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Kapppers, Astrid M.L.; Plaisier, Myrthe A.

**DOI**
10.1007/978-3-031-06249-0_5

**Publication date**
2022

**Document Version**
Final published version

**Published in**
Haptics

**Citation (APA)**
Kapppers, A. M. L., & Plaisier, M. A. (2022). Guidance for the Design of Vibrotactile Patterns for Use on the Human Back. In H. Seifi, A. M. Kappers, O. Schneider, K. Drewing, C. Pacchierotti, A. Abbasimoshaei, G. Huisman, & T. A. Kern (Eds.), *Haptics: Science, Technology, Applications - 13th International Conference on Human Haptic Sensing and Touch Enabled Computer Applications, EuroHaptics 2022, Proceedings* (pp. 39-47). (Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); Vol. 13235 LNCS). Springer. https://doi.org/10.1007/978-3-031-06249-0_5

# Guidance for the Design of Vibrotactile Patterns for Use on the Human Back

Astrid M. L. Kapppers[1(✉)] and Myrthe A. Plaisier[1,2]

[1] Eindhoven University of Technology, Eindhoven, The Netherlands
{a.m.l.kappers,m.a.plaisier}@tue.nl

[2] Delft University of Technology, Delft, The Netherlands

**Abstract.** In this paper, we present an overview of parameters that are of relevance for the perception of vibrotactile patterns on the back. These patterns are delivered via varying numbers of vibration motors fixed to the back rest of a chair, vests or belts. We present recent findings from the literature about vibrotactile anisotropy, timing, spacing, anchor points, resolution and intensity. From this overview, we derive recommendations that should be considered when designing a vibrotactile device for the back. The main recommendations are: 1) Use sequential stimulation for conveying spatial patterns; 2) Avoid tactors on the spine; 3) For a rectangular grid 4 × 4 tactors seems optimal; 4) Carefully consider relative horizontal and vertical spacing. We hope that this overview will raise awareness of several issues that play a role in perception and that our recommendations will provide guidance when designing vibrotactile communication devices.

**Keywords:** Vibrotactile · Illusions · Timing · Spacing · Resolution

## 1 Introduction

For already more than half a century, attempts have been made to convey information via haptic devices on the back [15]. Most early aims were to create aids for people with visual impairments, e.g. [1,18], but later the focus became more general on devices that could be used in circumstances where vision and/or audition were less reliable or overloaded, e.g. [6,13]. The number of vibration motors (tactors) used in these devices varies widely from only 9 to as many as 400. However, performance does not necessarily improve with this number. For example, even after several hours of training, only around 50% of block letter patterns presented via 400 tactors was recognized, whereas without any training, 87% of the letters presented via a grid of only 9 tactors were recognized [29].

For an optimal design of vibration patterns for the back, it is important to make use of existing knowledge about (mis)perceptions, anisotropies, perceptual illusions, and already published 'tricks' to improve performance. The current

This work was partially supported by the European Union's Horizon 2020 research and innovation programme under Grant 780814, Project SUITCEYES.


H. Seifi et al. (Eds.): EuroHaptics 2022, LNCS 13235, pp. 39–47, 2022.
https://doi.org/10.1007/978-3-031-06249-0_5

study is aimed at creating an inventory of all such non-veridical perceptions that could and should be considered. We will start with giving an overview of all such issues and end with a summary of design recommendations.

