What influences angular acuity in raised line drawings?

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Abstract

In this study we investigated the angular resolution subserving the haptic perception of raised line drawings. We found that for acute angles discrimination performance is highly dependent on exploration strategy: mean thresholds of 2.9° and 6.0° were found for two different exploration strategies. For one of the strategies we found that discriminability is not dependent on the bisect orientation of the angle. Furthermore, we found that thresholds almost double when the angular extent is increased from 20° to 135°. We also found that local apex information is of significant influence on discrimination for acute as well as obtuse angles. Overall, the results tell us that the acuity with which angles in raised line drawings are perceived is determined by the exploration strategy, local apex information and global angular extent.

Keywords: Haptic perception, psychophysics, raised line drawings, angle discrimination

1 Introduction

The vast amount of visual line drawings used in everyday life shows that representing a real object with a line drawing conserves the visual recognisability up to a large amount. With haptic perception, on the other hand, there is a large difference between recognising real objects and their 2D raised line depictions [8]. Whereas for the haptic recognition of real objects latencies of a few seconds are typically found [9], latencies can easily reach a minute or more in the case of raised line drawings [5, 12, 16]. One of the causes for these high latencies is the serial nature of spatial information acquisition of the fingertip. The study of Loomis et al. [15] showed that if the visual field of view is limited to the effective field of a fingertip, recognition latencies for vision and touch become of comparable length.

While numerous studies have reported on different aspects of the recognition process, such as the influence of visual status [5, 12], the benefit of categorical information [7] and the influence of depiction technique [20], there is little known about the perceptual performance subserving this recognition process. To understand the perceptual capabilities of the haptic system, it is necessary to study both perceptual biases as well as discrimination ability. The first category of experiments has already had some attention in the literature: Armstrong and Marks [1] showed that linear extent explored radially tends to be overestimated with respect to tangentially explored lines, and Lakatos and Marks [10] showed that haptically explored angles consisting either of raised lines or of wooden blocks tend to be overestimated. Furthermore, the subject of haptic illusions has been broadly studied [e.g. 4, 6, 17]. Although these investigations of perceptual biases are important to understand distortions that occur in line drawing perception, they do not give any insight into the accuracy with which the haptic system encodes or decodes a stimulus.

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Research into haptic spatial acuity relevant for haptic line drawings is confined to the well known two-point threshold [23] and research on the limited spatial bandwidth of touch [e.g. 13, 14]. These studies tell us what cutaneous limitations are to be expected and should be taken into account when studying the perception of raised line stimuli. Russier [18] investigated the influence of visual status (i.e. blind or sighted) on the ability to discriminate circles from ellipses but this study did not yield quantitative discrimination thresholds.

The study presented here intends to give more insight into the discriminability of the geometric features of raised line drawings, in particular the discrimination of angles. We studied two factors that could influence angle discrimination: the exploration mode and geometric properties of the angle, such as bisect orientation and angular extent.

In the first experiment the influence of the bisect orientation on the discriminability of acute 20° angles is investigated. Movement was constrained to moving the fingertip between the lines of the angle. In pilot experiments this exploration strategy yielded the lowest discrimination thresholds. In these pilots it was also observed that this type of exploration was spontaneously used by subjects who were free to move. The reason for varying the bisect orientation is motivated by findings in haptic research that perception is generally not isotropic, [e.g. 1, 3]. Knowledge about isotropic or anisotropic characteristics of discrimination ability would give more insight into how the fingertip processes geometrical information.

In the second experiment the influence on discriminability of two general geometric properties of an angle were studied: angular extent and apex presence. Instead of using the exploration strategy from Experiment 1, we instructed participants to follow the lines of the angle (see Figure 2). This strategy is suitable for both acute and obtuse angles. By using a reference angle of 20° for the acute angle condition we could quantitatively compare the two exploration strategies. The obtuse reference angle was 135°.To investigate the contribution of apex information we compared discrimination performances for angles either with or without apex. Voisin et al. [21, 22] found that cutaneous and kinaesthetic input were of equal importance for angle discrimination. Information about the angular extent in raised line stimuli can be retrieved from the global line orientations and from the local apex information. The line orientation information is likely encoded kinaesthetically (although guidance is always mediated by cutaneous cues) and the local information encoding of the apex is likely to be of a more cutaneous nature. Since Voisin et al. [21, 22] only used one reference angle it is unknown whether the kinaesthetic and cutaneous contributions depend on angular extent. On the basis of results of Experiment 1 we hypothesised that information from the apex would be particularly helpful for the discrimination of acute angles. The hypothesised result would thus be that discrimination thresholds increase only for acute 20° angles and not for obtuse 135° angles when the apex is removed.

