# Investigating The Speed-Accuracy Tradeoff in Discrimination of Electrotactile Stimuli

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## Abstract

Sensory feedback has been shown to improve the functionality of prosthetic devices in terms of increased control precision. This increase in control is related to the importance of sensory feedback in the context of motor control. To ensure precise control, ideal feedback should be recognized by the user both swiftly and accurately. Transcutaneous electrotactile stimulation is a prevalent choice for providing sensory feedback due to its non-invasive nature. However, it is not yet clear how to optimize this kind of stimulation for speed and accuracy of response. In this study, we set out to investigate how we can affect the Speed-Accuracy Tradeoff (SAT) during responses to an instantaneous change in electrotactile stimulation intensity. Nineteen participants completed an intensity discrimination task. Participants were asked to either prioritize speed or accuracy during specific blocks, while cognitive load, magnitude of intensity shift and direction of shift were manipulated. The results imply that the magnitude of intensity shift needs to be well beyond the just noticeable difference to ensure fast and accurate responses.

## Introduction.

The noise in our motor system results in executed motions not necessarily aligning with the movements we planned. Sensory feedback allows us to perceive the difference between planned and executed motor actions and make small corrections on the fly [2]. In healthy individuals real-time, closed-loop movement control is enabled by the integration of tactile, proprioceptive and visual information [3], [4]. People with upper limb difference do not have access to tactile and proprioceptive information, and therefore mainly depend on visual feedback. The lack of feedback through other modalities results in users relying more on feedforward control processes [5]. In the case of prosthetics, this results in diminished control due to the loss of ability to make small movement corrections, such as spontaneously adjusting grip shape and force. In order to improve closed-loop sensorimotor control in prostheses, additional sensory information needs to be provided.

Providing extra feedback through additional modalities does not necessarily result in better control: if the feedback carries a high amount of uncertainty, its impact on control will be negligible. For this reason, additional feedback has to be easily recognizable and distinguishable [6]. It is also known that in any kind of closed-loop control environment, sensory feedback delays have to be minimized to improve control stability [7]. The necessity of having to be simultaneously both fast and accurate causes a speed-accuracy tradeoff (SAT) to appear [8], [9]. Due to the decision making process needing time to accumulate evidence necessary to make a judgment, the sensorimotor system is faced with a dilemma: it can make a fast decision which compromises the response accuracy or it can wait for more evidence, compromising the reaction time. In order to minimize the effect of this tradeoff on real-time control, it is not enough to provide sensory feedback through a faster modality, but the feedback also needs to include the same amount of information within a smaller timescale.

Transcutaneous electrotactile stimulation is an attractive choice for closed-loop feedback as it is non-invasive and energy efficient [10], on top of tactile stimuli registering faster than visual stimuli [11]. Electrotactile stimulation has been used before to close the loop during prosthetic control, either by conveying information regarding sense of touch (eg. grasping force [12], [13]) or proprioception (eg. finger positions [14]). These studies report improved control precision in both cases, further making electrotactile stimulation an appealing choice. Although electrotactile feedback has been investigated in the context of prosthetics, it is not yet clear how the choice in parameters influences the SAT. Therefore, we investigated the SAT in a discrimination task, while varying both the perceived stimulation intensity and the cognitive load.

## Methods

### Participants

Nineteen participants (11 males, 8 females with mean age ± SD = 28 ± 5) without limb difference took part in the experiment. Participants provided written informed consent before the start of the experiment. The study was approved by the UCD Human Research Ethics Committee – Sciences (LS-22-46-Dupan).

### Transcutaneous Electrotactile Stimulation

Electrotactile stimulation was provided using an analog stimulus isolator (A-M Systems Model 2200) which was controlled using an NI board (NI USB-6211) connected to the experimental PC running a Python script. Stimulation was provided as biphasic square waves, with frequency and amplitude fixed at 50Hz and 5mA respectively. Perceived stimulus intensity was modulated by increasing and decreasing the pulse width. Stimulator electrodes were placed above the flexor carpi radialis of the non-dominant forearm of the participants.