## 2 Relevant Perceptual Findings

### 2.1 Anisotropy

One of the first researchers to report on tactile anisotropy was Weber [26]. Measuring two-point pressure thresholds on the back (and many other body parts), he noticed that thresholds in vertical direction were larger than in horizontal direction. In his experiments, either one or two compass legs were pressed against the body and the participant had to decide whether he felt one or two points. Hoffmann et al. [10] found a similar anisotropy for vibrotactile stimulation on the back. Their stimuli consisted of two consecutive vibrations, either at the same location or slightly shifted. Participants had to decide whether the second stimulus was to the right, left or at the same location for the horizontal condition, and up, down, or same for the vertical direction. Averaged over the three inter-vibrator distances, accuracy in the horizontal condition was significantly higher than in the vertical direction. Plaisier et al. [23] asked for length estimates between sequential vibrations on the back. They found that vertical distances were perceived as larger than horizontal distances, which seems in contradiction with the results of Hoffmann et al. [10], although direction perception and length estimates do not necessarily lead to the same results. In both studies, the influence of the spine as an anchor point is given as a possible explanation of the results (see Subsect. 2.3). Interestingly, Nicula and Longo [19] obtained similar results as in [23] for pressure stimuli on the lower back; on the upper back the results were reversed, indicating that anisotropy on the back is inhomogeneous.

Kappers and colleagues [14] investigated vibrotactile direction perception on the back in 12 directions. A first vibration was always given centred on the spine and a second vibration was presented on one of 12 equally spaced locations on a circle with a radius of 11 cm. Participants had to adjust a pointer on a frontoparallel plane to indicate the perceived direction. They found that both accuracy and precision were significantly higher for the cardinal (i.e., horizontal and vertical) directions than for the oblique directions, with vertical even better than horizontal. A partial explanation comes from the results of Hoffmann et al. [10]. The differences in the perception of horizontal and vertical lengths that they found will directly influence the perception of the *direction* of oblique stimuli and thus the accuracy of the responses.

### 2.2 Temporal Aspects

Weber [26] observed that it is easier to discriminate sequentially presented pressure stimuli than two simultaneously presented stimuli. Eskilden et al. [7] investigated this for vibrotactile stimuli, but they did not find a significant difference in threshold between sequential and simultaneous stimulation. This non-significance was possibly due to their limited number of participants (only 5), but in any case, the difference was quite small. v. Békésy [2] showed that if the delay between two subsequent vibrations on the arm became shorter, the perceived location of the stimulations moved to halfway the actual locations. In the study of Plaisier et al. [23], participants had to estimate the distance between the locations of two vibrotactile stimulations. In the case of simultaneous stimulation, the distances were estimated to be much shorter than in the sequential condition. Moreover, there was hardly any difference between the estimates for a 4-cm and a 12-cm presented distance, indicating that simultaneous stimulated locations are hard to distinguish. These results can be understood from the findings of v. Békésy [2] as simultaneous stimulations will be perceived as halfway between the vibration locations and thus lack a clear distance. Van Erp [25] showed that a longer time between two vibrotactile stimuli (larger Stimulus Onset Asynchrony) resulted in better performance if participants had to indicate whether the second stimulus was to the right or the left of the first stimulus. Measuring two-point vibrotactile discrimination thresholds on the lower back, Stronks et al. [24] found that an SOA of 0 ms (i.e., simultaneous stimuli) resulted in significantly higher thresholds than an SOA of 200 ms.

This advantage of sequential stimulation becomes even more clear when more complicated patterns are presented. Loomis [18] tested recognition of letters presented on a $20 \times 20$ grid of tactors on the back and clearly performance was worse with letters presented statically (that is, all required tactors for a letter vibrating simultaneously) compared to conditions where a slit moved over the letter or the letter itself moved. Novich and Eagleman [20] used a $3 \times 3$ grid of tactors to compare spatial (that is, all tactors of a pattern vibrate simultaneously) with spatiotemporal stimulation. Pattern identification was significantly higher for the spatiotemporal patterns than for the spatial patterns.

An interesting effect of timing of vibrotactile stimulations was reported by Geldard and Sherrick [8]. Presenting 3 bursts of 5 brief pulses to the forearm, one burst near the wrist, one at the centre of the forearm and one near the elbow, was perceived as 15 pulses equally spaced moving from wrist to elbow. Varying the number of pulses in each burst influenced the perceived spacing of the locations. They termed this effect ‘cutaneous rabbit’, as it felt as if a tiny rabbit was hopping over the arm. So again, timing of vibrations has a distinct influence on perceived location.