2 Experiment 1

Method

Six participants were reimbursed for their participation. All participants were rated 'strongly right handed' according to the handed-

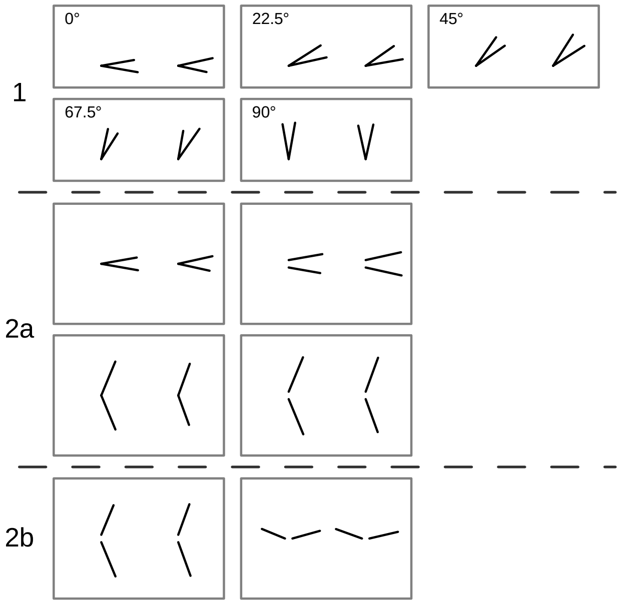

Figure 1: Examples of the stimulus sheets. For clarity, the scale of the gap sizes and line width is doubled. In these examples, angles on the left of the sheets are equal to the reference angle and angles on the right are 5° larger. **1** Stimulus sheets used for Experiment 1. At the top left the 0° bisect orientation stimulus sheet is depicted, followed by 22.5°, 45°, 67.5°, and 90°. **2a** The stimuli used for Experiment 2. The upper graphs show the 20° angles with and without apex, the lower graphs show the 135° angles. Note that the apices and gaps are located at a fixed position. **2b** Stimulus set used for the control experiment.

ness test of Coren [2]. The participants were naive with respect to the purpose of the experiment and did not participate in a related experiment before.

Examples of the stimuli can be found in Figure 1. All stimuli were produced with Zytech Swell Paper. Drawings of lines depicting the angles were printed on regular A4 paper. The width of the lines was 1 mm. To prevent participants from using the distance between the endpoints as a cue, the length of the lines was randomised between 45 and 68 mm. The printed images were photocopied on Zytech Swell Paper which was treated with a special heater to emboss the lines. The resulting height of the lines was approximately 0.5 mm.

In the following, the terms vertical and horizontal are defined as both lying in the horizontal (table) plane, where vertical means parallel to the observers' midsagittal plane and horizontal means parallel to the observers' frontoparallel plane.

Participants were blindfolded and did not receive feedback throughout the experiment. During the experiment, the experimenter placed the stimulus sheet in a stainless steel mold (see Figure 2) which was mounted onto the table. Every stimulus sheet contained a reference angle and a test angle. The vertical size of the sheets and mold were 14.3 cm and the apices of the angles were located at a vertical distance of 3.8 cm (note that Figure 2 shows the mold used in Experiment 2, which had a different vertical dimension). The distance between the apices of the two angles was 13.4 cm. The mold was 13.4 cm longer than the length of the stimulus sheet. After the stimulus sheet was placed on the left side of the mold, the participants started to feel the right angle with their right hand index finger. The participants were instructed to move their fingertip between the lines of the angle following the imaginary

