ShoulderTapper: Providing Directional Cues through Electrotactile Feedback for Target Acquisition in Pick-by-Light Systems

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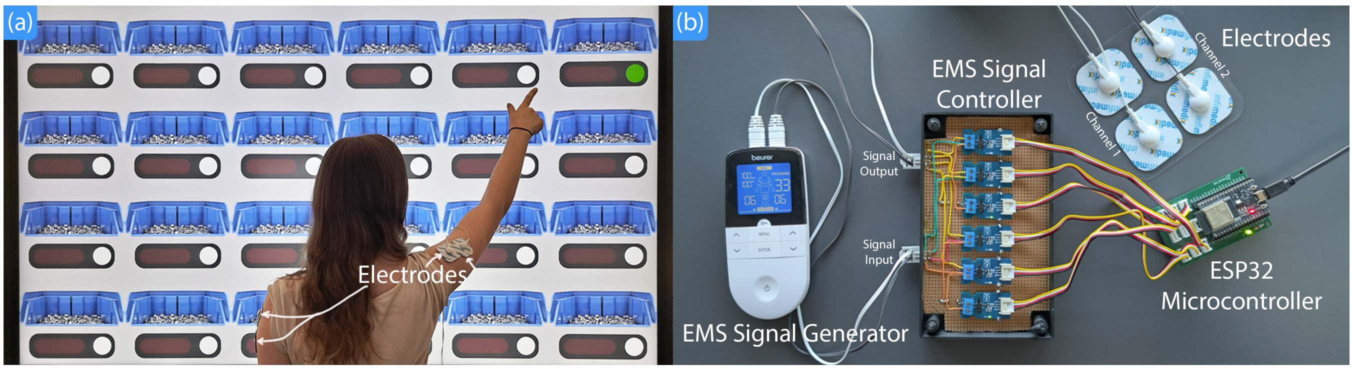

Figure 1: *ShoulderTapper* prototype in use in front of a simulated pick-by-light workstation – (a) electrotactile feedback comes from electrode pairs that are attached to the left and right deltoid muscles and (b) are connected to an electrical muscle stimulation (EMS) signal generator through an EMS signal controller with optocouplers.

Abstract

In work environments with overwhelming or insufficient visual cues, maintaining spatial awareness and accurately acquiring targets can become challenging, particularly for users facing high cognitive load, multitasking demands, or visual impairments. This study explores the effectiveness of electrotactile feedback compared to pick-by-light feedback in enhancing task performance and user experience during a target acquisition task. Eighteen participants completed target acquisition tasks under three conditions: Baseline (pick-by-light), Electrotactile Pressure, and Electrotactile Tap. A significant improvement in task completion time was found in the rightmost column of the pick-by-light grid for the Electrotactile Pressure condition. Subjective feedback indicated that electrotactile feedback significantly reduced mental demand and effort and enhanced the overall user experience compared to the baseline condition. These findings suggest that electrotactile feedback can reduce cognitive load, particularly in tasks requiring quick responses and spatial attention, offering valuable insights for the design of haptic interfaces providing direction cues.

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CCS Concepts

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

Keywords

target acquisition, electrotactile feedback, pick-by-light, directional cues

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1 Introduction and Related Work

Research on pick-by-light systems, which are prevalent in the industry, particularly for order picking tasks, has shown their potential to reduce picking time and errors while also lowering mental load [28]. Pick-by-light and other order picking systems, including pick-by-paper, head-up displays (HUD), and cart-mounted displays (CMD), have been compared in various studies [3, 13, 28, 33]. While pick-by-light systems can reduce errors and mental load compared to pick-by-paper [3], they may increase physical strain [28]. HUD systems, particularly when compared with pick-by-light, demonstrate improved efficiency and reduced workload, though error rates remain similar [33]. While wearable and context-aware technologies like HUD and CMD appear superior to traditional methods [13], those technologies also underscore the importance of developing more efficient, user-friendly order picking solutions.

To further enhance the effectiveness of order picking solutions, it's crucial to consider systems that also enhance spatial awareness, since it plays a key role in quickly and accurately locating targets within an environment [10]. There are many approaches to enhance users' spatial awareness [5–9, 15, 16, 18, 20, 22, 25–27, 29–32]. However, since the use of electrotactile feedback is not well studied in the context of order-picking and pick-by-light systems, we consider spatial awareness enhancement through the use of electrical muscle stimulation and electrotactile feedback [7, 9, 15, 16, 18, 22, 26, 27].

