Cutaneous and Kinaesthetic Perception of Traversed Distance

Wouter M. Bergmann Tiest* L. Martijn A. van der Hoff Astrid M. L. Kappers

Helmholtz Institute, Utrecht University, The Netherlands

ABSTRACT

Discrimination thresholds for tactually perceived traversed distance were measured in three conditions: cutaneous-only, kinaesthetic-only and combined information. The results were 25 mm (32 %) in the first and 11 mm (14 %) in the latter two conditions. Although cutaneous length perception was shown to be possible, perception in the combined condition was found to be mainly based on kinaesthetic information. The maximum-likelihood estimation model of cue combination was not supported.

Keywords: length perception, cue combination, movement

Index Terms: H.1.2 [Models and Principles]: User/Machine Systems—Human Information Processing; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

In daily life, we often move our hands over objects or surfaces. We can obtain information about the size of these objects by determining the distance our fingers traversed over the surface. This haptic length perception is about as accurate as visual or bimodal length perception [1, 15]. In haptic length perception, we make use of two channels of information: kinaesthetic perception tells us how much our hand has moved in space. At the same time, cutaneous perception tells us how much of the surface has slid over our fingers. These two sources of information are combined in some way to produce a single percept of the traversed distance. In this experiment, we wanted to investigate how these two cues are combined and what their respective roles are in perception of traversed distance.

Two main types of haptic length perception can be distinguished: First, there is the finger-span method, in which the size or length of an object is determined by perceiving the distance between thumb and index or middle finger that enclose the object. With this method, lengths can be perceived that are related to the physical length by a power function with an exponent of 1.3 [20]. The perception is independent of pushing force or compliance of the object [3], but there seems to be an adaptation effect [14]. Using discrimination experiments, the threshold for distinguishing different lengths in this way was determined to lie in the range of 0.5–1.3 mm [6, 13, 17]. This value increases with increasing distance between the fingers up to about 3 mm for the largest finger span [7, 9, 20]. This range of thresholds can be considered as a base line for length discrimination between the fingers. Due to physiological constraints, this method is limited to distances of about 80 mm. For larger distances, movement is required. With this second method, the length of the object is determined by perceiving the traversed distance between the endpoints of the object. This method seems to be somewhat less accurate than the finger-span method [12]. Interestingly, when a length perceived with the movement method is reproduced with the finger-span method, it is greatly exaggerated—up to a factor of 2.5. An underestimation occurs if the methods of perceiving and reproducing are interchanged [12]. Also when a visual match is to be made, lengths perceived through the movement method are judged to be larger than through the finger-span method [10]. Length perceived using the movement method also has a less steep relationship with physical length than with the finger-span method, with a power function exponent ranging from 0.89 [16] to unity (a linear relationship) [21]. However, there are many influencing factors, such as orientation effects [2, 4, 5] or adaptation effects [23]. Also, the perceived length depends on the speed of movement, both with passive movements (the subject's finger is being moved) [24] and active movements (the subject moves his/her own finger) [11]. In general, the perceived traversed distance is larger with slower movement speeds. However, in the range of 4–12 cm/s, the perceived distance does not seem to depend on movement speed [11]. A similar plateau was found earlier in experiments regarding the perceived path length of a point moving over the skin of the forearm [18, 25]. This indicates that this range of speeds is suitable for minimising the effect of speed on length perception.

It is surprising that for haptic length perception with the movement method, no discrimination experiments have been published. It is unknown how accurate length perception in this way is. Moreover, hardly anything is known about purely cutaneous perception of traversed distance, apart from the two studies on the perceived path length of a point moving over the skin [18, 25]. This is a fundamentally different situation (the point moves over an extended area of skin, as opposed to a surface moving over a single location on the skin). Therefore, the purpose of the present study is to measure for the first time discrimination thresholds for tactual length perception using the movement method.

