MASTER

Towards Refreshable Tactile Displays
Perceived Orientation of Microlines

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Towards Refreshable Tactile Displays: Perceived Orientation of Microlines

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Abstract

Touchscreens, commonly integrated into smartphones and tablets, lack tactile feedback despite the remarkable sensitivity of human tactile perception to variations in surface structure, such as minute height differences of surface structures at the micrometre scale. Refreshable tactile displays, which possess the ability to render such subtle variations in surface structures, can create diverse surface textures and thereby leverage human tactile sensitivity.

A possible application of tactile feedback in touchscreens is to convey the orientation of surface structures to the user during navigation or the display of graphics. In the current study, microlines were chosen as a means to convey orientation and the effects of tuning three types of spatial properties on tactile perception were examined, which were line height, line width and line spacing. Participants completed matching tasks to determine the matching error for different values of each spatial property. During the matching task, participants matched their perceived orientation of microlines on 3D-printed stimuli with a protractor.

Results from a linear mixed model showed that increasing line height and line spacing significantly decreases matching error, whereas increasing line width significantly increases matching error. Out of the three properties, line height was the most influential spatial property. This model allows for the estimation of matching errors, based on a given height, width and spacing for microlines. These findings contribute to fundamental tactile perception knowledge and provide insights for the development of tactile displays. Further research is encouraged to explore trade-offs, interactions between spatial properties and the impact of exploratory movements.

Keywords: Refreshable tactile displays, texture perception, matching task, matching error

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Touchscreens have become ubiquitous in various settings, including cashier desks, shopping mall screens, and airport check-in desks. The touchscreens most commonly utilized are integrated into smartphones and tablets. While these devices offer feedback in the form of visual or auditory information, they lack the provision of tactile feedback to the user since the incorporated touchscreens remain flat at all times. However, human tactile perception is remarkably sensitive to variations in surface structure at the scale of micrometres and nanometres (LaMotte & Srinivasan, 1991; Skedung et al., 2013). Thus, techniques that allow surface morphing on such a minute scale are suitable for providing tactile feedback.

There is significant potential in advancing towards dynamic touchscreens that are capable of rendering varying surface structures. Such refreshable tactile displays unlock new opportunities for interactions with technology and enhance the user experience by adding tactile feedback. Although refreshable braille displays do exist, they are limited to displaying a fixed set of structures (e.g. pins) to convey letters or graphics and are not created to display these on a micrometre scale. They are therefore challenging to integrate into touchscreens. Another benefit of refreshable tactile displays is their compactness, allowing them to display a range of information while occupying less space than traditional maps or braille books, resulting in an efficient information display.

The concept of refreshable tactile displays as touchscreens has broad applications. The most interesting application is a feedback mechanism for users interacting with technology. Tactile feedback provides an additional modality for information reception and can be combined with visual or auditory feedback to increase redundancy or to provide complementary information. Refreshable tactile displays can also pave the way to a new generation of braille displays and therefore revolutionize them. Another application relates to virtual reality (VR). The integration of refreshable tactile displays into handheld VR consoles or the development of new virtual reality gadgets that enhance the tactile dimension results in a more immersive VR experience for the user.

The Chemistry department at the Eindhoven University of Technology (TU/e) is actively researching and working towards displays that are capable of rendering variations in surface structures (Liu et al., 2017). Their research focuses on liquid crystal networks that can be actuated by external stimuli, including light, temperature, or electric fields (Astam et al., 2022). Current early prototypes have a height resolution range of 25-125 μm and a width or spacing resolution range of 200-600 μm. The department is interested in the range of values for spatial properties of surface structures, where meaningful information can be conveyed to the user during tactile perception. The current study examines how spatial properties of microlines (i.e. small line structures) affect the conveyance of orientation through tactile perception. The state-of-the-art prototype resolutions mentioned above served as a guideline for the spatial properties of the stimuli used in the study.

During the development of refreshable tactile displays, it is essential to conduct perceptual research on the tactile sensory capabilities of humans for several reasons. Firstly, perceptual research studies are needed to build upon existing fundamental knowledge of human tactile perception. Surfaces with microstructures, due to their incredibly small size, can be seen as textures (Rosenholtz, 2015). While substantial literature exists on the perception of textures, little is known about how to convey information with microstructures and how tuning their spatial properties affects perceptual performance. Insights gained from such perceptual research can guide the design of refreshable tactile displays' characteristics. Already in the early stages of prototypes for a tactile display, the perceptual performance of users should be taken into account. Moreover, research on human tactile perception can provide valuable guidelines for the Chemistry department at Eindhoven University of Technology, indicating the boundaries to which microstructure characteristics should be pushed. Therefore, this research aids in determining the allocation of resources and research efforts in the development of such technology.

The general and broader research question of perception research on refreshable tactile displays is what the optimal spatial properties of its surface structure are to accommodate human tactile perception. Given the limited knowledge on this topic, it is unknown how the characteristics of different types of microstructures (e.g. circles, lines) affect perception in tactile displays and what their optimal properties are to convey information. Specifically, this study explores the optimal spatial properties of microlines on a tactile display for conveying information about orientation. Potential applications of microlines in touchscreens are displaying graphics, such as drawings and graphs, as well as assisting with navigation in digital (e.g. menus) and physical environments (e.g. walking navigation).