To address the aforementioned challenges, we developed *ShoulderTapper*, a low-latency two-channel EMS-based system that provides directional cues through electrotactile feedback on both shoulders. Simple tactile reaction time is approximately 40 milliseconds faster than simple visual reaction time [23], and according to Heller, tactile perception is 20 times faster than vision [14]. Moreover, visually impaired people perceive touch faster than those with sight, which suggests that the brain's processing of tactile information can be more rapid [4]. Hence, the device is designed to trigger the tactile sense to supplement visual information, thereby enhancing spatial awareness and reducing cognitive load. The tactile cues are provided to support users in identifying targets quickly, aiming to reduce the task completion time. Moreover, by providing one-dimensional tactile feedback (i.e., on the left or right shoulder), the likelihood of making errors during target acquisition is expected to decrease. Our hypotheses are as follows:

- **(H1)** Task completion time is less when users are stimulated with electrotactile and pick-by-light feedback, compared to pick-by-light feedback only;
- **(H2)** The number of errors is less when users are stimulated with electrotactile and pick-by-light feedback, compared to pick-by-light feedback only.

We conducted a study with 18 participants to evaluate performance, user experience, task load, and EMS perception of the *ShoulderTapper* prototype. Task completion times were 1007 *ms* for Electrotactile Tap and 994 *ms* for Electrotactile Pressure, compared to 1037 *ms* with visual only feedback, with similar accuracy across all conditions. NASA-TLX results indicated that both electrotactile conditions significantly reduced mental demand compared to the baseline ($p = 0.001$), and Electrotactile Tap required less effort ($p = 0.016$). No significant differences were found for physical or temporal demands, performance, or frustration, but the electrotactile feedback positively impacted task load. The User Experience Questionnaire indicated that electrotactile conditions significantly improved pragmatic, hedonic, and overall quality compared to the baseline ($p < 0.001$), with no significant differences between the two EMS feedback conditions. Most participants perceived both electrotactile conditions as "vibration" and "comfortable", with slight variations in sensation. While 15 participants found the electrotactile feedback supportive, four reported it as distracting or mentally demanding.

ShoulderTapper assists users in interpreting directional cues through electrotactile feedback before even perceiving the visual stimuli. Our work encompasses the following contributions:

(1) Design of a multichannel, low-latency electrotactile system based on optocouplers;
(2) Evaluation of the electrotactile system's performance when providing directional cues;
(3) Insights about the user experience and task load.

2 ShoulderTapper Prototype

To address our hypotheses, we built a prototype that could generate low-latency electrotactile feedback on two EMS channels. We chose electrotactile over mechanical tactile stimulation, as it enables the usage of a wider range of perceptions, including vibration, tingling, pressure, and tapping, among others [11, 12, 17].

2.1 Design

In our study, we used a commercial 2-channel EMS signal generator (Beurer EM 49[1]) to generate electrical signals. We use a frequency of 120 Hz, a stimulation length of 300 ms, and a square wave for both EMS channels. The pulse-width is set in accordance with the perception the feedback should trigger, i.e., 100 μs for an Electrotactile Tap and 250 μs for an Electrotactile Pressure. The aforementioned pulse-width values are based on the findings of Knibbe et al. [19]. As we provide the tap and pressure sensation through different pulse-widths, we expect the higher pulse-width to lower the task execution time, since a higher pulse-width implies a higher perceived urgency [1, 2]. However, we also want to find out which variant (Electrotactile Tap vs. Electrotactile Pressure) is more comfortable and reliable. Hence, we also use a low pulse-width of 100 μs for the tap sensation.

We stimulate the shoulder muscles for reasons, including ease of access and surface area of the muscles, and the alignment with arm movements. Furthermore, in preliminary tests, we determined that attaching the electrode pairs to the shoulders limits freedom of movement less than attaching them to the lower or upper arm, which causes hanging cables. To stimulate the mechanoreceptors, we used 45 × 45 mm gel-based electrodes (Manufacturer: *infimedix*) with a 3.5 mm push-button connector.

