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Abstract: Acoustic or visual warning signals for workers in hazardous situations might fail under loud and/or low-visibility work situations. A warning system that uses electrocutaneous stimulation can overcome this problem. The aim of this pilot study was to find spatio-temporal stimulation patterns for appropriate electrical warning. Eight electrode pairs were attached to the upper right arm of 16 participants. The stimulation was conducted with bi-phasic rectangular pulses of 150 µs and an amplitude of up to 25 mA. Pulse intervals that generate a single pulse, pulsating, vibrating, and continuous perception as well as varying spatial patterns (e.g. alternating between electrode pairs or circumferentially around the arm) were investigated and evaluated with regard to alertness, discomfort, and urgency. The pilot study revealed that a stimulation signal that generates a vibrating perception and is applied as a circumferential signal around the arm showed the highest values of alertness and is therefore considered a potential warning pattern for future studies with larger study groups.

Keywords: Electric stimulation, electrode, vibration, worker safety, wearable.

1 Introduction

In the field of occupational safety, the warning of workers in hazardous situations is an important task that must work reliably. Current methods use acoustic [1] or visual [2] warnings. These warnings might fail under loud and/or low-visibility work situations.

Therefore, a warning system should be developed that uses electrocutaneous stimulation. In our previous work [3], basic insights into perceptual thresholds and qualitative perception as a function of electrode size, pulse width, and electrode position were obtained for single pulses.

The aim of the current study was to investigate spatio-temporal warning signals. For this purpose, we evaluated perceived alertness, discomfort, and urgency for varying stimulation frequencies and spatial stimulation patterns.

2 Methods

2.1 Study group

The study was approved by the Local Ethics Committee. All 16 participants signed informed consent. Table 1 shows the descriptive statistics for the participants.

Table 1: Descriptive statistics for the participants of the pre-investigations and the main study.

Investigation	Number of participants	Male/ Female	Age in years (Mean±Standard deviation)	Right /left-handed
Pre-Investigation part 1	1	1/0	27	1/0
Pre-Investigation part 2	2	1/1	24.5±0.71	2/0
Main study	13	5/8	23.15±3.00	12/1

2.2 Experimental setup

The investigations follow the norm ISO EN 60601 [4] which defines safety requirements and ergonomic requirements for medical electrical devices and systems as there is currently no norm for electrical warning systems. Fig. 1 shows a scheme of the experimental setup. The operator sets the stimulation parameters in the user interface (in-house implemented in

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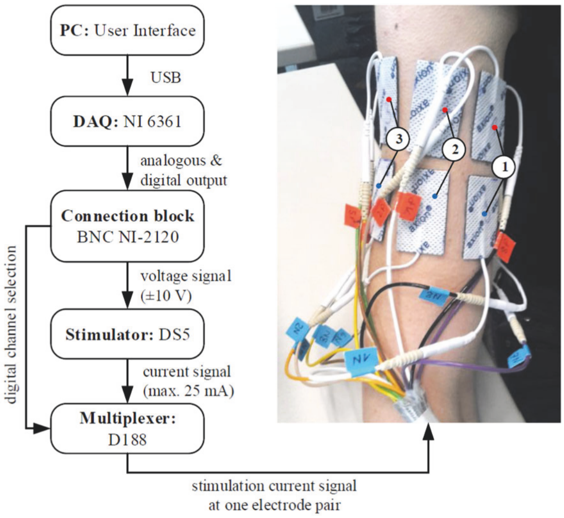

Figure 1: Scheme of the experimental setup. Left: block diagram of the stimulation setup. Right: example of electrodes at the upper arm (electrode pairs 1-3 of size 25 mm ×40 mm are visible). See text for detailed explanation.

LabVIEW 2017 (National Instruments, Austin, TX, USA)). This information is transferred to the data acquisition device (DAQ) NI USB-6361 (National Instruments, Austin, TX, USA) via USB. The output signal of the DAQ is transmitted to the connection block BNC NI-2120 (National Instruments, Austin, TX, USA), which sends a voltage signal to the isolated bipolar constant current stimulator DS5 (Digitimer Ltd, Letchworth Garden City, UK). The DS5 converts the voltage signal into the stimulation current, which is transferred to the multiplexer D188 (Digitimer Ltd, Letchworth Garden City, UK). It transmits the signal to the desired electrode pair using a digital channel selection procedure.

