processing, and a review feature in addition to the already provided recording, pre-processing, and analysis features.

6.1 Interface Workflow

This section describes the workflow from the user's perspective following the interface that accords with the technical pipeline in Chapter 2 "Theoretical Background". A finished technical setup of the SCI is assumed.

Figure 6.1: The setup screen which allows the user to plan the study session including the tasks and their maximal length. The design stems from Bangert [2026]’s interface and was adapted to include the calibrations tasks as conditions.

The interface workflow and therefore the structure of the study session can be divided into four main steps: planning, calibrating, recording, and reviewing the study session. In the following, we will elaborate each step along the interface.

6.1.1 Planning

To start the application the user has to press the *start setup* button on the start screen and is then able to navigate the set-up page. Here, a name for the session has to be chosen and the different tasks can be added as conditions to structure the study session. As shown in the Figure 6.1 the baseline and maximum are already set as tasks and can not be removed. Before moving on, the Muse EEG headset has to be connected.

6.1.2 Calibration

When the plan is set and a EEG headset device connected, the user can move on to the *electrode contact check* page. Here, the user is required to record a baseline and a maximum recording to establish low and high values of both the engagement and cognitive load index. The baseline is recorded first and used to check the electrode contact. The user sits relaxed with their eyes closed and avoids strong movements or distractions of any kind. The baseline has to

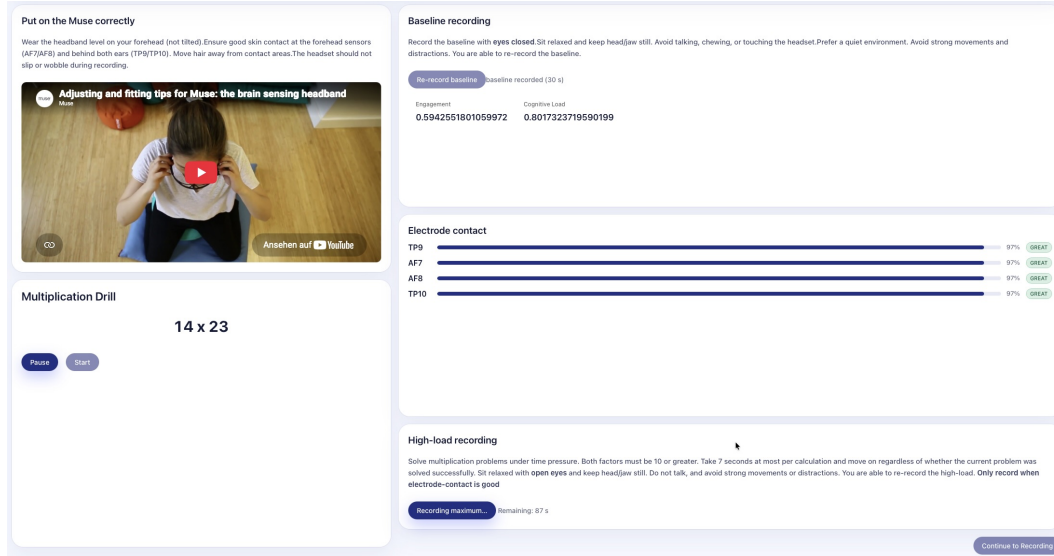


Figure 6.2: The calibration page for baseline recording, which is used for an electrode contact check as well as to establish a lower threshold, and for a high-load recording to establish an upper threshold. While the Muse positioning guide, the baseline recording and the electrode contact check are from Bangert [2026], the high-load recording and multiplication drill were added.

be re-recorded until the electrodes have good contact and there are no distractions or unnecessary movements. Once the baseline and therefore the lower thresholds are sufficiently recorded, the user can move on to the recording for the upper thresholds. While it is important to note, that the derived value is not necessarily the highest the indices can reach, we will refer to these upper thresholds as *maximum* in the following. For the maximum recording a multiplication drill is used. To minimize additional effort for the user and provide a good foundation, a multiplication generator is integrated into the interface (see Figure 6.2). The generator should be started before the recording, so that the user is already calculating when the recording starts. Being as still as possible is again important to get an ideal maximum. During the baseline and maximum recording the SCI is not activated, as the thresholds are calibrated using these recordings. The derived lower and upper thresholds for both indices are presented after the baseline and the maximum are recorded and only if both are valid thresholds, i.e.

if the minimum for both indices is smaller than the according maximum, the set up is ready and the SCI is activated.