Previous Research

As mentioned earlier, humans are extremely sensitive to detecting surface structures. LaMotte & Srinivasan (1991) reported on tactile sensitivity thresholds for detecting surface irregularities or textures. They found that for detecting a single raised element, the threshold height of a dot was 2 μm. For repeated patterns with bars and dots, the elevation thresholds were 0.06 μm and 0.16 μm, respectively. Skedung et al. (2013) even found that humans were able to detect patterns with an amplitude of 13 nanometres. While these studies indicate thresholds for the detection of surface irregularities, there remains a gap in research regarding the ways in which various textures can convey information to the user.

Hollins & Bensmaïa (2007) distinguish between two encoding mechanisms for perceiving roughness: vibrotactile encoding and spatial encoding. Fine textures moving across the skin are detected as vibrations. Fine textures are characterized as textures with a spatial period – centre-to-centre distance between texture elements – of 200 μm or less. Movement is necessary to detect these fine textures (Hollins et al., 2002). Perception of coarse textures, characterized by spatial periods above 200 μm, relies on the spatial properties of the surface, such as the size and spacing of texture elements. Perception of coarse textures is nearly independent of speed and direction of their movement across skin.

The surface structures that form textures are also known as textons. Tymms et al. (2018) conducted a roughness perception study with 3D-printed textures with cone-shaped textons. They varied the following texton properties: shape (rounded or flat-topped), spacing (0.6-1.4 mm), diameter (0.1-0.5 mm) and alignment (anisotropic or isotropic). They found that large spatial periods led to higher estimations of roughness and that textons with a small diameter are perceived as rougher than textons with a large diameter with the same spatial period. Moreover, they found that a correlation between perceived smoothness and texton contact area on the skin (depending on the diameter and spacing of the texton).

The orientation of microlines could be estimated through active touch, where both roughness encoding mechanisms play a role. Through spatial encoding, the shape of the lines could be felt in their length (if longer than 200 µm), whereas the microlines are felt as a texture through vibrotactile encoding when feeling along their width (if equal to or shorter than 200 µm). However, spatial encoding is expected to play a more important role, when there is a small spacing between the microlines making it difficult to distinguish the shape of each line. The feeling direction of microlines changes the felt spatial periods, felt diameter and texton contact area on the skin. Consequently, the feeling direction affects their perceived roughness. A (near) parallel feeling direction leads to a larger felt spatial period and larger felt diameter than a (near) perpendicular feeling direction. According to Tymms et al. (2018), a larger spatial period should increase perceived roughness, whereas a large diameter should decrease perceived roughness. It is unclear, however, whether one spatial property influences perceived roughness more heavily. Assuming that their influences are equal, the finding that increased texton contact area on skin increases perceived roughness suggests that a perpendicular feeling direction is perceived rougher than a parallel feeling direction. Together with spatial encoding, this vibrotactile encoding allows for estimating the orientation of microlines.

Research Question & Hypothesis

The following research question is the aim of this study:

What are the optimal spatial properties of microlines (i.e. small line structures) for conveying tactile information about orientation?

Three spatial properties were focused on in this study: line height, line width and line spacing. The effects of these spatial properties on the perceptual performance of perceiving orientation were investigated. Perceptual performance here is defined as the matching error between the presented orientation and the perceived orientation of microlines in degrees.

The following subquestions are addressed to gain insights into the effects and relative contributions of these spatial properties.

1) *How much is gained in tactile perceptual performance in determining orientation, when height, width and spacing are tuned more extremely?*
2) *What are the relative contributions of line height, line width and line spacing in the orientation perception of microlines?*

The hypothesis is that the more extreme all three properties are tuned, the better perceptual performance becomes and thus, the lower the matching error becomes. Based on the collected data of the current study, the expected matching error can be predicted given the height, width and spacing of microlines on a tactile display. It should be noted that there is a trade-off at a certain point for each spatial property based on the manufacturing limitations of refreshable tactile displays.

Method

Participants

A total of 20 students (12 males and 8 females) between the ages of 18 and 31 years took part in the current study. They were recruited through convenience sampling and via the JFS participant database owned by the Human-Technology Interaction Group of Eindhoven University of Technology. Although no selection was made on dexterity, the right hand of all participants happened to be their dominant hand. A requirement for participant selection was the possession of healthy, undamaged skin on their dominant hand the and absence of any underlying (neurological) disorders or diseases, since they could affect tactile perception during the study. The decision was made to recruit individuals between the ages of 18 and 35, because tactile sensitivity and acuity tend to decline with increasing age (McIntyre et al., 2021; Thornbury & Mistretta, 1981; Wickremaratchi & Llewelyn, 2006). One participant in the study had legal blindness in their left eye and had 25% vision in their right eye. Visual impairment was not an exclusion criterion during participant recruitment. Although this participant mentioned a potentially heightened sense of touch due to their partial blindness, their data did not notably differ from the data of the other participants.