The 16 electrodes (re-useable self-adhesive hydrogel electrodes, axion GmbH, Leonberg, Germany) are placed pair-wise along the centerline between the shoulder joint and the elbow (Fig. 1) of the right arm. In the circumferential direction, the electrodes are placed at distances of 1/8 of the arm circumference. For each electrode pair, one electrode is placed 5 mm above the centreline and the other 5 mm below. The electrode pairs are numbered consecutively, where electrode pair 1 corresponds to the anterior, 3 to the lateral, 5 to the posterior, and 7 to the medial position of the arm (Fig. 1).

The stimulation signal contains bi-phasic rectangular stimulation pulses (first phase: positive, second phase: negative) of pulse width 150 µs. The pulse width denotes the duration of one phase. The amplitude can be adjusted between 0 and 25 mA. The number of pulses and the pulse frequency were adjusted according to the investigated spatio-temporal pattern. The spatio-temporal patterns were evaluated by scales of alertness (0-9), discomfort (0-9), and urgency (0-9), where 0 stands for none, 5 for medium, and 9 for very high. The scale of urgency was prompted for the possible future use of the system encoding warning signals of varying urgency. An appropriate warning signal should produce high alertness values with mediocre discomfort values ensuring the compliance of the future user.

2.3 Threshold and frequency determination

Three thresholds were defined in this study: (1) a just noticeable stimulus defines the perception threshold A_p, (2) a stimulus drawing attention to itself defines the attention threshold A_a, and (3) a stimulus generating intolerable perceptions defines the intolerance threshold A_i. In order to determine these thresholds, a single biphasic stimulation pulse was applied to electrode pair 3. The amplitude was increased gradually from 0 up to a maximum of 25 mA by steps of 0.1 mA, 0.2 mA, or 0.5 mA. The steps were chosen adaptively by the trained operator. Before the start of the experiment, the meaning of the three thresholds was explained to the participant. The operator always told the participant which threshold will be determined next such that the participant could focus on the threshold determination [3]. If muscle twitching occurred, the measurement series was stopped and the current amplitude value was noted. Muscle twitches are not desired in the current study for the use of stimulation in a warning system. The threshold determination procedure was repeated for electrode pair 3 at least 3 times until at least 3 consecutive series with similar thresholds were obtained. Using the repetitive threshold determination, the participant was able to learn the detection of the thresholds. An individual warning amplitude A was calculated by

$$A = A_a + 0.2(A_i - A_a), \tag{1}$$

where A_a denotes the averaged attention threshold and A_i the averaged intolerance threshold. The averaged values were calculated from the last 3 measurement series.

For spatio-temporal stimulation, we used signal bursts containing the above-mentioned bi-phasic rectangular stimulation pulses of pulse width 150 µs with four varying intervals (pauses) between these pulses, which were individually determined. These four intervals were determined such that the participants reported the perception of single pulses (S), a pulsating (P), a vibrating (V), or a continuous stimulus (C). Initial values for these intervals were (S): 143 ms, (P): 56 ms, (V): 19 ms, and (C): 12 ms. To determine the four individual intervals, a burst of 5 pulses was presented at these initial intervals. The values were adjusted according to the reporting of the participants until the perceptions of S, P, V, and C were achieved. The bursts were applied with the warning amplitude A (1). The total duration of the burst trains in the spatio-temporal warning signals was 0.4 s, however, for some experiments the duration was varied.

2.4 Preliminary investigations

The pre-investigations aimed to reduce the parameter space for the selection of an appropriate warning signal. The pre-investigations consisted of two parts.

In part 1, temporal patterns (V-S, V-P, V-C, C-S, S-P-V-C) were presented at electrode pair 3. The burst train durations have been varied between 0.2 and 2.0 s. Next, spatial patterns (3 ↔ 7; 1 ↔ 5; 2 ↔ 3; 3 ↔ 4; 1 → 7) were applied, where the numbers indicate the electrode pairs and ↔ stands for a alternating (between two electrodes) and → for a one-directional circumferential pattern. The spatial patterns used the vibrating perception V, as they showed the highest alertness in the previous step. At last, spatio-temporal patterns (V-S, V-P) were presented for the same electrodes as for the spatial patterns and in forward/backward circumferential directions.