2.2 Technical Details

As depicted in Figure 1b, our prototype consists of two components: an EMS signal generator (Beurer EM 49) and an EMS signal controller. The EMS signal generator has two EMS channels, which are connected to the EMS signal controller. The controller consists of six optocouplers (Grove-Optocoupler Relay M281[2]) that can relay the output signal of each EMS channel to the electrode pairs or a dummy circuit consisting of a resistor with a fixed value of 550 Ohms, respectively. The M281 optocouplers are triggered by an ESP32 microcontroller and have an on-time latency of 2 ms and an off-time latency of 500 μs. The latencies are based on the M281 datasheet and were additionally confirmed through an oscilloscope. The latency of the prototype is, however, not defined by the latency of the optocouplers but through the period of the EMS signal, since the EMS signal generator is not synced with the EMS signal controller. As we use a stimulation frequency of 120 Hz, the maximum latency of our prototype is 8.33 ms (time interval in ms: 1/120 Hz ×

[1] https://www.shop-beurer.com/products/digital-ems-tens-device-em49
[2] https://wiki.seeedstudio.com/Grove-Optocoupler_Relay-M281/

1000). To ensure comparability between the Electrotactile Pressure and Electrotactile Tap conditions, we therefore chose to modify the pulse-width instead of the frequency.

To trigger the left or right deltoid muscle, a command has to be sent to the EMS signal controller based on the serial protocol of the *Let Your Body Move* toolkit [21]. For instance, if the left shoulder should be stimulated and assuming that channel 0 is connected to the left arm, the following string "C0I100T300G" is sent via the serial interface to the ESP32. The string would correspond to turning on channel 0 ("C0"), with 100% stimulation intensity ("I100"), and a stimulation time of 300 ms ("T300").

3 Study

3.1 Study Design

Our study has a within-subjects design, where all participants experienced each condition (Baseline, Electrotactile Tap, and Electrotactile Pressure) in a counterbalanced order to control for order effects. The baseline condition is the pick-by-light condition, consisting of visual feedback only when a button on the large display is highlighted – the large display serves as a simulation of a conventional pick-by-light workstation. The Electrotactile Tap condition extends the baseline through electrotactile feedback on the left or right deltoid muscle when a button appears on the left or right side of the touchscreen, respectively. The Electrotactile Pressure condition is similar to the Electrotactile Tap condition, but the sensation evoked by the electrotactile feedback is different. The independent variable was the type of directional cue provided for target acquisition. The dependent variables included task completion time (measured in milliseconds), accuracy rate (percentage of correct target selections), user experience (measured using UEQ Short Version), and task load (measured using NASA-TLX), assessed through a post-run (i.e., after each condition) questionnaire, respectively. For the electrotactile conditions, the dependent variables were extended to include the participants' subjective perception of the electrotactile feedback, as assessed by the questionnaire. The questions about EMS perception are based on the assessments used in [11, 12, 17]. The time for answering the questionnaires is also used to mitigate potential fatigue.

3.2 Setup

During the study, a laptop (XMG FUSION 15[3]) is connected to a SMART Board Interactive display (Model: SBID-7086P[4], refresh rate: 60 Hz, touch area dimension: 189,9 × 107 cm) via HDMI cable to visualize the bin trays of the pick-by-light workstation. A USB-to-Host cable is used to register the touch inputs. The bins of the pick-by-light workstation are displayed in a 6 × 4 grid. When a pick-by-light element corresponding to a bin lights up, the user is notified through either the left or right shoulder (only for the electrotactile conditions), depending on which half of the grid was activated. When the user touches a bin on the display, the touch event and the task completion time are logged. If a user touches a wrong bin, i.e., that is not highlighted, an error is logged.

[3]https://www.xmg.gg/en/xmg-fusion-15-e24/
[4]https://support.smarttech.com/docs/hardware/displays/smart-board-7000/en/about/sbid-7000-specifications/sbid-7086p.cshtml

3.3 Procedure

Participants were briefed about the study and provided with an informed consent form. After signing the consent form, they completed the demographic part of the questionnaire, were instrumented with EMS electrodes on both shoulders (the electrodes remained attached for all conditions), and self-adjusted the EMS intensity for both electrotactile conditions separately. They were given detailed instructions regarding the target acquisition task, which involved tapping a bin with a highlighted pick-by-light element as quickly as possible using one finger (see Fig. 1a). During the experiment, participants completed the target acquisition task for each bin under each condition on the large touch display while instrumented with the EMS electrodes.

