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# TUNING OF PARAMETERS FOR A VIBROTACTILE KINAESTHETIC FEEDBACK SYSTEM UTILIZING TACTILE ILLUSIONS

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ABSTRACT: Kinaesthetic and haptic somatosensory feedback is an integral part of the natural movement feedback loop. Afflictions like spinal cord injury potentially disrupt both efferent and afferent pathways, and thus neuroprosthesis research must address both control and feedback. Artificial somatosensory feedback has great potential to inform the user in an intuitive way and facilitate the integration of a prosthesis into their body image.
Our aim is to provide kinaesthetic feedback of arm movements via a sparse grid of vibrating actuators, manipulating actuator intensities in such a way that tactile illusions of temporally and spatially continuous movement are evoked. To this end, we examine parameter spaces of apparent tactile motion and phantom sensations, in order to design a comprehensive feedback system.

## INTRODUCTION

The ability to move is a vital prerequisite to leading a self-determined life. The goal of neuroprosthesis research is to provide a person afflicted with e.g. spinal cord injury with a tool to reclaim part of their autonomy in their daily life. An ideal neuroprosthesis would closely mimic the feedback loop of natural movement.
In recent years, progress has been made concerning intuitive control parameters from non-invasive electroencephalography, with respect to detecting goal-directed movement intention [1], [2], decoding grasps and upper-limb movements [3], [4] and decoding of kinematics [5], [6], as well as concerning the potential use of Error-Related Potentials to trigger corrective actions [7].
Apart from the challenges posed by the aspect of control, it is imperative that we also address feedback in order to facilitate intuitive use of neuroprosthesis. In many scenarios, neuroprostheses provide no natural means of somatosensory feedback to the user. Most commonly, (natural or artificial) visual feedback is used to compensate. While the visual sense has a high capacity to process a variety of information, the absence of other feedback modalities restricts the use of the visual sense for other tasks by mandating that the actions of the prosthesis be monitored at all times. Furthermore, matching the feedback modality and properties as closely as possible to the natural scenario would go a long way towards making prosthesis use more intuitive.
The absence of kinesthetic feedback has been shown to negatively impact the ability to produce cortical motor control commands [8]. Somatosensory feedback also plays an integral part in perceptually incorporating a prosthesis into one's own body image. In fact, a lack of tactile feedback is a prominent factor in prosthesis abondonment [9].
In non-invasive tactile stimulation, the most common modalities are mechanotactile [10], [11], electrotactile [12], [13], and vibrotactile. The vibrotactile modality has been used to provide force feedback [14] or discrete coded feedback for BCI applications [15], [16], but has also been demonstrated to be suitable to produce moving sensations by exploiting the inaccuracy of tactile perception.

As [17] and [18] demonstrated, when two stimuli are active with a certain temporal offset, termed Stimulus Onset Asynchrony (SOA) or Inter-Stimulus Onset Interval (ISOI), a moving sensation between stimulus locations ("apparent tactile motion") is perceived. If the SOA is too large, the two stimuli are perceived separately. If on the other hand it is too small, the two stimuli feel like one merged stimulus. In [19], a linear equation of optimal SOA control is proposed in dependence of the stimulus duration to reliably produce an apparent tactile motion.
Furthermore, two simultaneously active stimuli in relative proximity are perceived as a "phantom sensation" [20] in between the two stimulation sites. The location of the phantom sensation depends on the relative intensities of the physical stimuli. If they are equally strong, the perceived location of the phantom sensation is at the midpoint between the physical stimuli, while if they are uneven, the perceived location moves closer to the stronger stimulus. Concerning the mapping between stimulus intensities and the location of a phantom sensation, [20] examined linear and logarithmic relations, and claimed that a logarithmic mapping maintains constant intensity. Similarly, [21] compared one linear and three logarithmic models via a rating system with respect to consistency of perceived strength, location of the phantom sensation, and direction of movement, and found that the linear model fell short in all categories. In [19], a third mapping model was introduced, based on the energy summation model in the Pacinian channels. This publication concluded that this model can accurately

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predict the intensity of the phantom sensation, and works better to map the phantom sensation location than both the linear and logarithmic models. Recently, [22] compared the three models with different actuator layouts and stimulation locations, in conjunction with subject-specific sensitivity adjustment, and concluded that the power model performs best for circular layouts while the logarithmic model is preferred for straight layouts. Sensitivity-adjusted models outperformed generic models across the board.