6.1.3 Studying and Recording

After moving to the recording screen, the user chooses a predefined task in a drop down menu and presses the *start recording* button. While the recording stops automatically if the predefined maximal length is reached, it can be stopped manually by the user as well. The hedgehog adapts to the cognitive state of the user while a recording is running and returns to the upright position when a recording ends. Therefore, it alerts the user if the maximal time for a task is reached. During the recording the curl state of the hedgehog informs the user about their cognitive state and suggests breaks with its movements. If a user decides to take a break, the recording should be stopped and started a new after the break ends.

6.1.4 Review

After all tasks and therefore all recordings are finished, the user can proceed to the review page to analyze the study session post-hoc. The review is kept simple in line with the rest of the interface [Bangert, 2026] and offers a graph depicting the cognitive load and engagement index over time for the tasks. Additionally, it presents a summary over all tasks with the minimum, maximum and average values for each of the indices (see Figure 6.3).

6.2 Logical Mapping

The input for the SCI is based on the engagement index (ENG) and cognitive load index (CLI) which are derived from the live-processed data and normalized to values be-



Figure 6.3: The review page of the interface depicts a graph of the indices over time as well as a summary of the minimum, maximum and average values for each task.

tween 0 and 100. The curl state is calculated by applying:

$$C = 50 * \frac{CLI}{100} * (2 - \frac{ENG}{100})$$

Therefore, $C = 0$ equals the *no curl* state and $C = 100$ the *full curl* state with the states defined as described in Chapter 4. The hedgehog's movement stays between the *no curl*, i.e. $C = 0$, and *half curl* state, i.e. $C = 50$, as long as the cognitive load index stays underneath 50 or the engagement index is equal to 100. A state between *half curl* and *full curl* indicates a cognitive load index higher than 50 or an engagement index significantly smaller than 100.

The following mapping between the curl state and signs for the user was designed under the assumption of a prolonged high cognitive load index with a dropping engagement index as an potential overload and a high cognitive load combined with a high engagement index as a challenging but productive task. The assumptions were made based on the associations of the frequency bands as discussed in Chapter 2 as well as the results discussed in Chapter 3, which include a link between a low engagement and less information recall [Szafir and Mutlu, 2013] and a successful adaptive learning system that increases the task difficulty when the cognitive load falls below a predefined threshold Yuksel et al. [2016].

A curl state of $0 \leq C < 50$ indicates a cognitive state with a low to moderate cognitive load. This can be a state in which

the task difficulty could potentially be increased as well as a state of productive work if the curl is close to $C = 50$. A curling motion from a state above $C = 50$ signifies a rising cognitive load or a dropping engagement. Both imply a progress towards a break. In contrast, the uncurling motion implies a decreasing cognitive load or rising engagement, which can be interpreted as a cognitive regeneration. While the curl state of the hedgehog gives an estimation of the current cognitive state of the user, only prolonged signals should be seen as an indicator as both indices commonly fluctuate during a study task.

Overall, the curl state C of the hedgehog provides a guideline for the user whether a study session is productive or not, but should not be seen as a strict law. Simplified markers to watch out for are a quarter curl which has a high probability for a non-challenging task, a half curl which suggests productive work and a three-quarter curl which can be seen as a first nudge towards a break. Additionally, it is unlikely to reach a constant state of $C = 100$ which implies that the upper range should already be seen as a break indicator.