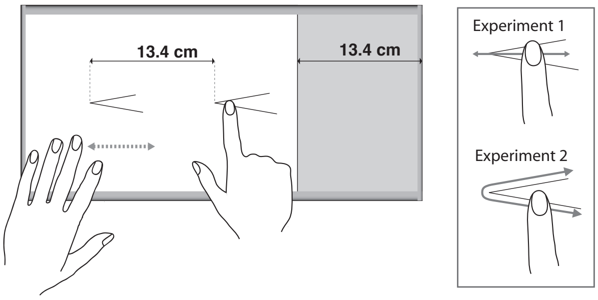

Figure 2: One the left it can be seen how the mold was used to switch between test and reference stimulus: after feeling an angle the sheet was moved to position the other angle in exactly the same location. On the right, sketches of the exploration strategies can be seen.

bisect without losing contact with either of the lines (see Figure 2). After moving maximally four times back and forth, participants lifted their right index finger, shifted the stimulus sheet with their left hand to the right and began to feel the left angle. This procedure could be repeated until each angle was felt twice. At the end of such a trial the participants verbally indicated which angle was perceived as larger.

Because we are interested in the influence of bisect orientation on discrimination performance, it was essential to keep the finger orientation constant. This was realised by fixating the forearm onto the end of a parallel drafting machine. Using this apparatus the movement of participants could only be translational.

A reference angle of 20° was used and the test angles were $20 \pm \{1, 2, 3, 5\}$ degrees. The different bisect orientations were presented randomly and were balanced within a session which lasted 112 trials. Each of the five bisect orientation sets consisted of 8 different test angles which were presented 10 times each, except for the 45° and 90° orientation which were presented 20 times. This resulted in a total number of 560 trials per subject spread out over 5 sessions of approximately one hour. For each test and reference stimulus pair, two stimulus sheets were fabricated, one with the reference angle on the left and one on the right. Using these stimulus sheets an equal number of times ensured that the reference was equally often presented left and right.

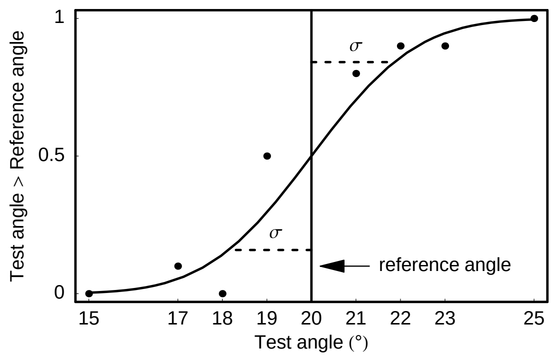

Figure 3: Example of a cumulative Gaussian fitted to the data. The best fit parameter σ gives the 84% correct response threshold. σ is based on at least 80 measurements.

The collected Two Alternative Forced Choice (2AFC) responses were transformed into fractions of number of times that the test angle was judged as larger than the reference angle. The psychometric function on which the data were fitted was the (normalised) cumulative Gauss distribution which can be written as:

$$f(\alpha,\sigma,\mu) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{\alpha} e^{-\frac{(\alpha'-\mu)^2}{2\sigma^2}} d\alpha' \qquad (1)$$

where α denotes the test angle and μ the point of subjective equality (PSE). Since the stimulus set was completely counterbalanced, we only fitted the threshold value σ and not the PSE μ. The discrimination threshold at 84% correct is defined by the parameter σ since $f(\sigma,\sigma,0) = 1 - f(-\sigma,\sigma,0) \simeq 0.84$.

Taking into account the binomial distribution of each separate data point with lower and upper limits of 0 and 1, respectively, we used the method of maximum likelihood to estimate the threshold parameter σ. This can formally be written as maximizing the likelihood function L for the parameter σ:

$$L(\sigma) = \prod_{i}^{N} P(f(\alpha_i,\sigma,\mu), n_i|y_i) \qquad (2)$$

The product is taken over N test stimuli. P denotes the binomial chance that a data point y_i is described by the parameters of the psychometric function f.

An estimate of the variability of the fitted threshold parameters is determined using the bootstrap method described by Wichmann and Hill [24]. Using the stimulus set interval, the number of trials per test stimulus, and the measured threshold value as initial conditions we calculated a set of $N = 10000$ simulated threshold values. From this distribution we calculated the 95% confidence interval.

Results and discussion

Individual thresholds as a function of bisect orientation are presented in Figure 4. Visual inspection does not reveal a general effect of orientation on discrimination performance. This is confirmed by a repeated measures Analyses of Variance (ANOVA) which shows that the influence of bisect orientation on discrimination thresholds is not significant ($F_{4,20} = 2.764$, $p = 0.056$). The average discrimination threshold for all directions and participants is 2.9° and the 95% confidence interval around this mean was calculated to be $[1.9°, 4.2°]$. All threshold values are within the 95% confidence interval of the mean threshold. This is an extra confirmation that the within-participant fluctuations are likely due to chance.