We are developing a vibrotactile stimulation system providing spatiotemporally continuous kinaesthetic feedback via a sparse tactor grid. To this end, we wish to exploit the aforementioned tactile illusions (i.e. apparent tactile motion and phantom sensations).

This work presents the results of two experiments that were performed to inform design choices for a vibrotactile stimulation system providing kinaesthetic feedback of arm movements.
In experiment 1, we employed a similar paradigm as proposed in [19] to determine the limits of SOA to reliably produce apparent tactile motion. The main objective was to verify that we can obtain comparable results with considerably larger stimulus durations.
Experiment 2 served the purpose of finding out which phantom location mapping model was best suited for our feedback system.
Experiment 1 was performed with a preliminary setup, while experiment 2 was performed using a prototype of a stimulation device for comprehensive feedback.

## MATERIALS AND METHODS

*Experiment 1:* Seven participants (7 female, average age 27 years) took part in the first experiment. Two C-2 tactors (Engineering Acoustics Inc., Casselberry, USA) were placed on the subjects' right shoulder blade, with a horizontal inter-tactor spacing of 5 cm. The control signal was produced using an Arduino UNO (Arduino, Turin, Italy).
The stimulation frequency was fixed to 250 Hz, the recommended driving frequency of the C-2 tactors which is near the sensitivity peak of rapidly adapting Pacinian corpuscles [23]. Three stimulus durations were tested: 1200 ms, 2000 ms and 2800 ms. The order of the tactors and thus the direction of the perceived movement was varied pseudorandomly between subjects. In the beginning of the experiment, subjects completed a practice run to get used to the procedure, followed by one run per stimulus duration.

Participants were seated in front of a computer screen. They were subjected to a 1I-2AFC (one-interval two-alternative forced choice) paradigm with one-up one-down adaptive procedures. One run consisted of a test for the upper SOA threshold (continuous moving sensation vs. two discrete stimuli) and the lower SOA threshold (moving sensation vs. one perceptually merged stimulus) for a given stimulus duration.
In the test for the upper threshold, the initial SOA was considerably larger than the expected threshold (which was estimated in pre-tests). The stimulation sequence was presented to the subject, along with the instruction to focus on whether the stimuli felt apart or whether they could feel a transition. Then, they were prompted to answer the question of whether they perceived the stimuli as separate on a keyboard with "y" (two separate stimuli) or "n" (transition between the two stimuli). Subjects were allowed to take their time and replay the stimulation sequence as often as they wanted in order to produce a decisive answer. When the answer was "y", the SOA was decreased, in the opposite case it was increased again. After the SOA was decreased and then increased twice, the step size was decreased. After three more changes of direction at the smaller step size, the iteration was terminated.
The test for the lower threshold worked in a similar fashion. It started at a low SOA, and subjects were asked whether they perceived a movement sensation ("y"), as opposed to the stimuli feeling simultaneous ("n"). At every "y" answer, the SOA was decreased, while at every "n" answer it was increased.
The subject-specific thresholds are determined by averaging over the decisions after the first change of direction at the smaller step size.

The responses were recorded to a log file and analyzed using Matlab (Mathworks, Inc., Nattick, USA).