A script running on the host computer recorded task completion time and error rate for each trial. Each participant completed a total of 216 trials (24 button presses × 3 repetitions × 3 conditions). After completing each condition, participants answered the post-experiment questionnaire.

3.4 Participants

We recruited 18 individuals (10 males, 8 females; M = 26.1, σ = 8.67) from the university through flyers and compensated them with €20 each. Seven participants reported having no history of neurological or physiological conditions affecting sensation, motor function, or sight (P1, P2, P4, P6, P12, P13, and P17). Ten participants reported that they were either nearsighted or farsighted, with each condition corrected by glasses (P3, P5, P7, P8, P10, P11, P14, P15, P16, P18). Additionally, one participant reported being color-blind (P9), and another reported having a tremor (P14). Sixteen participants were right-handed, while two were left-handed. Seven participants (P1, P4, P6, P7, P9, P15, and P16) had prior experience with EMS, primarily due to participation in previous studies.

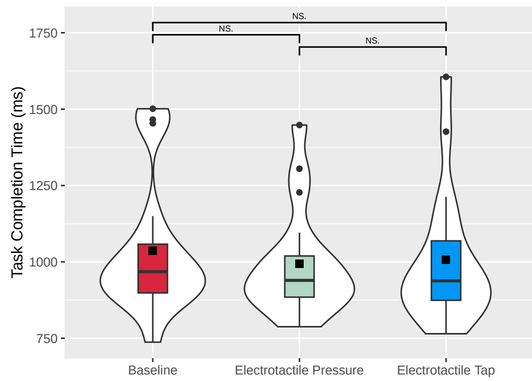
4 Results

4.1 Objective Measures

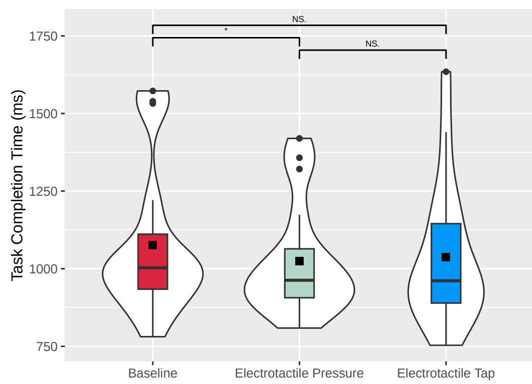
4.1.1 Task Completion Time. We performed a repeated-measures ANOVA to evaluate the task completion time for all conditions (see Fig. 2a). We calculated the average task completion times using the geometric mean, as suggested by [24]. The mean task completion time was 1007 ms (σ = 220 ms) for Electrotactile Tap, 994 ms (σ = 176 ms) for Electrotactile Pressure, and 1037 ms (σ = 220 ms) for the baseline condition. We could not find any statistically significant difference between condition and task completion time (p = 0.109).

We also analyzed the task completion time per column of the 6 × 4 button grid and labeled the columns "L1", "L2", "L3", "R3", "R2", and "R1" respectively, going from left to right. For the "R1" column, there is a statistically significant difference between condition and task completion time (p = 0.04), as demonstrated in Figure 2b. The post-hoc comparison reveals a statistically significant difference between the baseline (μ = 1076 ms, σ = 238 ms) and the Electrotactile Pressure (μ = 1024 ms, σ = 179 ms) condition (p_{tukey} = 0.044).

4.1.2 Accuracy. Each participant was required to perform 216 correct button presses during the study. When a wrong button was pressed, this was recorded additionally. Since we had 18 participants in total and the total number of errors is 39, the accuracy



(a) Overall task completion time.



(b) Task completion time for the rightmost column "R1".

Figure 2: Task completion time per condition.

across all participants is 99.0 %. The error rate per condition across all participants is as follows: baseline condition (15 errors, accuracy: 93.06 %), Electrotactile Pressure (16 errors, accuracy: 92.59 %), and Electrotactile Tap (7 errors, 96.76 %). After performing a repeated measures ANOVA, there is, however, no statistically significant difference between the conditions and the error rate (F = 1.75, p = 0.189).

