Towards Enhancing Spatial Awareness through Electrical Muscle Stimulation

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ABSTRACT

With advances of new technologies there is a growing interest in augmenting human senses with sensory information. This paper aims at using electrical muscle stimulation (EMS) to support sensing the proximity of objects. We propose a concept relating distance to properties of electrical muscle stimulation. Our study provides first evidence that our approach can be used to convey information on the proximity of objects to users of the EMS system. We report on the correlations between a simulated proximity and the proximity felt based on EMS. Based on this we propose fields of applications which can benefit from such a system. Our approach can be used where people need to be notified with regard to spatial information, e.g., dangerous objects approaching from behind.

CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**.

KEYWORDS

Electrical Muscle Stimulation; Haptic Feedback; Enhancement Device; Spatial Awareness

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1 INTRODUCTION AND RELATED WORK

In this work a special form of human enhancement is considered. Electrical Muscle Stimulation (EMS), which is broadly studied in fields including "medicine, biology, biomechanics, psychology and art" [12], can also be employed to discover new means of human computer interaction. EMS can be used to generate haptic feedback using different parameters and waveforms [10]. Electrodes used in conjunction with off-the-shelf EMS devices enable an epidermal application, that is non-invasive, easily adjustable and removable. The principle underlying EMS is to provide an electrical signal to a muscle via electrodes attached to the skin above the specific muscle. Upon delivering an EMS signal, a muscle or a muscle group is activated and can produce a body movement. The muscle or muscle group that requires activation can specifically be targeted by the placement of the electrodes on the body [12]. Surface electrodes can be used to provide EMS feedback to well-reachable surface muscles [10].

EMS has been employed extensively in the domain of situational awareness [6, 7, 9]. Pfeiffer et al. use EMS to control walking direction and thus relieve users from their navigation task [9]. Lopes et al. use EMS to communicate the affordance of objects [6] and to provide haptics to walls in virtual reality [7]. Important features of related works include approaches to enhance spatial awareness, the use of Transcutaneous Electrical Nerve Stimulation (TENS) and sensory augmentation. Cassinelli et al. developed a module, that acts as a *haptic radar*, meaning that it is able to provide spatial information via vibro-tactile cues, wherever the module is placed on the skin. Metaphorically, this module can be regarded as "an artificial hair capable of sensing obstacles" [1]. A headband with 360 degrees of spatial awareness allowed a significant number of participants to avoid an unseen object coming from behind. Most participants reacted appropriately in response to incoming obstacles, and they stated that the *haptic radar* is intuitive and easy to use [1]. *HindSight* enhances spatial awareness through object detection using 360-degree videos and provides users with audio feedback when relevant objects are detected. The approach used for the system is based on computer vision and supports users by continuously notifying them about points of interest in their surroundings. Furthermore, *HindSight* can potentially redirect its users' attention when they are distracted by other stimuli [13]. However, the developed system is quite bulky since users need to carry a laptop. Kawahara and Suzuki propose a system capable of enhancing spatial awareness for vehicle drivers using TENS. The study encompassed measuring the minimum distance between the walls of a virtual course in conditions with or without TENS assistance. Half of the participants in the study avoided the walls of a virtual course using the TENS assistance. Kawahara and Suzuki state, that TENS has potential as an assistance system, for drivers to gain spatial awareness [5].

In this paper we propose a concept for enhancing spatial awareness by relating properties of the EMS design space to properties of spatial perception. Our work has three contributions:

- We propose an intensity-proximity mapping for making the distance of objects perceivable using EMS feedback.
- We conducted a user study showing that participants were able to encode our intensity-proximity mapping.
- We present potential use cases for our concept of mapping spatial distance into perceivable EMS feedback.

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2 CONCEPT FOR ENHANCED SPATIAL AWARENESS THROUGH EMS

Both EMS and spatial perception have a broad spectrum of aspects or more specifically parameters that could be combined to feed users with content characteristics via EMS. To keep the complexity on an acceptable level, attention is focused solely on perception of proximity. This implies that only distance and not direction is taken into account. Regarding EMS, the position on the body, application of current and impulse characteristics play a significant role in the proposed concept. The zones defined in the theory of proxemics [4] have largely shaped the definition of the proposed concept for enhanced spatial awareness. The zones defined in our work are not associated with metric distances, but are rather left unlabeled, thus leaving room for interpretation of the participants using the concept in practical settings. However, the concept can also be adapted to concrete use cases, that require the definition of exact distances.