*Experiment 2:* The second experiment was conducted with six participants (4 female and 2 male, average age 27). Tactors were arranged as illustrated in Fig. 1, and held in place on the right shoulder blade using a custom shirt. To assure good contact of the tactors as well as comfort for the participants, shirts in several sizes were prepared. The inter-tactor spacing was between 5 cm and 6 cm, depending on the shirt size.
The stimulation frequency was 250 Hz. Each stimulation sequence lasted for 2 s. The direction of the simulated movement and the pairing of models (as well as their order) was varied pseudorandomly.

The tactors were controlled via an ARM Cortex M4 micro-controller (STMicroelectronics, Geneva, Switzerland) and custom amplifiers.

Participants were seated facing a computer screen. Tactor intensities were calibrated such that they were well perceived but not uncomfortable, and perceived equally strongly.
In each trial, the participant was presented with two stimulation sequences evoking the sensation of a unidirectional movement, starting from the middle tactor to one of the outer ones. Each sequence was computed to represent a movement with constant velocity, according to one of the three intensity models (linear, logarithmic,

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Figure 1: The stimulation device and tactor layout used in experiment 2. Inter-tactor spacing: 5-6 cm.

power). After the presentation of the sequence pair, the participant was prompted to choose which sequence they perceived to have a more constant velocity by clicking on the corresponding button on the screen using a computer mouse. Participants were allowed to replay sequence pairs as often as they needed.

The responses were recorded to a log file and analyzed using Matlab.

## RESULTS

*Experiment 1:* Fig. 2 shows the distributions of the thresholds across subjects, where the upper box plots correspond to the upper thresholds, and the lower box plots to the lower thresholds, respectively. Median values are indicated in red. Fig. 3 depicts the mean thresholds over subjects with black circles. The shaded area between represents the parameter space where a movement sensation exists, with the center of this space indicated by the black line. This line represents the optimal offsets to evoke apparent tactile motion. The dashed blue line is an extrapolation of the analogous line determined in [19] for stimulus durations of 40 ms and 160 ms.

*Experiment 2:* The distribution of subject choices is illustrated in Fig. 4. The colours in the left-hand plot identify the individual subjects. The preferred model of each subject is marked with a star.
Three subjects preferred the power model (on average by 15% compared to the logarithmic model), and two subjects narrowly preferred the log model over the power model (by 3%), while one subject equally preferred those two models. The linear model was the least preferred by every subject.
Subjects 1-5 most frequently replayed sequences for the pairing of the logarithmic vs. the power model, while subject 6 replayed more often for the linear vs. logarithmic pairing. Furthermore, it took subject 1-4 the longest to reach a decision between the logarithmic and the power model; subjects 5 and 6 took longer to decide between the linear and the logarithmic model. The individual average

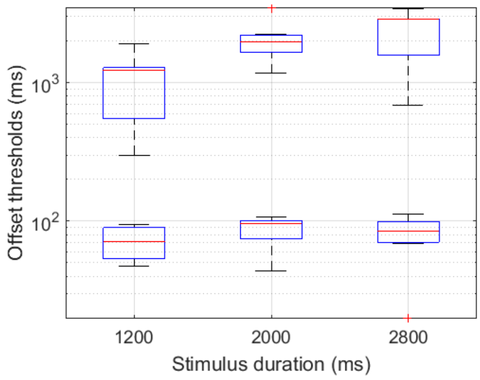


Figure 2: Upper and lower SOA thresholds. The top box plots represent the distribution of the upper thresholds across subjects, and the bottom box plots the distribution of the lower thresholds, respectively, each for the three durations that were tested.

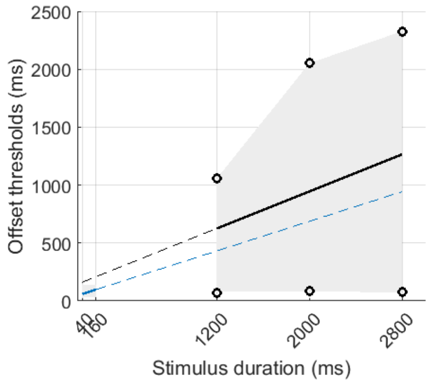


Figure 3: Mean thresholds and optimal SOA for movement sensation. The black circles mark the average thresholds, with the parameter space in between (where a movement sensation exists) shaded in grey. The black line indicates the optimal SOA as the center of this space, while the dashed blue line identifies an extrapolation of the analogous result obtained for stimulus durations of 40 ms and 160 ms in [19].

response times and number of repeats are listed in Fig. 5, where the response time is defined as the total amount of time needed to reach a decision, including the presentation of the stimulation sequences.