The aim of vibrotactile stimulation is often to convey dynamic patterns or traces. Kim et al. [16] showed that a more continuous trace produced by overlap in stimulation of subsequent tactors on the foot resulted in better recognition performance. This is again an application of the findings of v. Békésy [2]. Also, Israr and Poupyrev [11] made use of this mislocalization in their sophisticated Tactile Brush algorithm. Virtual locations on their intended trace, i.e., locations on the line connecting two tactors, were simulated by an appropriate scaling of the intensity of the two tactors. In a small evaluation study, they tested 3 vibratory patterns on a device with 12 ($4 \times 3$) tactors on the back generated with either the Tactile Brush algorithm or subsequent stimulation of the tactors. Participants had to decide how many strokes they felt, but in all cases, the intention was that it should feel as one continuous stroke. The more conventional stimulation resulted in a number close to 3, whereas for the Tactile Brush algorithm this number was just above 1, indicating the perception of a continuous stroke.

### 2.3 Anchor Points

Misperceptions of localization are often due to nearby anchor points such as wrist, elbow, and other joints. Boring [3] describes these anchor points as forming a frame of reference to which the perceptions of other points are drawn. For vibrotactile stimuli Cholewiak and Collins [5] showed that localization performance on the forearm was best for stimuli near the wrist, the elbow, or the shoulder, and worse at other locations on the arm. In a subsequent study [4], they showed that for localization around the torso both navel and spine served as anchor points, especially in conditions where the spacing between the possible vibration locations was small (i.e., 12 possible locations around the torso).

Van Erp [25] measured tactile acuity by asking participants whether a second vibration was located to the left or the right of the first vibration location. To determine thresholds, they varied the actual distance between locations. They found that thresholds were much lower (and thus performance better) near the spine and the navel. Hoffmann and colleagues [10] used a similar experimental paradigm to measure vibrotactile acuity on the back. They found that horizontal accuracy for direction perception was *lower* near or across the spine compared to more peripheral areas. As a probable explanation for this lower accuracy near the spine, they argue that there will be an increased spread of the vibrations along the spine (i.e., bone conduction), making the perception task harder. However, they did not find this effect for vertical accuracy and their vibrators were not actually placed on the spine, so it remains to be seen whether this is the real explanation. In the length estimation experiment of Plaisier et al. [23], the proximity of the spine in the vertical condition is also given as a possible explanation for their finding that vertical length estimates were larger than horizontal ones.

### 2.4 Resolution

The resolution of vibrotactile stimuli on the back depends on various experimental factors, such as the SOA, the exact location on the back, tactor type, the participant, and the experimental task. Eskilden et al. [7] found a median threshold of 17.8 mm in a task where participants had to say whether they felt one or two simultaneous vibrations (i.e., a two-point discrimination task). In a second experiment, participants had to estimate the distance between two vibration locations in both a simultaneous condition and a successive condition. They found thresholds of 11.36 mm and 10.15 mm, respectively, which were not significantly different. Van Erp [25] found a uniform acuity of 2 to 3 cm on the torso, except near the spine where the acuity was 1 cm. Stronks et al. [24] report two-point vibrotactile discrimination thresholds on the lower back of 51 mm for simultaneous stimulation and 28 mm for stimulation with an SOA of 200 ms.

Johannesson et al. [12] measured direction accuracy for three different inter-tactor distances: 13 mm, 20 mm and 30 mm. Accuracies for the different distances were 64%, 82% and 91%, respectively. In a subsequent study, Hoffmann et al. [10] compared several tactors and they found best performance with N ERMs (Normal rotation eccentric rotating mass motors). The accuracy in this direction experiment was 65% for 20 mm between the tactors and 50% for a 10 mm distance. Finally, in a pattern recognition task, Novich and Eagleman [20] found that an inter-tactor distance of 6 cm was necessary for a performance of 80% correct vibrotactile pattern recognition.