All participants signed an informed consent and received either study credits or a financial compensation of 10 euros for their participation. The experiment was approved by the Ethical Review Board of the Human-Technology Interaction Group at Eindhoven University of Technology, The Netherlands.

Stimuli and Set-up

The stimuli and a stimuli holder, seen in Figure 1B, were modelled in Fusion360, a Computer Aided Design software. The stimuli were printed with Grey V4 material using a resin printer (Formlabs 3+ and Formlabs 3L), since this type of printer can achieve the fine resolution that is needed for the current study. The stimuli holder was printed with black PVA material using an SLA printer (Ultimaker 3). The stimuli were small tactile displays in the shape of 4 x 4 centimetre squares with a thickness of 4 millimetres. The surface of these stimuli were covered with parallel microlines. The spatial properties of these microlines that were under investigation in this study systematically varied across the stimulus set. These properties of interest were line height, line width and line spacing. Table 1 provides an overview of all stimuli and their spatial properties. A black stimuli holder, seen in Figure 3, was modelled with an opening of 4 x 4 centimetre, such that the stimuli could be placed within the stimulus holder during the experiment. The stimulus holder was attached with duct tape to a table, such that it could not be displaced when participants felt the stimuli. Stickers with stimulus codes and degree values written on them were placed on the back of the stimulus to identify the type of stimulus. When the stimulus was placed with the sticker facing downwards, such that the degree value was facing towards a person, then that was the orientation of the microlines with respect to them (e.g. experimenter) and to the person sitting across them (e.g. participant). The stimuli were placed behind a cardboard screen, such that the participant was not able to see which stimulus was picked up and placed back by the experimenter.

A protractor was used as a tool for participants to exhibit their judgement on the orientation of the felt microlines. The blurry goggles were worn by participants to prevent them from being able to see the exact degrees on the protractor and the microlines on the stimulus. The blurry goggles also allowed the participant to distinguish between the stimulus and the stimulus holder when feeling, since these differed in colour. The blurry goggles were adjustable to fit any head size by adjusting the tightness of an elastic band. A stopwatch was used for enforcing a ten-second time limit for participants to make their judgement.

The laptop was used for the experimenter to read the stimuli sequence and input the responses during the experiment. A stimuli sequence was generated randomly for each participant into an Excel file. The experimenter reads the stimulus code and places the corresponding stimulus with the correct orientation in the stimuli holder. After the participant made their matching judgement, the experimenter read the protractor and input the degree value in the Excel file for the current stimulus.

Table 1

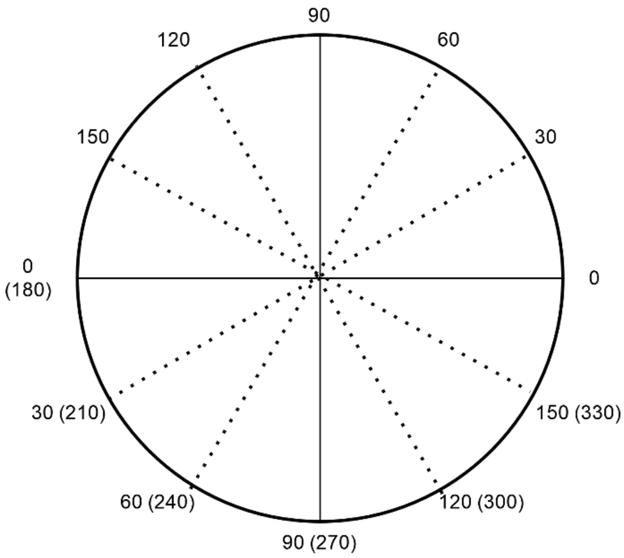
Overview of stimuli used in the study with their code and spatial properties (line height, line width and line spacing).

Stimulus Code	**Line height (µm)**	**Line width (µm)**	**Line spacing (µm)**
BS	30	200	200
H60	60	200	200
H90	90	200	200
W400	30	400	200
W600	30	600	200
S400	30	200	400
S600	30	200	600

Note. The codes of the stimuli were determined by their spatial properties. BS stands for baseline and corresponds with the baseline values. H, W and S stand for height, width and spacing, respectively, and indicated which spatial property was modified followed by its value.

Figure 1

Presented orientations on stimuli and protractor from participant's perspective



Design

The study utilized a matching task, similar to the study conducted by Plaisier & Kappers (2022), to investigate perceptual performance in determining orientation when varying the spatial properties of microlines on a tactile display.