Based on the results of part 1, the parameter space for spatial-temporal warning pattern was reduced for part 2. The spatial patterns (3 ↔ 7; 1 ↔ 5; 2 → 5-5 → 2; 1 → 8) were applied at the perception intervals S and V. Further, spatio-temporal patterns were investigated: 3 ↔ 7; 1 ↔ 5; 2 ↔ 3; 3 ↔ 4; 1 → 8 and with alternating temporal perception intervals: V-S and S-P-V-C.

2.5 Main study

Circumferential patterns with the temporal perception interval V have been beneficial in pre-investigations 1 and 2 and were therefore used as the only temporal pattern in the main study. The aim was to investigate whether a few neighbouring electrodes (e.g., 2→5) show similar alertness values as more electrodes (e.g., 1→7) and if a forward/backward pattern (e.g., 2→5-5→2) shows benefits in this regard. The benefit of fewer neighbouring electrodes would be that medial positions with muscle twitching could be avoided. The thresholds and individual intervals for vibrating perception V have been determined for the 13 participants and forward and forward/backward patterns (1→7, 1↔7, 2→5, 2↔5, 1→5, 1↔5, 1→6, 1↔6) have been evaluated regarding alertness, comfort, and urgency.

3 Results and Discussion

3.1 Preliminary investigations

In part 1, a warning amplitude of 7.1 mA and the perception intervals S (250 ms), P (100 ms), V (19 ms), and C (7 ms) were determined for the participant. The alertness values were highest for temporal patterns with the combinations V-S with 9 and V-P with 7. In consequence, these two temporal perception intervals have been selected for further investigation of varying signal part durations and break durations. No clear favourite could be identified for the signal part and break durations regarding alertness, comfort, and urgency, but the participant reported that the shorter signal part durations and breaks reflected a better warning signal for him. In consequence, a duration of 0.4 s has been fixed. For the investigated spatial and spatial-temporal patterns, the highest alertness values with 9 were achieved for circumferential patterns of electrode pairs 1→8. The pattern V-S was described as good perceivable and distinguishable by the participant. At the end of the experiment, the participant reported that for a fluent presentation of the warning signal, the break duration should be short and he would prefer 0.1 s.
In part 2, the warning amplitudes were 8.4 mA for the male and 7.2 mA for the female participant. The perception intervals were S (m: 143 ms, f: 143 ms), P (m: 56 ms, f: 37 ms), V (m: 19 ms, f: 14 ms), and C (m: 12 ms, f: 9 ms). Both participants showed the highest alertness values (m: 8, f: 7) for spatial patterns with the circumferential configurations: 2→5-5→2; 1→8. The male participant showed the highest alertness (8) for 3 ↔ 7 and 1 → 8 with V-S, the female participant for 1 → 8 with S-P-V-C with a rating of 7.

3.2 Main study

The mean value ± standard deviation was 8.53 mA±1.55 mA for the warning amplitude A and 20 ms±2.5 ms for the intervals. The results shown in Table 2 indicate that the highest alertness values were reached with circumferential patterns with at least 5 neighbouring electrode pairs. The use of a forward/backward pattern showed no benefit. The discomfort and urgency were also smallest for pattern 2→5. The results should be understood as a preliminary trend since the number of participants is low.

Varying perception intervals were investigated in the field of electrical muscle stimulation, where longer intervals (≥20 ms) lead to more long-lasting beneficial effects on the muscle. In contrast, shorter intervals (<20 ms) induced stronger forces and a more convenient feeling, but the effects lasted shorter

[6]. Changing intervals can be distinguished if they are >20 ms, which could be used in encoding strategies for touch feedback in a bionic hand or feet [7]. It was concluded in [8] that the intervals between the pulses influenced the tactile perception quality and thereby the effective rate of information transfer through a feedback channel within the development of an upper limb prosthesis. They recommend the use of intervals <40 ms. These results are in line with our findings, where intervals around 19 ms produce a vibrating sensation and were beneficial for an electrical warning signal.