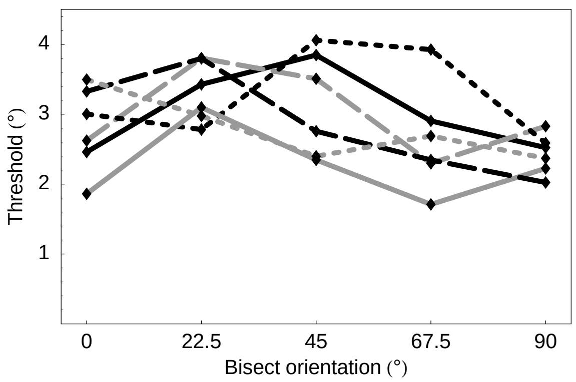

Figure 4: Threshold values as a function of bisect orientation for all 6 participants in Experiment 1.

The variation of thresholds between different directions and participants seems to fall in a well defined range of 2° to 4°. This indicates that the bisect following strategy yields a robust discrimination performance.

3 Experiment 2

A second experiment was designed to measure the discrimination performance for both acute and obtuse angles. The angle of reference for the acute angles was chosen to be 20° in order to make comparisons with Experiment 1 possible; the angle of reference for the obtuse angles was 135°. Besides angular extent, the presence of the apex was used as an independent variable. Different use of the local apex information could account for possible differences between the discrimination of acute and obtuse angles. Participants were instructed to follow the lines of the angles for the exploration of the stimuli (see Figure 2).

A difference between the two exploration strategies is the simultaneous contact with the two lines. Although much less than with the first strategy, there is still simultaneous contact of the fingertip with the two lines using the second strategy. This is caused by the fingertip moving along one line and while approaching the apex already touching the other line and thus feeling how fast the lines are converging and diverging. The amount of simultaneous contact is obviously decreasing with increasing angular extent. If this phase of the exploratory trajectory would be beneficial for discrimination, then removing the apex would particularly influence the discriminability of acute angles. Thus we hypothesise that removing the apex will mainly have an effect on the discriminability of the 20° angle.

Method

Eight strongly right-handed [2] participants were reimbursed for their participation. The participants were naive with respect to the purpose of the experiment and did not participate in a related experiment before.

The stimuli, which can be seen in Figure 1, were produced in the same way as in Experiment 1. The same length randomisation was applied as in the first experiment. The size of the reference angle was either 20° or 135° and the bisect orientation was fixed at 0° with respect to the horizontal. The gap caused by cutting of the apex was chosen not to exceed the contact area of the exploring finger because this would generate extra path following difficulties during exploration. Contact area measurements during pilot experiments indicated that a gap size of 6.5 mm should be well within the range of average fingertip contact area. The gap-size was independent of the angle size. The vertical size of the sheets and mold were 21 cm and the apices of the angles were located at a vertical distance of 10.5 cm. As in the first experiment, the two angles were printed 13.4 cm apart.

In this experiment the observers were free to move, that is, no movement restricting apparatus was used. The exploration of the angle was prescribed in the following way: the lines of the angle should be followed with the index finger of the preferred hand (see Figure 2). They were allowed to move the finger maximally two times back and forth along the complete angle path. The starting point could be chosen freely but during instructions the observers learned to use the apex or the gap as a starting point. Each angle could be felt up to two times. Thus, if we assign a to the apex location and b and c to the locations of the endpoints, the maximally allowed movement is described by *abacabaca*. The switching procedure between test and reference stimulus by shifting the stimulus sheet was the same as in the first experiment. Before the start of the experiment, a training period of maximally six randomly chosen stimuli allowed the participants to become familiar with the procedure and the stimuli. No feedback was given during the training or the experiment.

Participants were presented with a complete block of 20° stimuli with randomly assigned gap conditions, followed by a complete block of 135° stimuli. In the 20° reference block, the sampling set consisted of $d = 10$ different test stimuli which were presented $N =$

12 times and in the 135° reference block, the sampling set consisted of $d = 12$ different test stimuli which were presented $N = 10$ times. As in the first experiment, test and reference angles were presented an equal number of times to be felt first. For each participant, a total of 480 trials ($N \times d \times conditions$) were distributed over 6 sessions of approximately 1 hour.