The stimuli presented to the participants varied one spatial property (line height, line width or line spacing) with respect to the baseline stimulus. This baseline stimulus had the minimum values for each spatial property, based on the state-of-the-art resolutions of the dynamic surface prototypes within the Chemistry department at Eindhoven University of Technology. The XY resolution (25 µm) of the resin printer used (Formlabs 3+ and Formlabs 3L) was also taken into account when determining baseline values to prevent undesired artifacts. The baseline stimulus used had a line height of 30 µm, a line width of 200 µm and a line spacing of 200 µm. The other stimuli varied one of these spatial properties and were coded by the manipulated spatial property, accordingly, as shown in Table 1. Line height was varied to 60 µm and 90 µm, line width to 400 µm and 600 µm, and line spacing to 400 µm and 600 µm. Each stimulus was presented twice at six different orientations per participant: 0, 30, 60, 80, 120 and 150 degrees. Figure 1 shows the presented orientations on the stimuli and the protractor from the participant's perspective.

The perceptual performance was measured in terms of a matching error, the absolute difference between the presented orientation and the perceived orientation of microlines on a stimulus. This matching error was measured in degrees and calculated by taking the absolute difference between the presented orientation of the stimulus and the orientation judged on the protractor by the participant.

Procedure

The study took place at the General Purpose Lab in the Atlas building on the campus of the Eindhoven University of Technology. The participant was received in the lab and was explained the tasks of the experiment. They were then asked to read the consent form and sign it if they consented to participate in the study. The experimenter also encouraged them to ask any questions that arose while reading the consent form. The participant was also asked whether they climb regularly, play the guitar or engaged in any other activity that encouraged the growth of calluses on their fingers. This question was posed to participants to ensure that they did not have reduced tactile sensitivity in their dominant hand, which was an exclusion criterion. One participant was excluded after starting the practice trials, since they indicated that they had calluses due to rock climbing and were unable to complete the test trials. They were also requested to put away their phones to avoid distraction during the experiment. The participant was given a pair of blurry goggles, which they adjusted to fit their head.

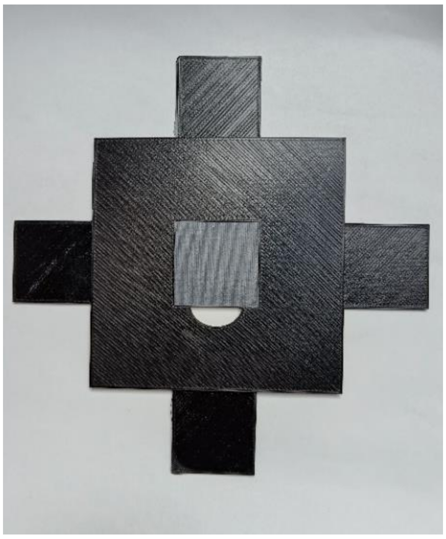
Before the start of the experiment, a few practice trials were conducted in order to make sure the participant was comfortable with the task and know what to expect during the experiment. The practice trials were also a good opportunity to discover any participants that may have impaired tactile acuity (e.g. due to calluses).

Figure 2

Participant feeling a stimulus and turning a protractor

Figure 3

Stimulus holder with stimulus



After the practice trials, the participant felt a set of 80 stimuli. The participant was asked to seat themselves with their body midline centered in the middle between the stimulus holder and the protractor, as shown in Figure 2. For each trial, the experimenter placed a stimulus in the stimuli holder and the participant used their index finger on their dominant hand to feel the surface of the tactile stimuli by staying within the stimulus holder surrounding the display. A close-up of the stimulus holder with a stimulus placed inside is displayed in Figure 3. While feeling, the participant matched their perceived orientation of the microlines with the protractor by using their other hand within a time limit of ten seconds. Halfway through the set of trials, a scheduled break of a few minutes was incorporated to allow participants to regain any lost concentration and to restore any diminished tactile sensitivity that might have occurred in their index finger, potentially leading to numbness. At the end of the experiment, the participant was asked about their concentration during the experiment and any other remarks they might have about the experiment. Finally, the participant was debriefed about the study, thanked for their participation and received their compensation.

Analysis

Responses from the participants were entered into an Excel file by the experimenter. During the first step of pre-processing, 168 entries with missing data were deleted. 160 of those entries were entries for the two earlier-mentioned missing stimuli from the stimuli set, which could not be presented during the study. Five entries were intentionally left unfilled, as the experimenter mistakenly believed the stimuli were among the missing ones, resulting in the stimuli not being presented. The experimenter inadvertently omitted to fill in the three remaining missing entries, despite having presented the stimuli. Secondly, the responses of the participants were converted to a 0-150 degree scale by subtracting 180 degrees from all responses that were equal to or larger than 180 degrees on the protractor. Thirdly, the matching error (absolute deviation) was calculated between the presented orientation and perceived orientation with the following formula:

$$Matching\ Error = \min\{|\alpha - \beta|, |\alpha + 180 - \beta|, 360 - |\alpha - \beta|, 360 - |\alpha + 180 - \beta|\},$$

where α is the presented orientation and β is the perceived orientation.