4.2 Subjective Measures

4.2.1 NASA-TLX Score. Regarding the NASA-TLX score by condition, Friedman's test revealed statistically significant differences between mental demand and condition ($\chi^2(2)$ = 13.4, p = 0.001) and effort and condition ($\chi^2(2)$ = 8.27, p = 0.016), as shown in Figure 3. Durbin-Conover post-hoc tests were conducted to examine pairwise differences. For mental demand, there is a statistically significant difference between the baseline (μ = 6.89, σ = 3.97) and the Electrotactile Tap (μ = 4.61, σ = 3.07) condition (p = 0.003) and between the baseline and the Electrotactile Pressure (μ = 4, σ = 2.83) condition (p < 0.001). Concerning effort, there is a statistically significant difference between the baseline and the Electrotactile Tap condition (p = 0.003).

4.2.2 UEQ Score. As displayed in Figure 4, Friedman's tests revealed statistically significant differences between pragmatic quality and condition ($\chi^2(2)$ = 22, p < 0.001), and hedonic quality and condition ($\chi^2(2)$ = 25, p < 0.001). Moreover, repeated measures ANOVA revealed a statistically significant difference between overall UEQ score and condition (p < 0.001). Durbin-Conover post-hoc tests were conducted to examine pairwise differences. Regarding pragmatic quality, there are statistically significant differences between the baseline (μ = 0.89, σ = 1.08) and Electrotactile Pressure (μ = 2.36, σ = 0.51) condition (p < 0.001), and between the baseline and Electrotactile Tap (μ = 2.13, σ = 0.74) condition (p < 0.001). Similar observations were made for hedonic quality, with statistically significant differences between the baseline (μ = -1.36, σ = 1.16) and both the Electrotactile Tap (μ = 1.22, σ = 1.02; p < 0.001) and Electrotactile Pressure (μ = 1.15, σ = 1.03; p < 0.001) conditions. Overall, both electrotactile conditions have significantly higher UEQ scores than the baseline condition in terms of pragmatic, hedonic, and overall quality.

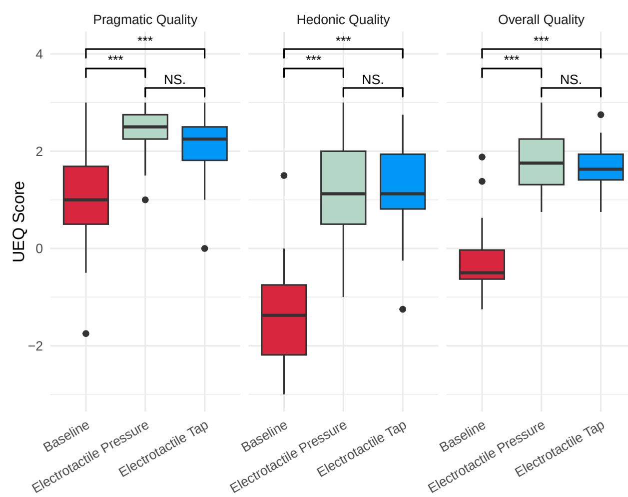


Figure 4: UEQ-S results.

4.2.3 EMS-based Results. To compare the subjective perception of the Electrotactile Tap and Electrotactile Pressure conditions, the participants were asked to rate the sensation, location, feel, and support, respectively. 16 participants perceived both electrotactile conditions as "vibration". "Tingle" was also repeatedly reported (eight reports for tap, seven for pressure), followed by "pressure" (four reports for tap, five for pressure) and "touch" (four reports for tap, three for pressure), showing no significant differences between the electrotactile sensations. Electrotactile pressure was exclusively sensed locally, whereas Electrotactile Tap was perceived as spreading by four participants. Most participants found Electrotactile Tap and Electrotactile Pressure to be "comfortable" (nine reports for both) or "rather comfortable" (five reports for tap, six for pressure), with a slightly higher number reporting comfort with Electrotactile Pressure. The acuity was rated as neither blunt nor sharp but neutral by most participants (six reports for both), with Electrotactile Pressure tending toward sharp sensations and Electrotactile