### 2.5 Intensity

The intensity of the vibrations will also play a role in how the vibrotactile stimulation is perceived. Wu and colleagues [27,28] used a $6 \times 8$ grid of tactors on the back to present letters and simple geometric figures. Subsequent tactors of a trace had a small overlap in activation time and tactors on the vertices of a pattern were activated with higher intensity. They found increased recognition performance if vertices were given a higher vibration intensity than the other tactors representing the pattern. In their Tactile Brush algorithm, Israr and Poupyrev [11] used the relative intensity of vibrations to vary the perceived location of the vibration in between two tactors.

An interesting new illusion was reported by Hoffmann et al. [9]. They found that a weak vibration followed by a strong vibration at the same location, was often perceived as an illusory upward movement, and vice versa. Also, if the locations of the tactors actually differed, the perceived movement could be made stronger via this illusion.

## 3 Design Recommendations

From the above overview, it should be clear that various parameters such as timing, spacing, and intensity will play a role in how a vibration pattern will be perceived. However, it will depend on the intended application which aspects of the stimulation are relevant. Here, we will present a list of design recommendations for a vibrotactile device on the back that should at least be considered.

1. Use sequential stimulation for conveying spatial patterns
   Several studies showed that sequential stimulation results in better performance in terms of acuity, direction perception, pattern recognition and length estimates than simultaneous stimulation [18,20,23–25]. So especially when the intention is to present a spatial pattern, sequential presentation is essential. If the strength of a stimulus but not the exact location is relevant, simultaneous stimulation would be an option. Also, a spatial pattern consisting of simultaneous symmetric stimulation at both sides of the spine will probably be recognized.

2. Avoid tactors on the spine
   Several studies showed that tactors on or very near the spine will influence acuity, length estimates and direction perception [4, 10, 23, 25]. Informal observations and introspection also indicate that stimulation on the spine feels different than stimulation at other back areas; especially persons with a hearing impairment mentioned that vibrations on their spine were uncomfortable.
3. For a rectangular grid, $4 \times 4$ tactors seems optimal
   The density of tactors does not have to be higher than the human resolution. Moreover, with an algorithm like the Tactile Brush [11], the density can be further reduced. Therefore, given the vibrotactile resolution on the spine [7, 10, 12, 20, 24, 25] and to avoid tactors on the spine, a $4 \times 4$ grid of tactors seems a good choice, although a $6 \times 6$ grid also lies within the resolution of the back.
4. Carefully consider relative horizontal and vertical spacing
   Tactile acuity in horizontal direction is better than in vertical direction [26], and this was also found for vibrotactile acuity [10]. It is unknown whether this holds for all areas on the back. However, it should be kept in mind that spatial patterns presented on the back might not be perceived veridically, but instead be shrunken in vertical direction.
5. Miscellaneous recommendations
   Preliminary research suggests that emphasizing corners via a stronger vibration might help recognition of patterns [27, 28]. If a pattern consists of several traces, a short break between two separate traces will improve recognition [22].

## 4 Conclusions

In this paper, we summarized the most relevant perceptual findings from the literature for the design of a vibrotactile device for the back. Both spatial and temporal parameters have a strong influence on how a stimulus will be perceived. Often perception of a stimulus is not veridical. Many of the results depended on the exact experimental conditions, but still, we could derive several design recommendations that seem generally valid. All recommendations are aimed at maximizing recognizability of the vibrotactile patterns and are based on published psychophysical studies.

One interesting application of vibrotactile stimulation is the possiblity to convey Social Haptic Communication (SHC) via vibration patterns on the back [22]. SHC is used for communication with persons with deafblindness, mainly to provide environmental information, such as, ‘the size of the room’, ‘the number of people in a room’, ‘there is applause’, etc. [17, 21]. This type of information is usually given by a second interpreter, the other interpreter translating the spoken language. Our first co-design sessions with teachers of SHC, both persons with and without deafblindness, showed that emulating SHC via vibration patterns is promising [22]. From these sessions, we also learned that efforts to create such vibrotactile devices are highly appreciated by the target population.

Of course, there are many other possible applications, such as in gaming, virtual words, navigation, etc. We hope that our design recommendations will provide some guidance to all researchers who want to create useful vibrotactile devices.

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