## DISCUSSION

We conducted two experiments to tune parameters for a vibrotactile feedback system utilizing tactile illusions to provide smooth kinaesthetic feedback.

In experiment 1, we identified the range of SOA to produce apparent tactile movement, employing a similar paradigm as in [19], but with longer stimulus durations (by a factor of $\approx$ 20-30). On average, a line of optimal SOA control can be determined that is similar to the extension of the one proposed in [19], albeit with a rather large inter-subject variance.
Some subjects initially struggled to identify the transition

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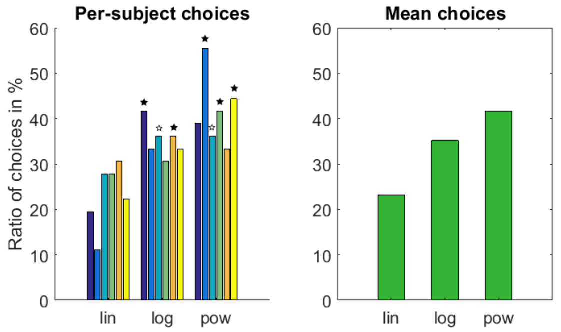
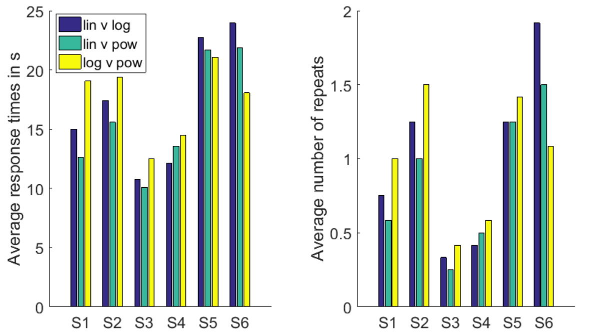



Figure 4: Distribution of model choices. Black stars mark the preferred model for each subject (white stars indicate equal preference of two models).




(a) Average response times (b) Average number of repeats

Figure 5: Average response times and number of repeats of individual subjects. The response time is the time needed to reach a decision, including the presentation of stimuli.

around either the lower or upper threshold, but proceeded to oscillate around their perceived threshold after some time.

The objective of experiment 2 was to determine the optimal mapping of tactor intensities to produce a smooth movement sensation. To this end, we chose a paradigm using dynamic stimulation sequences rather than temporally discrete stimuli. Our results are in agreement with previous ones obtained in different testing scenarios with discrete stimuli ([19], [20], [22], [21]), in that logarithmic and power models are found to be superior to a linear model.

Most subjects found it harder to decide between logarithmic and power model sequences, as reflected in the longer response times and the higher number of replays for these pairings.

The first experiment was conducted with a makeshift setup that permitted fewer options to adapt to subjects' sensitivity profiles. However, this did not constitute a problem, since a calibration of the output intensities of both tactors to the same value proved to be sufficient, and all intensities were kept constant over the duration of the experiment.

Experiment 2, on the other hand, demanded a more flexible setup with fine control of individual tactor intensities. In both instances, subjects reported the stimulation to be pleasant.

## CONCLUSION

The results presented above are used to tune parameters for a vibrotactile feedback system intended to provide artificial kinaesthetic somatosensory feedback of arm movements.

During experiment 2, a prototype of a custom stimulation device was utilized. We conclude that the device, as well as the tactor shirts and calibration procedure are well suited to our purposes.

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