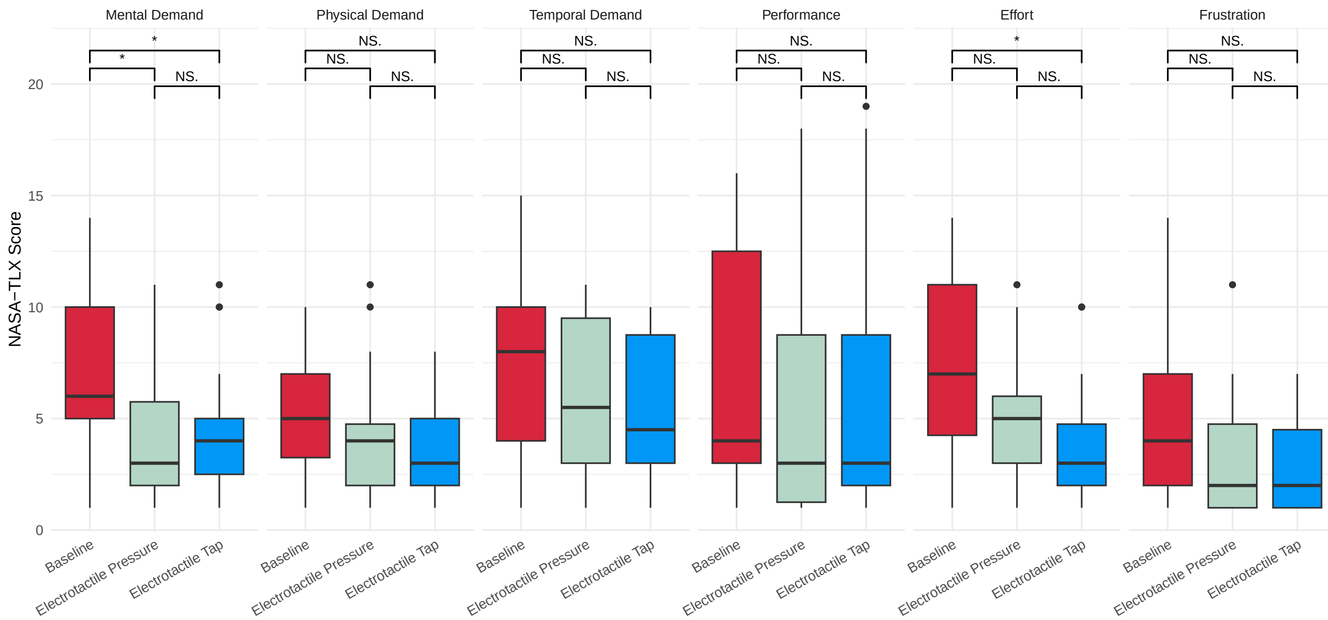


Figure 3: NASA-TLX results.

Tap tending toward blunt. The strength of the EMS sensation was rated mild (six reports for tap, seven for pressure) or rather mild (seven reports for both) by most participants for both electrotactile conditions.

The EMS feedback, including Electrotactile Tap and Electrotactile Pressure, was deemed supportive by 13 participants as it reduced the area they needed to search for the target light. For instance, participant P2 mentioned "It reduces the area to look for the light" and participant P14 mentioned "it helps to focus on one side". Three also felt that the feedback lowered their cognitive load, allowing for a more automatic response (P1: "it felt more supportive for my mental load [. . .]", P6: "it makes the task much easier and one doesn't have to think much [. . .]", P7: "[. . .] I can use less concentration because the vibration is always there, and I can feel [it] clearly"). Two participants mentioned that EMS increased their focus and concentration, while another two felt less need to consciously decide which arm or hand to use. Participant P18 viewed the feedback as a compensatory mechanism for their narrow field of vision. However, three participants reported that the feedback distracted them from the task, and one noted that the addition of tactile feedback, alongside visual attention, increased their cognitive load. Five participants expressed doubts about whether EMS actually improved their performance in terms of task completion time.

5 Discussion

5.1 Implications of Results

5.1.1 User Performance and Accuracy. Our results indicate that there is no statistically significant difference in overall task completion time between the conditions. Although these differences did not reach statistical significance, they suggest a trend where electrotactile feedback might contribute to faster task performance under certain conditions.

When analyzing task completion times by specific grid columns, a statistically significant difference was observed in the rightmost column ("R1"), where the Electrotactile Pressure condition resulted in faster completion times compared to the baseline condition (p_{tukey} = 0.044). This localized effect suggests that the benefits of electrotactile feedback may be more pronounced in specific spatial contexts, which warrants further investigation.