Chapter 7

Evaluation

7.1 Autobiographical (Design) Evaluation

Autobiographical design approaches are commonly used in HCI research, even though often under documented. This method is often applied as it provides the researchers with a first evaluation. In this way first errors can be ruled out easily before the prototype is presented to a larger group of users [Neustaedter and Sengers, 2012]

7.1.1 Evaluation Goal

Overall, our autobiographical evaluation aims to fill in on the gap whether it is possible to use EEG data as an input for SCIs. For that we investigate different aspects of the user experience. We focus on whether the curl state is an adequate representation of the user's subjective workload. Additionally, we explore the user's association with the hedgehog and if it is perceived as supportive or distracting, also with regard to its position on the desk.

We investigate the user
experience in our
evaluation

7.1.2 Evaluation Method

Our procedure includes
a questionnaire

The method of evaluation is an autobiographical test consisting of performing a set task for a maximum of 30 minutes or until the SCI signals a break. Each round it can be chosen between memory and sudoku. After the task is finished, a questionnaire, evaluating the user experience is answered. The questionnaire consists of seven questions with answers possibilities being a number from one to five. Five equals 'completely agreed', while one equals 'not true at all'.

The questions are the following:

1. I felt focused/ concentrated
2. I felt engaged/ motivated
3. I noticed the hedgehog
4. The hedgehog was a distraction
5. I noticed the information conveyed by the hedgehog's movement
6. I solved the memory/ sudoku successfully
7. The break was adequate (additionally from ranking the statement 1 to 5, the options too early and too late are added)

When the questions are answered, the break starts. The next round is started, when the SCI indicates *no curl*. This method is repeated at least three times.

7.1.3 Setup and Procedure

The evaluation setup
resembled a work desk

The evaluation setup consists of a desk with a monitor and a mouse to resemble a study environment. The SCI is placed on the desk near the monitor in the user's peripheral view. In the first setup, the SCI was turned to face towards



Figure 7.1: The workplace setup as used in the evaluation study. The hedgehog faces the user.

the user as shown in Figure 7.1. Later, it was turned to show a three-quarter view.

The user is positioned in front of the monitor, wearing the EEG connected to the SCI. The user is required to keep as still as possible. The use of the mouse is to be the only movement allowed. Typing and writing is not permitted.

7.2 Results and Discussion

7.2.1 Influence of the SCI on the Study Session

The size of the hedgehog was found to be suitable for positioning next to the monitor, without hiding part of the screen. The only adaption which had to be made, was to slightly adjust the height of the screen. For future work a height adjustable box for the hedgehog to sit on could be considered. The view of the hedgehog was changed from

The size and position of the hedgehog were suitable for a desk setup

a frontal view to a three-quarter view to get a better estimate of the curl state. This allowed for a better awareness of the motions and could later be adapted by user's based on their personal preferences as well as the intensity of the primary task.

The noise and restricted movement caused distractions

Regarding the design and position, only the noise of the motor was found to be distracting, despite the layers of foam to dim the noise. Even though the noise was seen as a slight distraction in the beginning, it also caused curiosity about the curl state as it served as indication of movement. The bigger distraction was found within the limitations of the EEG. As other signals, which includes muscle movement, can influence the quality of the EEG data, every kind of movement has to be kept minimal. This takes focus from the primary task and shifts it towards the minimization of movement. Additionally, this restriction was a limitation in choosing a suitable task for the study, which implies a limited use in real life applications.

Furthermore, it was found that after an acclimatization period the distraction by the noise decreased and the apprehension of the signals increased. After the completion of three task windows, the hedgehog was perceived as calming and motivational companion.

7.2.2 Does the Timing of SCI States Match the Feeling (Cognitive State)?

Perception of the SCI output

Overall the SCI output aligned with the subjective cognitive state. There is a tendency to perceive the hedgehogs curl state as roughly 10 percent more recovered as it is, which could be explained by the fact that neither the minimum nor the maximum are marked as such and due to the baseline not likely to be reached.

Additionally it was found that the breaks were more efficient, when the user closed the eyes or looked through a window in the distance.

Furthermore, the test rounds were not ended by a signal from the hedgehog, instead the time window of 30 minutes was over. The curl state indicated no need for a break, which matched the users feeling of still being focused. To avoid this in future tests, the difficulty of the test task could be enhanced.