### Experimental Protocol

Participants were asked to sit in front of a monitor and provide their responses using a numpad keyboard. The experiment consisted of 3 parts, which are represented in Fig. 1a. The experiment began with measuring the dynamic range (DR) of stimulation. The stimulation pulse width was increased from 50µs in 50µs increments, with the stimulus trains lasting 3 seconds. Participants were asked to press a button when they felt the stimulation, which resulted in the pulse width dropping by 100µs. The same intensity had to be matched 3 times in row for the detection threshold (DT) to be determined. Following that, the pulse width was increased to a point where the participant reported a feeling of pain or discomfort which corresponded to the pain threshold (PT). The DR was determined as the pulse width range between the DT to the PT.

The just noticeable difference (JND) was measured with respect to a stimulus set to 25% of the DR using a staircase procedure [15]. The participant was instructed to determine the stronger of two consecutive stimuli, with the compared intensity starting from 50% DR. The order of the reference and compared intensities was randomized. Every correct response resulted in the compared intensity dropping by 10µs and every incorrect one in the intensity rising by 20µs. JND was determined as the difference between the reference intensity and the average of the ten intensities, where a reversal has taken place.

During the experimental task, participants were asked to respond to an instantaneous shift in stimulus intensity via a button press indicating the direction of shift (higher or lower). The reference intensity was set at 25% DR and the magnitude of change in intensity corresponded to 1-4 times JND. The direction of intensity shift (rising/falling) was randomized over the trials. The first stimulus lasted between 2 and 4 seconds, while the second stimulus continued until the participants responded with the button press or timed out after 3 seconds. At the start of each block, participants were instructed to prioritize speed or accuracy in their response. To impose cognitive load, participants were asked to simultaneously listen to paragraphs from an audiobook (*Dr. Ox's Experiment* by Jules Verne) and answer a multiple choice question afterwards in half of the blocks [16], [17], [18]. Speed/Accuracy conditions were changed every block, while cognitive load conditions were changed every two blocks. The outcome variables of the task were response speed and response accuracy. A timeout was registered as an incorrect response with a reaction time of 3 seconds.

## Results

Four-way ANOVA reveals that stimulus shift magnitude had a significant effect on both reaction times and response accuracies ($p < 0.001$ in both cases). In depth analysis revealed that a notable proportion of overall responses were timeouts at lower shift intensities (36.49% at 1xJND and 6.44% at 2xJND), most likely resulting from the participants not noticing the shift (Fig 1b.). Subsequent analysis shows significant differences between all shift intensities for reaction times ($p < 0.001$ in all cases); as shift intensities increase, the reaction times get faster

(Fig 1c). The presence of cognitive load only affected reaction times ($p < 0.001$, Fig. 1d), but not response accuracy ($p = 0.756$). In the case of shift direction, the analysis reveals an interaction effect with shift magnitude regarding both reaction times and response accuracies ($p = 0.0257$ and $p < 0.001$, respectively; Fig. 1e-f). Further analysis using a paired T-test revealed that a significant difference was only present for the lowest shift magnitude in both cases ($p = 0.0184$ and $p = 0.0012$ for reaction times and response accuracy respectively). Explicit instructions regarding focus on response speed or response accuracy did not have a significant effect on either reaction times ($p = 0.1945$) or response accuracies ($p = 0.0978$).