The core idea behind the concept, is to provide individuals with an enhanced haptic sense for proximity. To realise this, EMS is employed to provide different intensities of feedback. EMS is chosen as a feedback modality due to its broad design space and easy epidermal application. The discrete intensity levels are generated using different current amplitudes. To establish the maximum current or the maximum intensity of the EMS signal, also denoted as $max_{EMScurrent}$ in figure 1, the signal has to be calibrated separately for each body part of the participant. Distinct proximities labeled with egocentric, relative proximity values: Very close, close, mid-range, far, very far and out of range are conveyed to users. Egocentric in this context implies, that the proximity values are described from the viewpoint of the individual wearing the enhancement device.

Humans rely on multiple information sources to make decisions or plan actions. These sources are typically called signals or cues. Information originating from one sense may contain multiple cues. The visual sense, for instance, provides human beings with cues, such as, texture and motion, and supports them with judging the three-dimensional layout of the environment [15]. The combination of multiple senses can provide rich information about the environment and its objects. Combining or integrating cues can help humans to better understand environmental properties and therefore enhance decision-making, when acting or navigating in environments [15]. The concept we propose builds upon the principle of cue integration by combining visual and haptic cues for tasks where estimating proximities are essential.

3 STUDY OF CONCEPT

The purpose of our study is to investigate whether participants understand the intensity-proximity mapping. The stimulation using EMS signals is performed using three different waveforms: Saw, sinus and square waveform. The perception of participants during the experiment is recorded using a semi-structured questionnaire. The study is executed with the help of the *Let Your Body Move* toolkit and the *Wizard of Oz* [8] mobile application.

3.1 Study Design

Prior to the execution of the study, candidates are handed a consent form consisting of a disclaimer, that highlights the potential health risks associated with the use of EMS devices and also explicitly states that candidates need to be healthy to participate. Demographic data such as age, gender and dominant hand of the candidates is collected, and it is enquired whether these candidates have prior experience with EMS. Participants are allowed to get accustomed to the EMS device and its basic functions. The pulse width (250 μs) and the frequency (6 Hz) of the signal, which are values based on the warm-up program of the EMS device *Beurer EM49*, are kept constant during the study. The feedback given ranges from an EMS signal with zero intensity to an EMS signal with high intensity. Participants calibrated the individual maximum signal intensity via the off-the-shelf EMS device (*Beurer EM49*). We recorded this value for each body part that is stimulated during the study. The feedback is divided into six signal intensities on a linear scale (Fig. 1).

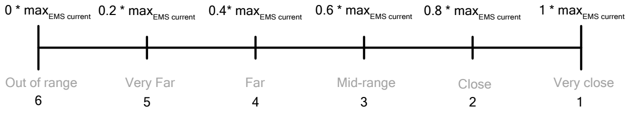


Figure 1: Intensity-proximity mapping

Each condition (4 body parts x 3 waveforms = 12 conditions) consists of 18 trials in randomized order. There are three repetitions for six distinct intensity levels ranging from zero intensity to the maximum intensity determined by the participant. For each trial, participants are asked to rate the perceived level of intensity (one data point per trial) which is provided manually by the experimenter using the off-the-shelf EMS device. More specifically participants orally rate the proximity coded into the EMS signal via the intensity-proximity mapping, using a Likert scale with 1 = "Very close", 2 = "Close", 3 = "Mid-range", 4 = "Far", 5 = "Very far" and 6 = "Out of range". The rated proximities each correspond to the distance between a virtual object and the participant. No time limit is imposed on participants for the rating of the trials performed.

After experiencing each condition, candidates are asked to describe the quality of the EMS stimulation, since it could help researchers and designers building upon the proposed concept, to make informed design decisions. The descriptors of qualitative EMS perception are based on the works of [2], [14], [11] and [3]. Prior to the end of the study, potential applications scenarios for the haptic EMS feedback with encoded spatial information are elaborated collectively with the participants. Themes for applications scenarios are identified using a thematic analysis.

3.2 Candidates

For the study 6 participants were invited (6 male, average = 29.83 years old, standard deviation = 3.92 years). Due to the circumstances of the pandemic situation during the development of this work, the sampling method had to be restricted to convenience sampling: participants included close friends and co-workers. Participants P1 and P6 have prior EMS experience. Out of the six participants, only P6 reported his left-hand as being the dominant hand. Participant

P2 had to be excluded from the study after the calibration phase of the lower arms, because he could not perceive the EMS stimulation at the maximum intensity level for both lower arms. In this within-group design study participants are divided in two groups of equal size, and each group is exposed to a different test sequence to reduce order effects.