For the data analysis, the pre-processed Excel file was analysed in R to conduct a t-test and run a linear mixed model. Since the oblique effect is a common phenomenon in perception literature (Apelle, 1972; Furmanski & Engel, 2000; Plaisier & Kappers, 2022), its presence was tested in the current study. A paired t-test was carried out to evaluate whether the mean matching error for cardinal orientations was significantly lower than the mean matching error for oblique orientations. Using the LmerTest package, a Linear Mixed Model (LMM) was run with matching error as the dependent variable and line height, line width and line spacing as the independent variables:

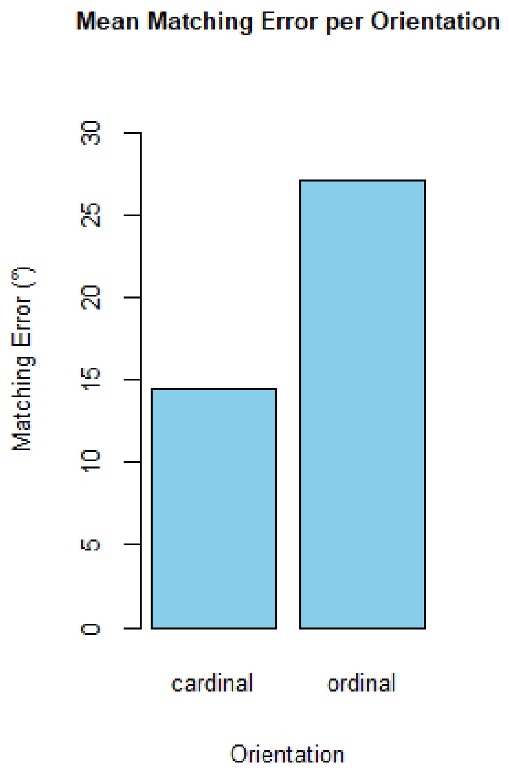
$$Matching\ Error \sim height + width + spacing + (\ 1\ |\ Participant\ ID\ )$$

Results

Oblique Effect

Figure 4

Mean matching errors for cardinal and ordinal orientations

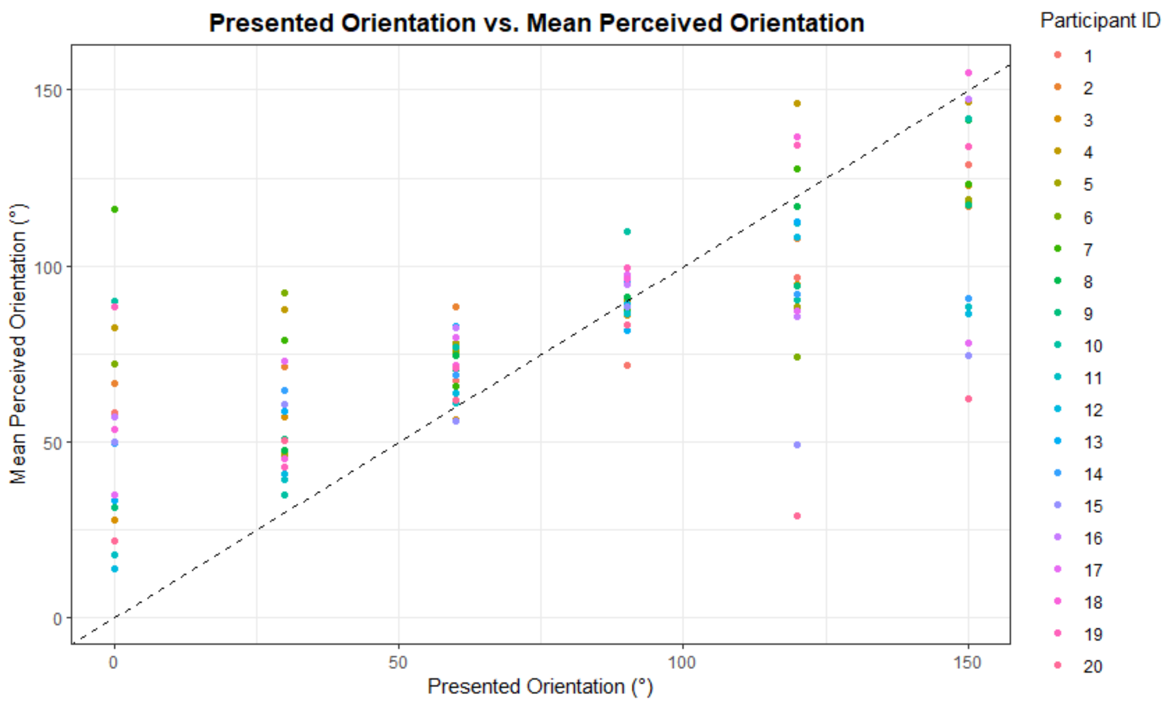


The paired t-test showed that the mean matching error for cardinal orientations (M = 14.42, SD = 7.43) was significantly lower than the mean matching error for ordinal orientations (M = 27.06, SD = 7.82), $t(19) = 7.5281$ ($p < .001$). This provided evidence for the presence of the oblique effect in tactile perception of orientation. All t-test assumptions were met. No outliers were found and the normality assumption was met (Shapiro-Wilk test, skewness and kurtosis tests) for both the ordinal ($p > .76$) and cardinal data ($p > .16$). Levene's robust test also showed that the assumption of homogeneous variances was met (p >.68).