Results and discussion

The 84% correct response thresholds defined by the best fit parameter σ from Equation 1 are plotted in Figure 5. A repeated measures two-way ANOVA reveals that both the presence of the apex ($F_{1,7} = 9.893$, $p = .016$) and the angular extent ($F_{1,7} = 19.307$, $p = .003$) have significant influence on discrimination performance. There is no significant interaction between the two conditions ($F_{1,7} = 2.383$, $p = .167$). As can be seen in the lower graph of Figure 5, the thresholds almost double from 20° to 135°, independent of the apex condition. Visual inspection of Figure 5 shows that the effect of apex information has a more idiosyncratic influence on the discrimination of 135° angles than on 20° angles. In Table 1 all mean thresholds, standard deviations and the quotients of variation (standard deviation divided by the mean) of all experiments are presented. There, it can be seen that the relative variation of the 135° with gap condition is much larger than for other conditions. Leaving out the apex increased the discrimination thresholds for both the acute and the obtuse angles.

In order to compare the different exploratory procedures used in the first and second experiments, two groups were compared: the first group consisted of thresholds of the six participants from Experiment 1, averaged over bisect orientations; the second group consisted of data drawn from the 20° reference angle with apex thresholds from the second experiment. The mean thresholds were 2.9° for the bisect following procedure and 6.0° for the line following procedure. An unrelated *t*-test for unequal group sizes showed a significant difference ($t = 4.298$, $p < 0.001$) between discriminating 20° angles using the line following and the bisect following procedure.

Both angular extent and the presence of local apex information influence the discriminability significantly. Controlling the local apex information as an independent variable in this experiment was originally motivated by the hypothesis that the apex would be of particular importance for discriminating acute angles and not for obtuse. If this would be the case, then different use of the apex would explain why obtuse angles are more difficult to discriminate than acute angles. As this hypothesis is disproved we should find other explanations for the large effect of angular extent on discriminability. For acute and obtuse angles the average path length is equal and the only difference is that the distance between the midpoints of lines is larger for obtuse angles than for acute angles. It could thus be that the encoding of an angle is more efficient if the lines are near each-other. Before continuing this line of reasoning we should be certain that there are no other differences between the acute and obtuse angle condition. One clear difference is the average movement direction used for the exploration. To factor out this difference we conducted a control experiment.

4 Control experiment

In Experiment 2 there was an uncontrolled factor between the small and large angles which should be excluded as cause for discrimination differences: average movement direction. Since the exploration procedure in Experiment 2 is different from that of Experiment 1 we do not know whether the same movement direction independence holds for the line following mode. For the 20° stimuli the movement can be characterised as being more horizontal than that for 135° stimuli. Although unlikely, it is possible that using

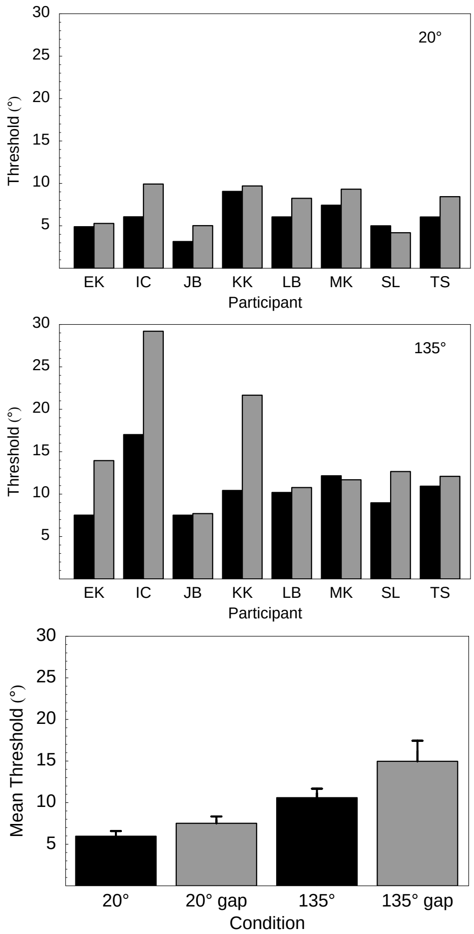

Figure 5: Comparison of thresholds per participant. **Upper graph** Angle of reference is 20°, black bars denote thresholds for stimuli without gap, gray bars denote thresholds for stimuli with gap. **Middle graph** Angle of reference is 135°, black bars denote thresholds for stimuli without gap, gray bars denote thresholds for stimuli with gap. **Lower graph** Mean results across conditions. Error bars denote standard errors.

horizontal movement yields higher acuity than vertical movement. To address this issue this control experiment was performed.