Chapter 8

Summary and Future Work

8.1 Summary and Contributions

In this chapter, we conclude the thesis by summarizing the main contributions and proposing future work.

The primary objective of this work was to explore the potential posed by a neuroadaptive shape-changing interface. For this, we designed and implemented a shape-changing interface in the form of a hedgehog which adapts to the user's cognitive state. To estimate this state, the brain sensing technique EEG was used and the both the cognitive load index and engagement index were derived. These indices were then combined in a formula to estimate the user's concentration and provide a guideline as to whether the ongoing study process is still productive or a break should be taken.

Shape-changing
interfaces as
neuroadaptive
systems

As the SCI indicates the guideline live during the primary task, the design of the SCI aims to be ambient and not disrupt the user's focus. Additionally, the design aimed to mimic the natural movements of hedgehogs and elicit empathy in the user.

Design goals for an
ambient interaction

Evaluation of the
suitability and feasibility

The prototype was evaluated through an autobiographical evaluation approach, which allowed us to investigate both the effect of the SCIs motions as well as the overall setup as a neuroadaptive system and therefore, the suitability and feasibility of a connection between SCIs and BCIs. The evaluation found that the SCIs output aligned with the subjective cognitive state. Furthermore, after an acclimatization period, the hedgehog was perceived as a calming and motivational study companion, suggesting that the physical and organic design can support an ambient form of cognitive state communication.

Potential and limitations
of a neuroadaptive SCI

The evaluation also identified practical consideration for integrating EEG-based SCIs into everyday study environments. The hedgehog's size and position were suitable for a desk setting while different orientations influenced the user's awareness. A three-quarter view was found as a suitable starting orientation while adjustments could be made based on the cognitive demand of the primary task. At the same time, the restricted movement due to the EEG device represents a distraction and highlights an important limitations of using EEG in real-life learning environments.

Contributions of the
thesis

Overall, the work demonstrates the feasibility of using an internally estimated cognitive state as an input for an ambient shape-changing interface. It thereby connects approaches from neuroadaptive learning and shape-changing interfaces and provides a basis for investigating physical, peripheral representations of the cognitive state.

8.2 Future Work

Reducing the motor
noise and offer more
positioning options

Future work should address the physical limitations of the SCI prototype. The motor noise should be reduced, as it was initially perceived as distracting. Additionally, future versions could offer more positioning and orientation options such as an adjustable stand for the height or a wall mount to offer positions above a screen as well. To better indicate the curl state, a box design which subtly communicate the minimum and maximum curl would be advantageous.

Beyond improving the current prototype, future work could investigate the neuroadaptive approach with a version of the SCI which could be placed on the user's lab during studying and therefore, communicate the state through haptic feedback. Here, a breathing mechanism could be added by expanding and subtracting the belly.

Adding a breathing mechanism

Furthermore, the effect the SCI has on the user's current state could be explored and a closed-loop between the SCI and BCI could be constructed. The SCI could aim to calm the user during breaks in addition to the state indication in work periods.

Aiming for a closed-loop between the SCI and BCI

As the restricted movement through the EEG caused distractions, a fNIRS based system could be build. This approach could be advantageous when exploring cognitive regeneration and the break periods as well. Lastly, the mapping between the cognitive state and the motion could be validated and improved in future work.

Building a fNIRS based system

Appendix A

Shape-Changing Interface Setup

A.1 Setup

A.1.1 Initial Setup

1. Flash code on microcontroller
2. Read USB-port and adjust it manually in the code

A.1.2 Usual Setup

1. Connect the microcontroller and laptop by cable
2. Connect the microcontroller to a voltage source with 12 Volt
3. Press the reset button of the microcontroller if ketchup (SCI) does not curl
4. make sure SCI is activated in code (see above)
5. Start backend and frontend as usual (see Bangert [2026]'s work)

A.2 Stopping the SCI

1. Make sure that the SCI is not moving (Ketchup should not be curled)
2. Stop frontend and backend
3. Disconnect the connecting between the microcontroller and the power source

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