Table 2: Alertness, comfort, and urgency as median [25-75% percentile] of the investigated stimulation pattern in investigation 3: $a \rightarrow b$ circumferential pattern from electrode pair a to b, F: forward, F/B: forward/backward.

		1→7	**2→5**	**1→5**	**1→6**
Alertness	F	7[5.75-8]	5[3-7]	7[4.75-7]	8[6.5-8]
	F/B	7[5-7.25]	5[3-7]	7[4.75-7]	7[5-8]
Discomfort	F	4[3-6.25]	3[2-5]	5[4-6.25]	6[4.75-7]
	F/B	5[4-7]	3[2-5]	5[3.75-6.25]	5[4-7]
Urgency	F	5[3-6.25]	5[2.75-5]	6[5-7]	7[5-8]
	F/B	5[3.75-6]	4[3-5]	5[4.75-7]	5[4.75-7.25]

In future research, it might be beneficial to present a reference pattern to the participants, which is assigned to alertness, discomfort, and urgency at a value of 5. The following stimulations can be rated relative to this reference pattern. The sequence of warning patterns in this study was fixed which might have affected the alertness, discomfort, and urgency values due to a sequence effect. Future research might consider a randomizing of the presented warning patterns.

Future developments of the electrical warning system plan to use a wearable textile cuff with knitted fabric and integrated electrodes as used in [5]. However, the current textile cuff prototypes still show usability problems. For this reason, self-adhesive hydrogel electrodes have been used in this study. However, for applications in the field, self-adhesive hydrogel electrodes are inappropriate as the hydrogel might get dry after some hours of wearing and the effort for placement is too high.

4 Conclusions

We conclude that the use of a circumferential stimulation pattern that causes a vibrating sensation or an alternating vibrating/single pulses sensation might be used as a warning signal pattern. The resulting recommendations should be confirmed in a larger group of participants and under working conditions, e.g., using a vibrating machine during electrocutaneous stimulation.

Author Statement

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References

[1] International Organization for Standardization. Ergonomics — Danger signals for public and work areas — Auditory danger signals. ISO 7731 Berlin: Beuth, 2008.

[2] European Committee for Standardization. Safety of machinery, visual danger signals, general requirements, design and testing. EN 842:1996+A1:2008 Berlin: Beuth, 2009.

[3] Dölker EM, Lau S, Bernhard MA, Haueisen J. Perception thresholds and qualitative perceptions for electrocutaneous stimulation. Sci. Rep.12, 7335 (2022). https://doi.org/10.1038/s41598-022-10708-9

[4] European Committee for Standardization. Medical electrical equipment - Part 1: General requirements for basic safety and essential performance. IEC 60601-1:2005 + Cor. :2006 + Cor. :2007 + A1:2012); German version EN 60601-1:2006 + Cor. :2010 + A1:2013 (Beuth, Berlin, 2013).

[5] Dölker EM, Mubin A bt, Supriyanto E, Haase E, Krzywinski S, Haueisen J. Sensation thresholds in electrocutaneous stimulation: comparison of textile cuff and TENS electrodes. (2020). Curr. Dir. Biomed. Eng., 6(3). https://doi.org/10.1515/cdbme-2020-3096.

[6] Doucet BM, Lam A, Griffin L. Neuromuscular electrical stimulation for skeletal muscle function. *Yale J Biol Med*. 2012;85(2):201-215.

[7] Graczyk EL, Christie BP, He Q, Tyler DJ, Bensmaia SJ. Frequency Shapes the Quality of Tactile Percepts Evoked through Electrical Stimulation of the Nerves. J Neurosci. 2022 Mar 9;42(10):2052-2064. doi: 10.1523/JNEUROSCI.1494-21.2021.

[8] Paredes, L.P., Dosen, S., Rattay, F. et al. The impact of the stimulation frequency on closed-loop control with electrotactile feedback. J NeuroEngineering Rehabil 12, 35 (2015). https://doi.org/10.1186/s12984-015-0022-8.