3.3 Results

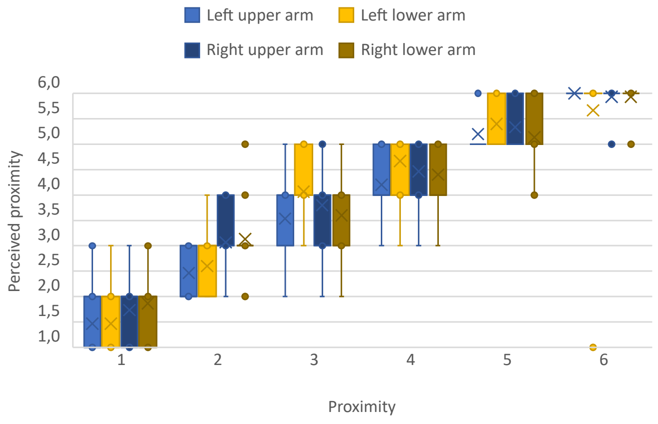
The perception of proximity of the participants is shown using box plots for each proximity and each waveform. This helps to understand how the data is distributed for individual proximities and to compare the performance of individual waveforms. In the box plots (Fig. 2), the interquartile range (IQR) is calculated using the exclusive method.

The square waveform, depicted in Figure 2, can be considered as being more accurate than the sinus and saw waveform, concerning the perceived proximity for all participants. The mean of the perceived proximity deviates by less than 0.6 units from the expected proximity for the measurements of the square waveform. This level of precision and accuracy could be attributed to the quality of the square waveform, namely, that the duration for which a peak of the signal is perceived is considerably longer, than for the sinus and saw waveforms. The Spearman correlation for the relationship of proximity and perceived proximity ranges from +0.751 (Saw waveform, Right lower arm, p: <0.001) to +0.971 (Square waveform, Left lower arm, p: <0.001) for all conditions, and can thus be described by a very strong monotonous function. Moreover, the Pearson correlation ranges from +0.716 (Saw waveform, Right lower arm, p: <0.001) to +0.970 (Square waveform, Left lower arm, p: <0.001) across all conditions, which implies a strong positive correlation.

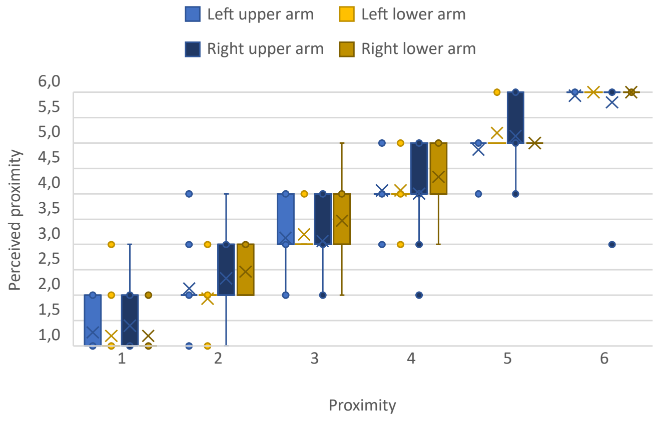
Qualities that were perceived for all waveforms include "Muscle Twitch", "Pinch", "Pinprick", "Tingling", "Vibration" and "Tap" (Fig. 3). However, some qualities that are thematized in related works were not felt like "Movement", "Cold" and "Warm". The least perceived qualities include "Pain", "Pinch", "Itch" and "Pressure", which can be considered as uncomfortable qualities. The scarcity of such qualities could be related to the individual calibration of the maximum intensity for the EMS feedback.

Surprisingly, we were able to find a very good correlation between EMS intensity and our given scale already at a very low overall EMS intensity due to calibration. Therefore, negative qualities such as "Pain" have not been experienced by our participants. This gives rise to using this approach in different domains for conveying such ordinal information.