Perceived Orientation

Figure 5

Scatter plot of participants' mean perceived orientation for each presented orientation



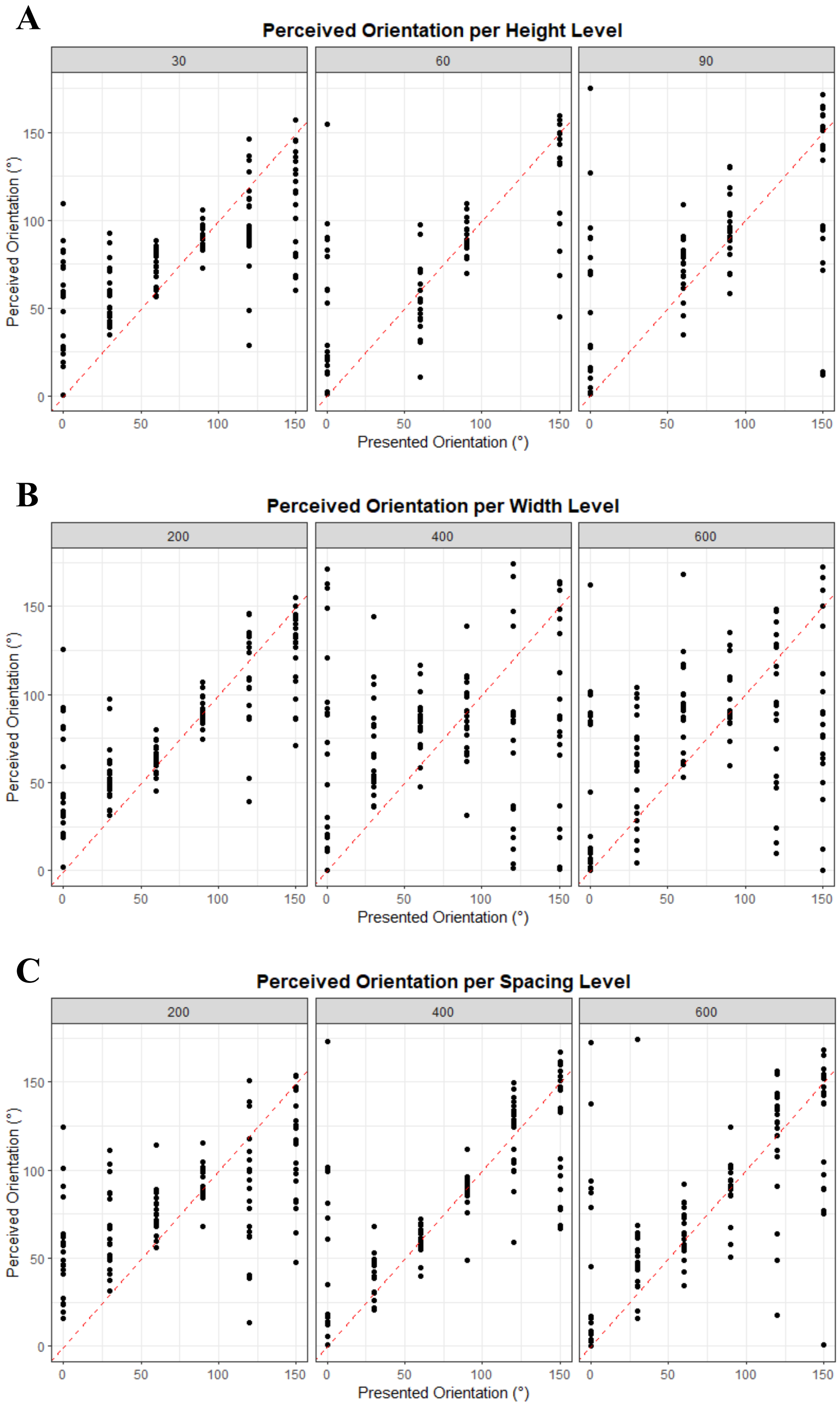
Note. The dashed line is an identity line serving as a visual aid to observe the variance around the presented orientation.

Figure 5 shows the variance of participants' average perceived orientation for each presented orientation over all stimuli with an identity line. The variance is smaller near orientations of 60 and 90 degrees.

Figure 6 plots the mean perceived orientation of each participant for each spatial property level separately. Visually, the variance of the data points at line height levels 60 µm and 90 µm are more centred around the identity line compared to the baseline level (30 µm). Likewise, the variance of the data points at line spacing levels 400 µm and 600 µm are more centred around the identity line compared to the baseline level (200 µm). For line width, the variance is larger at the 400 µm and 600 µm levels compared to the baseline level (200 µm).