Our hypothesis (**H1**), stating that task completion time would be shorter with electrotactile feedback compared to pick-by-light feedback, was only partially supported by the results. While the overall difference in task completion time between conditions was not statistically significant, the trend of faster completion times in the electrotactile conditions, particularly in specific grid columns, such as the rightmost column ("R1"), aligns with our hypothesis. This indicates that electrotactile feedback has the potential to improve performance speed, though this effect may be context-dependent and not uniform across all tasks.

The results did not provide statistical support for our second hypothesis (**H2**) that electrotactile feedback would lead to fewer errors compared to pick-by-light feedback. It is therefore rejected. Despite the Electrotactile Tap condition showing a slightly higher accuracy rate, this difference was not significant, suggesting that electrotactile feedback does not consistently reduce the number of errors in comparison to pick-by-light feedback.

5.1.2 Performance and User Experience. The NASA-TLX results reveal that participants perceived a significant difference in mental demand and effort between the conditions. Specifically, both electrotactile conditions (Electrotactile Tap and Electrotactile Pressure) were associated with significantly lower mental demand compared to the baseline condition. This finding suggests that electrotactile feedback helps to reduce cognitive load during task performance. Similarly, the effort required was significantly lower in the Electrotactile Tap condition compared to the baseline condition, indicating that participants found this type of feedback to ease the task's physical or cognitive burden.

The UEQ results further support the positive impact of electrotactile feedback on user experience. Both pragmatic quality and hedonic quality scores were significantly higher in the electrotactile conditions compared to the baseline condition. This suggests that participants found the electrotactile feedback not only more effective in achieving task goals (pragmatic quality) but also more enjoyable and satisfying (hedonic quality). The overall UEQ scores were also significantly higher for both electrotactile conditions, showing that the addition of tactile feedback enhances the overall user experience.

Participant feedback provided nuanced insights into the subjective experience of electrotactile feedback. Electrotactile Pressure and Electrotactile Tap were perceived similarly. Interestingly, the perceived acuity of the sensations varied, with Electrotactile Pressure tending toward sharper sensations and Electrotactile Tap toward blunter sensations, though neither was perceived as particularly extreme.

The subjective feedback also highlighted the supportive nature of the electrotactile feedback. 13 out of 18 participants felt that the EMS feedback, including both Electrotactile Tap and Pressure, helped them narrow down the search area for the target element, effectively reducing their cognitive load. This aligns with the lower NASA-TLX scores for mental demand and effort in the electrotactile conditions. Some participants noted that the feedback allowed for a more automatic response, enhancing their focus and concentration. However, some participants found the feedback distracting or believed that it increased their cognitive load. These mixed responses suggest that while electrotactile feedback can be beneficial for many users, it may not be universally effective and could be distracting for some.

5.2 Limitations and Future Work

The sample size of the study is relatively small, which might have reduced the statistical power to detect differences in task completion time across conditions. Since a virtual pick-by-light environment is used, it might be difficult to adapt the findings to a real pick-by-light setting, as the interaction might differ from the interaction with a touchscreen. However, to address the study goal, i.e., measuring task completion time for pressing on the pick-by-light element, only the target acquisition task performed at a real pick-by-light workstation is required. Future work could focus on providing feedback of increasing intensity to the participants if the target they need to touch is on the outmost columns of the screen.

6 Conclusion

In this paper, we presented *ShoulderTapper*, a prototype for providing directional cues through electrotactile feedback in pick-by-light workstations. Our design focused on the task of target acquisition, where participants search for a pick-by-light element that needs to be processed next. *ShoulderTapper* communicates the half of the bin tray grid, where a pick-by-light element lights up and provides electrotactile feedback to the left or right shoulder muscle accordingly. We thereby aim to reduce task execution time for target acquisition in the given context. Through a within-subjects study performed with 18 participants, we gained valuable insights into participant's performance and their subjective experience with our prototype. Our findings indicate that for the task execution time, there is a tendency that electrotactile feedback reduces the time slightly and that the accuracy rate is almost equal to or better than the baseline condition. A statistically significant difference was observed for the rightmost column, where the Electrotactile Pressure condition was faster than the baseline condition. Moreover, for the subjective measures, statistically significant differences have been found for mental demand, effort, pragmatic quality, and hedonic quality. Ultimately, our research highlights the potential of electrotactile feedback for providing directional cues in a pick-by-light workstation setting.

Acknowledgments

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