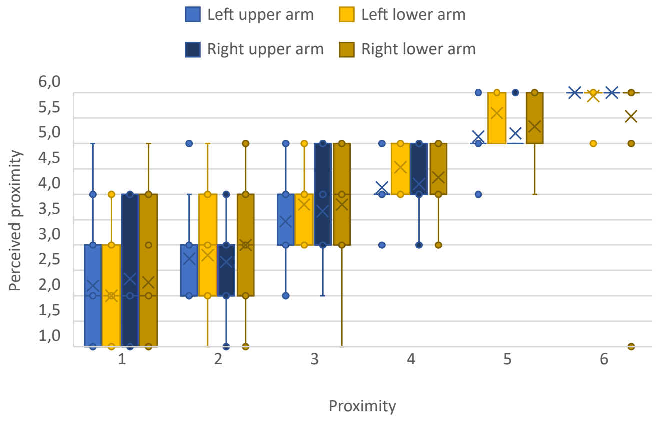
Participants stated that the concept could be used to "aid navigation and prevent loss of orientation" (Participant P2), promote "a healthy posture in workplaces" (Participant P6) and "simulate events in video games with different intensities" (Participant P2). According to the themes identified in our thematic analysis, the EMS enhancement device could have potential in three domains: "Use for driving", "Use in workplaces" and "Recreational use". This shows, that EMS technology has potential in domains that require safe navigation and where situational awareness of users needs to be supported.



(a) Sinus waveform



(b) Square waveform



(c) Saw waveform

Figure 2: Distribution of the perceived proximities for the tested waveforms

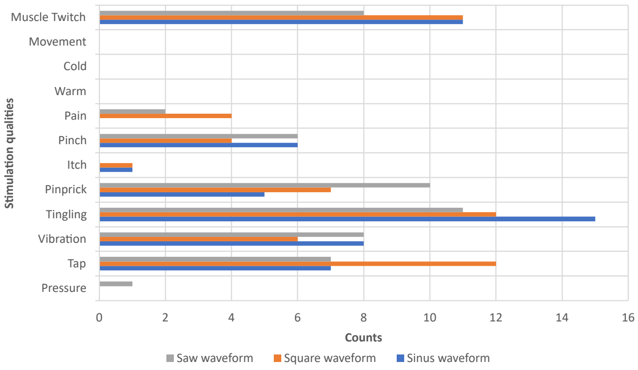


Figure 3: EMS stimulation qualities

4 DISCUSSION

Limitations regarding the study design, acquisition of participants and technical matters are addressed. Furthermore, ethical hurdles that need attention in the present and in the future are discussed.

4.1 Limitations

Our study lacks external validity since participants were gathered by convenience sampling. Moreover, all the candidates were male and were predominantly right-handed. Therefore, potential differences across genders and in handedness could not be interpreted from the data collected. However, other aspects like "tissue sickness, body fat percentage, skin moisture and hair" [10] might have an even larger impact on EMS than gender, handedness and age.

The effects of muscle and mental fatigue could have an impact on the results of this study. The study had a mean duration of 136 minutes. Despite minimizing carryover effects there could still have been factors affecting the quality of collected data, due to the length of the study.

Furthermore, it should be noted that all candidates were exposed to the study only in a sitting position. Enhancing spatial awareness for moving bodies is however, also an essential aspect to consider, since a greater situational awareness is required when navigating environments. Moving bodies also imply that the rate at which the candidates are stimulated by EMS feedback varies according to the proximities being communicated in the given environment.

Finally, proximity was only simulated in our study: We simulated a virtual object at a given distance and asked participants to guess their distance based on haptic EMS feedback. Obviously, we did not want participants to see a real object since we could not have outperformed sense of sight. However, this was reasonable for scenarios where users cannot see objects like hazardous objects approaching from behind (e.g., in traffic).

4.2 Ethical Implications

There are ethical implications when using EMS in general and when EMS is applied for the purpose of enhancing spatial awareness. The proposed concept does not rely on actuation of limbs or more specifically force feedback, but rather on different intensities of notifications using haptic EMS feedback. This implies that the autonomy of candidates is preserved. Moreover, the calibration procedure ensures, that the candidates are safe and the fact that the surface electrodes are easily removable, could enforce the feeling of control and instil trust in the enhancement device.

5 CONCLUSION

This paper proposes to use haptic EMS feedback as a new modality for supporting spatial awareness. More specifically, an intensity-proximity mapping has been proposed, that connects properties of the EMS design space with spatial perception. We encode proximity into EMS signals from an egocentric perspective of users. Our approach relates spatial distance between an object and a user to the intensity of EMS feedback.

Our study demonstrates how participants understand spatial information coded in haptic EMS feedback. Besides the perception of proximity, this work has also shown what qualities are perceived from the haptic EMS feedback by participants. There is also a potential relationship between the qualities perceived and the waveform used for the feedback. Potential applications scenarios for the haptic EMS feedback with encoded spatial information have been elaborated collectively with the participants. The enhancement concept proposed in this work gives direction for further research and could be used for enhancing spatial awareness for driving, at workplaces and for recreation.

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