Figure 6

Scatter plots of mean perceived orientation for each presented orientation per spatial property level



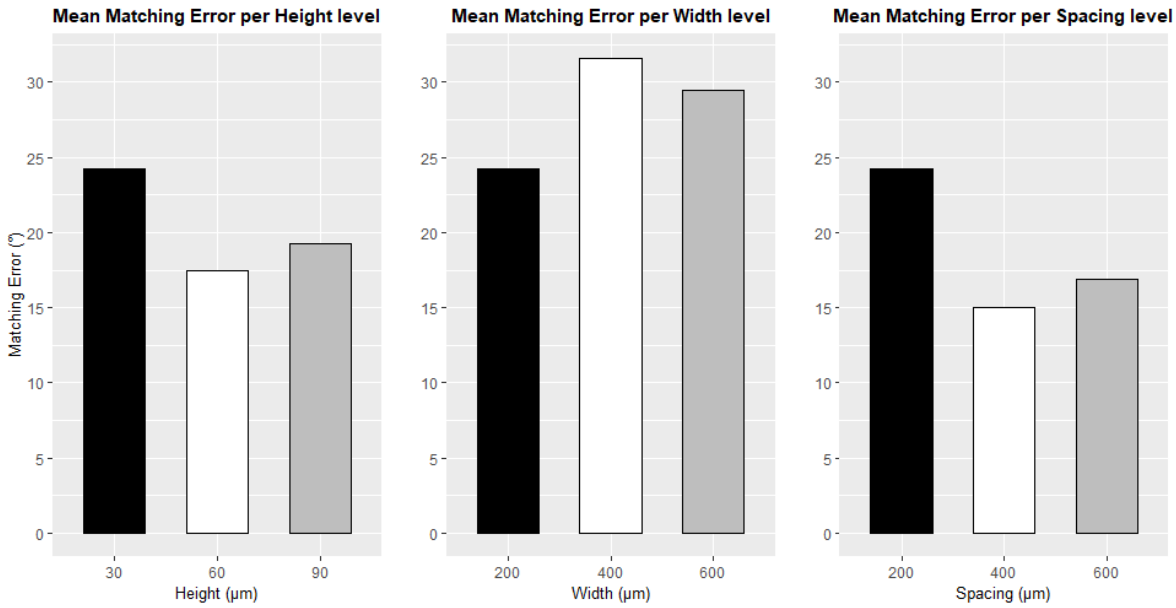
Note. All spatial property levels are in the unit µm. The mean perceived orientations of all participants are plotted for each presented orientation. Due to two missing stimuli, data is missing for height levels 60 µm and 90 µm.

Matching Error

Figure 7

Bar plots of mean matching error for each spatial property level

A **B** **C**



Note. The mean matching error is the same for the baseline value of each property, since this was calculated on all baseline stimulus data.

In Figure 7, the mean matching errors for each stimulus are plotted and compared to the baseline stimulus. The matching errors at line height levels 60 µm and 90 µm are lower than the matching error for the baseline height (30 µm). Similarly for line spacing, the matching errors are lower at spacing levels 400 µm and 600 µm compared to the baseline spacing (200 µm). It is also noticeable that the medial spatial property value for both height and spacing is slightly lower than the highest value. The matching errors at line width levels 400 µm and 600 µm are higher than the matching error for the baseline value (200 µm). The medial line width value is slightly higher than the highest line width value.

An LMM with matching error as the dependent variable and height, width and spacing as the independent variables was fitted:

$$Matching\ Error = 26.07 - 0.09 * height + 0.02 * width - 0.02 * spacing$$

This LMM showed a significant negative relation between matching error and height (β = -.09020, t = -2.862, p < .001), a significant positive relation between matching error and width (β = .02067, t = 4.885, p < .01) and a significant negative relation between matching error and spacing (β = -.02113, t = -4.991, p < .001). The beta coefficient of height is the largest – approximately 4.5 times larger than both the width and spacing beta coefficients. A check for multicollinearity with variance inflation factor (VIF) reveals no signs of strong correlation between line height, line width and line spacing, as all VIF values were approximately 1.5.

The beta coefficient for line height is approximately 4.5 times larger than the beta coefficient for line width and line spacing. Thus, increasing line height leads to the largest relative gain in perceptual performance. Specifically, an increase in line height by 11 μm corresponds to a decrease of 1 degree in matching error.

Discussion

The current study investigated the relationship between the spatial properties of microlines on tactile displays and human perceptual performance in perceiving orientation. A paired t-test showed that the oblique effect was present in the current study, as participants performed better at estimating the orientations of cardinal stimuli than those of ordinal stimuli, which is in agreement with previous research that addresses the oblique effect in both vision and haptics (Apelle, 1972; Furmanski & Engel, 2000; Plaisier & Kappers, 2022). The LMM showed that increased line height, increased line spacing and decreased line width significantly decreases the matching error. Line height was the most influential spatial property (β = -.09). Increasing line height is 4.5 times as effective for lowering the matching error, compared to increasing spacing (β = -.02) and decreasing width (β = -.02). The findings of this study provide an answer to the research question by concluding that an ideal tactile display with microlines has a large line height, a small line width and a large line spacing. These properties contribute to minimizing matching error and therefore maximizing perceptual performance.