The horizontal movement employed for the 20° in the previous experiment can be simulated by the rotation of a 135° stimulus. By looking at the effect of a 90° counterclockwise rotated 135° stimulus with respect to a non-rotated one, we isolate the direction of exploration movement as an independent variable.

Method

Four observers participated in the control experiment, all of whom had participated in the second experiment. We used the 135° with gap stimuli and compared this with the same stimuli rotated 90° counterclockwise. The two conditions can be seen in Figure 1. The stimuli were presented in 24-trial blocks of the same bisect orientation. The test stimulus set consisted of 12 angles distributed symmetrically and equidistantly around the reference angle. The stimulus set was designed individually for each participant assuming that the thresholds measured in Experiment 2 would be reproduced approximately. Each test angle was presented 10 times. The bisect orientation of the first block was counterbalanced over the participants. The total number of trials per subject was 240 which was distributed of three sessions of approximately one hour. The same procedure and data analysis were used as in the second experiment.

Results and discussion

The results of the four participants are presented in Figure 6. For each subject the first two bars show the results of Experiment 2, the second two bars show the results of the control experiment. The first bar denotes the threshold found for the 20° condition and the second bar the threshold for the 135° condition, both from Experiment 2. The third bar denotes the threshold for the rotated 135° condition and the fourth bar the non-rotated 135° condition. The first and third bar thus denote thresholds found for horizontal movement and the second and fourth bar for vertical movement. The second and fourth bar originate from the same condition which shows that three out of the four subjects performed better the second time for the non-rotated 135° condition. Half of the subjects performed better for the rotated 135° condition from the control experiment than for the non-rotated 135° condition from Experiment 2.

It can clearly be seen that rotating the angle does not yield discrimination improvement. This would be the case if the third bar would be lower than the fourth, i.e. when horizontal movement would decrease discrimination thresholds. The contrary seems to be the case: for all participants the threshold for the 0° bisect orientation is lowest.

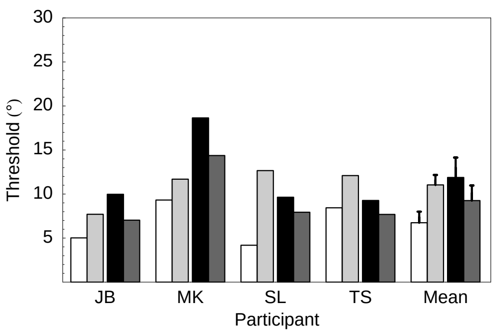

Figure 6: Comparison of thresholds per subject for the control experiment. The first two bars are results from Experiment 2: from left to right: the first two are the with-gap conditions for 20° and 135° respectively. For the second two bars, the first (black) denotes the result for the rotated 135° stimulus and the second (dark grey) denotes the non-rotated 135° stimulus. For the first and third bars movement direction is more horizontal and for the second and fourth bars the movement is more vertical.

5 CONCLUSION

The research presented here investigated what factors influence angular acuity in raised line drawings. First, we did not find an influence of movement direction in Experiment 1. Furthermore we found that exploration strategy, angular extent and the apex are of significant influence on discrimination ability. We will now discuss how these results can be interpreted.

In the first experiment, no directional influence on discrimination performance was found for bisect orientations between 0° and 90°. The apparent movement direction independence and the low relative variation (see Table 1) show that the discrimination threshold values are fairly robust. It is thus likely that participants used the same cues or mental strategy to perform the discrimination task.

Table 1: All mean thresholds per experiment per condition. For the first experiment the average was taken over all conditions and participants. The quotient of variation (QV) equals the quotient of standard deviation (SD) with the mean threshold.