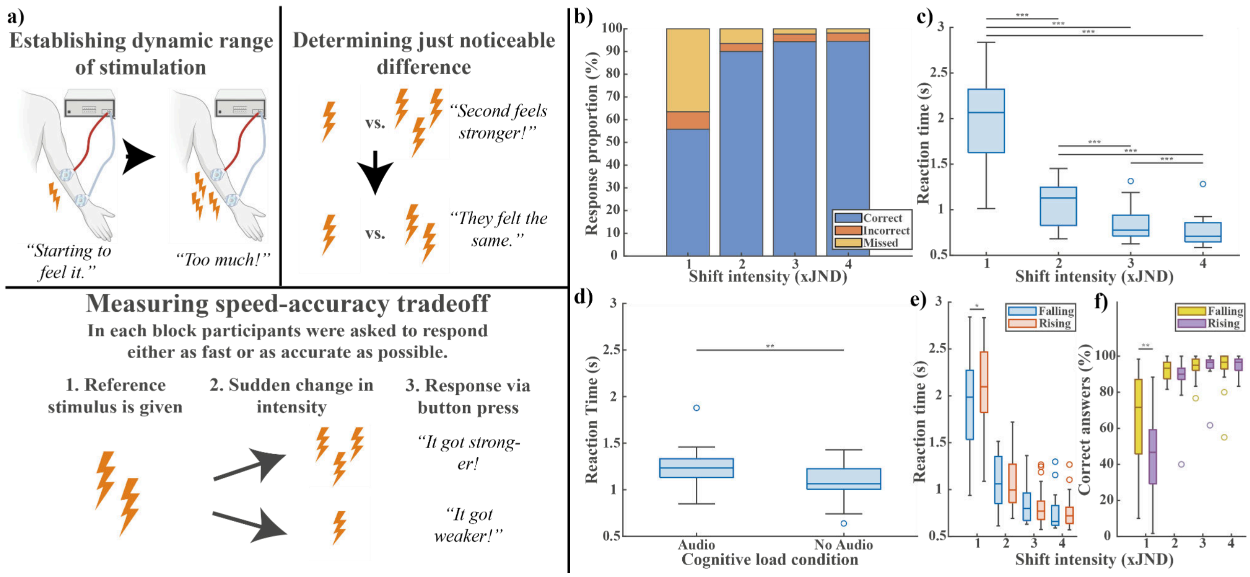


Figure 1: a.) Structure of experimental protocol. b.) Response proportions grouped by accuracy. c.) Average reaction times depending on shift intensities. d.) Average response times with and without the presence of cognitive load. e.) Interaction effect of shift direction and shift intensity regarding response times; a significant difference is only observable at the lowest intensity. f.) Interaction effect of shift direction and shift intensity regarding response accuracies; a significant difference is only observable at the lowest intensity.

## Discussion

In this study, we investigated how stimulus-related and environmental variables affect the speed-accuracy tradeoff. We have shown that, during shifts in electrotactile stimulation, the intensity of shift significantly affects both response accuracies and reaction times. Higher shifts in intensity result in less missed shifts and overall significantly more correct responses. Reaction times also reduced significantly with increased shift intensity. Our results indicate that the presence of cognitive load only affects reaction times, but not response accuracies, which implies that accurate discrimination of electrotactile stimuli is possible even with divided focus. Additionally, we have shown that at lower shift intensities the response accuracy is affected differently depending on the direction of the shift, further reinforcing the importance of higher intensity shifts.

Previous research has shown that providing additional sensory information during prosthetic use eases the cognitive load on the user and allows for more precise control of the device [19], [20]. Sensory feedback is commonly used to inform the user on object interactions or hand/grip posture, replacing tactile or proprioceptive information, respectively [12], [13], [14]. We found that, for electrotactile stimulation, the stimulus shift intensity should be at least 3 times the value of the JND to ensure discrimination of the stimuli. Providing additional feedback which is both fast to register and easy to interpret could result in the decrease of cognitive load by alleviating the burden on the visual system, which in turn could improve sensorimotor control of the prosthetic.

Increased reaction times and decreased response accuracies at small shift intensities are in line with previous research regarding closed-loop error tracking using electrotactile feedback [21]. Continuous modulation of pulse-width along the DR - using small intensity shifts - resulted in high control delay during the task [21]. Based on our results, we hypothesize that the benefits of encoding information through higher intensity shifts are likely to carry over to closed-loop control in the form of decreased control delay.

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