The present study highlights the significance of research on refreshable tactile displays within the Chemistry department of Eindhoven University of Technology. The derived model allows for an estimation of the matching error for perceiving orientation based on a given height, width and spacing of microlines. Pushing the boundaries of spatial properties of microlines with liquid crystal networks proves to be a promising direction, with the following guidelines to be pursued: a larger line height, a smaller line width, and a larger line spacing.

The most influential property, line height, is likely extensively capitalized upon by vibrotactile encoding in humans. Given humans' remarkable sensitivity to surface irregularities at the nanometre scale (Skedung et al., 2013), an elevated line height may make the textons more obvious to perceive and heightens the vibration intensity when felt. This is in line with literature that discusses vibrotactile encoding as a mechanism for perceiving the roughness of fine textures, such as those used in the current study. It should be noted that the study did not investigate the perceptual performance when the spatial properties are tuned even more extremely. Hollins & Bismaïa (2007) reported that extremely large spacing between adjacent dots could reduce perceived roughness as skin touches the smooth floor of the surface. This could be the same case for other microstructures, such as microlines. Similarly, tuning the line width to extremely high values, reduces the area of skin touching the floor while increasing the area in contact with microlines. This is also in accordance with the correlation found by Tymms et al. (2018) between perceived smoothness and texton contact area and may explain the negative relationship found between line width and matching error. The finding that a large line spacing is perceived rougher than a small line spacing by Tymms et al. (2018) could explain the improved performance for larger line spacing levels. These findings leave room for future research to explore the potential optimal upper limits and lower limits of these spatial properties.

Limitations

The presence of missing stimuli, specifically with height values of 60 µm and 90 µm and orientations of 30 and 120 degrees, might have influenced the overall findings. The absence of these stimuli did not likely influence the results but could have impacted the precision of the data. Including these missing stimuli in future studies could confirm or deny this possible influence.

Another limitation is the quality of the 3D-printed stimuli. Various issues were encountered during the printing process, frequently leading to unsuccessfully printed stimuli. All stimuli were checked with a profilometer (DektakXT) to ensure that the resolution did not vary too much from the intended model. One factor was that the printer resolution (25 µm) was close to the baseline height value (30 µm) for many stimuli. Secondly, the material used made a difference in the print quality of the stimuli. Thirdly, the resin printer might not be reliable for printing microlines at a 30- and 120-degree orientation, which could be the reason for the repeated failure of printing the two missing stimuli. It is therefore recommended for future research to utilize high-resolution printers, select appropriate materials and verify the resolution of their stimuli with a profilometer.

During the debriefing session, a participant revealed that their approach to the task slightly differed from the intended approach. They mentioned that their focus was not on indicating precise orientations but rather on identifying cardinal orientations and oblique orientations close to 45 degrees. Additionally, they mentioned that they used the tape on the protractor as a reference for the 45-degree orientations. However, it is important to note that the tape was merely intended for attaching the protractor to the table and was not symmetrically positioned nor intended as a specific reference for the 45-degree orientations. Although it is deemed unlikely that the data of this one participant influenced the data, participants in future studies should be instructed not to rely on any additional materials as references, except for the designated protractor knob to maintain study reliability and validity.

Future research

One suggestion for future research is to investigate possible interactions between line properties, such as the possible interaction between line width and line spacing. Although the current study did not find evidence of this interaction within the studied range of properties, it is possible that with properties values beyond the range of this study an interaction does occur.

Examining the impact of exploratory movements on the orientation perception of microstructures is another promising direction for future research. Since all stimuli, except the spacing stimuli (S400 and S600), had a spatial period of 200 µm, their roughness is classified as fine according to Hollins & Bismaïa (2007). However, the exploratory direction relative to the lines has an impact on whether a rough or fine texture was felt. Feeling the lines back and forth from any direction that is not the perpendicular direction leads to different felt spatial periods that are larger than 200 µm, classifying them as rough. Therefore, the speed of the exploratory movements by the participants likely had little to no impact on the perceived roughness when feeling back and forth in a specific direction. Examining how different movement strategies affect participants' perceptions would contribute to a more comprehensive understanding of tactile perception processes.

Moreover, focusing on the perceptual performance of tactile displays with different types of microstructures, such as dot patterns or lines composed of smaller lines, could offer further insights into the optimal spatial properties for conveying information. Comparing the perceptual performance and user experience of different microstructure types would allow for a more comprehensive evaluation of their effectiveness and potential applications in various contexts.

Conclusion

To conclude, the current study established significant relationships between three spatial properties of microlines (height, width and spacing) and the matching error in perceiving the orientations of these lines. The larger the line height and line spacing of microlines, the lower the matching error in perceiving orientation. The larger the line width, the higher the matching error. Out of these three, height emerged as the most influential spatial property.

These findings contribute to our understanding of how to convey orientation through spatial properties of microlines and provide an estimation model for matching error given the height, width and spacing of a microline texture. Future research is encouraged to explore the impact of exploratory movements and the impact of different types of microstructures on tactile performance.

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