Experiment	Condition	Mean (°)	SD (°)	QV (°)
1	20 bisect	2.87	0.64	0.22
2	20 apex	5.96	1.76	0.30
	20 gap	7.52	2.31	0.31
	135 apex	10.59	3.06	0.29
	135 gap	14.97	7.00	0.47
control	135 bisect 0	9.26	3.43	0.37
	135 bisect 90	11.88	4.52	0.38

Our data do not give insight in how the encoding works and introspective reports taken from the participants do not hint in a particular direction.

Comparison between Experiments 1 and 2 showed that exploration strategy influences discrimination performance highly. Moving the fingertip between the lines of an angle yields discrimination thresholds which are twice as low in comparison with angles explored by following the lines. This difference illustrates a difficulty which haptic scientists often encounter: how to control for the information input when subjects explore stimuli in various ways? It is known that humans actively use different exploration procedures for the assessment of different 3D object properties [11]. There exists some literature which reports about the spontaneous exploration procedures [19] utilized for the assessment of raised line stimuli but a quantitative study on the influence of exploration mode does not exist. The research presented here shows that for the discrimination of acute raised line angles, exploration mode is of high significant influence. This could in the long run have implications for studies into the perception of raised line drawings: if there exist different exploration modes optimal for the assessment of different geometric features, it could be useful to instruct observers to use those.

The second experiment showed that both angular extent and the presence of the apex influence discriminability significantly. Our results do not answer the question of why large angles are more difficult to discriminate than small angles, although Experiment 2 and the control experiment show that both the information from the apex and the average movement direction cannot account for this effect. Observing increasing thresholds with increasing angular extent induces a notion of Weber's Law which states that thresholds increase linearly with stimulus intensity. Due its periodical nature, an angle is a nonlinear quantity and thus Webers' law cannot be applied directly. It can also be easily deducted from table 1 that the Weber fractions (threshold divided by angular extent) are not constant. It could be that the workspace spanned by the lines or some measure of the average distance between the lines serves as intensity. Since we do not know what should be used as intensity the question whether Webers' law applies cannot be answerred.

Introspective reports of the participants revealed another difference between the acute and obtuse angles: the 135° angles were sometimes perceived as being curved, without having a well defined angle. More research on this topic is certainly needed since not only does it give insight into fundamental processes of haptic perception, it could also be of importance for the research on the distorted perception of raised line drawings.

The influence of the apex was not what we had hypothesised. Not only does the presence of the apex influence discrimination for acute angles but also for obtuse angles. The results of Experiment 2, shown in Figure 5, could give the impression that the significance of the apex effect for 135° is largely caused by three participants. This, however, is not the case because having high variance in the data should decrease the significance level: low idiosyncrasy increases the significance. It is also noteworthy that there is only one participant showing the opposite effect which was also the case for the 20° condition.

As mentioned in the introduction, there has already been research in haptic angle discrimination. Voisin et al. [21] investigated haptic discrimination ability of a 90° angle made of two metal strips. They found a mean threshold for 75% correct response of 4.7° corresponding to an 84% threshold of 7.0°. Even though the study of Voisin et al. [21] made use of different stimulus material and constrained movement by only allowing shoulder joint movement, it is worth noticing that the 7.0° thresholds for a 90° angle is well within the thresholds of 6.0° and 10.6° for our raised line angles of 20° and 135° respectively. In an accompanying study, Voisin et al. [22] showed that kinaesthetical and cutaneous information contributed equally to discrimination ability. This could also hold for our results if we interpret the apex as a primarily cutaneous information source and the movement along the lines as kinaesthetical information.

Our results show that it could be interesting to further study the exploratory behaviour of raised line stimuli. Knowledge about what exploration strategy fits which geometric feature, and training to use this knowledge would be helpful for visually impaired who use tactile maps and pictures in everyday life. Also the effect of increasing thresholds with increasing angular extent is worth investigating further. If we can understand what geometric properties influence the mental load of spatial information we will be in a much better position to understand why the recognition of raised line drawings is so difficult. The third aspect which should get attention in the future is comparing the perception of raised line stimuli and real (or virtual) 3D shape properties such as curvature. Research in tactile displays and raised line aids could benefit from the knowledge of haptic perception of real or virtual shapes and vice versa.

Acknowledgements

This research was supported by a grant of the Netherlands Organisation for Scientific Research (NWO).

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