It should be noted that the experiments described in [11] and [24] only used kinaesthetic information: the subject's finger rested on a plate or rider that could slide back and forth, either driven by an electric motor or the subject him/herself. This is a highly unnatural situation in the sense that in normal haptic length perception, also cutaneous cues are available in the form of the skin of the fingers sliding over the surface of the object. It has been found that cutaneous information also play a role in length perception using the movement method [22]. In that experiment, magnitude estimation using cutaneous, kinaesthetic, and combined information was performed. In all cases, lengths were underestimated, the effect being the largest with only cutaneous information and the smallest with combined information. In the present study, we would like to investigate the role of these cutaneous cues in length *discrimination*. To this end, a length discrimination experiment was performed with three conditions: kinaesthetic (the finger moves without touching a surface), cutaneous (the stationary finger touches a moving surface) and a combination of kinaesthetic and cutaneous (the moving finger touches a stationary surface). A secondary goal of the experiment is to determine the weight factors for cutaneous and kinaesthetic cues in the combined condition. This enables us to check whether these cues are combined in a statistically optimal fashion, i.e. according to the maximum-likelihood estimation (MLE) model of cue combination [8].

2 METHODS

The experiment consisted of measuring discrimination thresholds for traversed distance in three conditions. A two-alternative forced-

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*email: W.M.BergmannTiest@uu.nl

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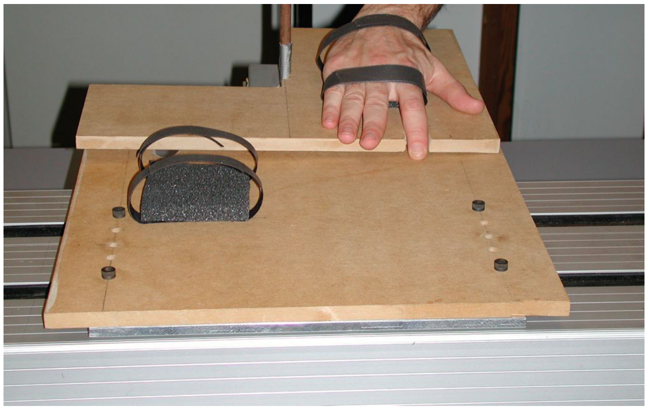

Figure 1: Photograph of the set-up in the cutaneous condition. The hand rests on a stationary surface while the index finger touches a moving surface. The other set of straps is used in the kinaesthetic and combined conditions, where the hand moves and the surface is stationary.

choice paradigm was used. Each trial, the subjects had to feel two lengths and say which was the greater. Passive perception was used in this experiment. In the case of cutaneous perception, this is justified since there was found little difference in performance between active and stationary passive length perception [19]. A similarly small difference between active and dynamic passive length perception is assumed to exist, although this was not tested. Passive perception has the advantage that there is complete control over the movement speed, preventing any confounding effects thereof.

2.1 Subjects

Twelve people (4 women) volunteered to participate. They were naïve with regard to the purpose of the experiment. They ranged in age from 22 to 51 years. Eleven were right-handed and one was ambidextrous. All used the index finger of their right hand.

2.2 Apparatus

The lengths were presented using a computer-controlled linear positioning system (Isel-automation) interfaced with a CNC controller (Isel C142-1). The system provides a positional accuracy of 0.013 mm. Mounted on the system was a medium density fibreboard (MDF) surface with a smooth area for touching and another area where the subject's hand could rest. On the edge of the board, there was a notch for the index finger. The hand was held in place with Velcro straps. A similar MDF board was mounted on a lab stand and could be adjusted in height to be just above or just below the moving board. A photograph of the setup is shown in figure 1. The setup could be easily adapted to accomodate the three conditions.

2.3 Conditions

There were three conditions: cutaneous (C), kinaesthetic (K) and combined (C+K). These are illustrated in figure 2. In the cutaneous condition, the hand was attached to the stationary holder with the index finger in the notch touching a smooth surface that was attached to the movement device. In the kinaesthetic condition, the hand was attached to the moving holder with the index finger in the notch, but not touching anything. The combined condition was similar to the kinaesthetic condition except that the finger touched the stationary surface. In the C and C+K conditions, subjects were asked to let their finger touch the surface with a natural force, but this force was not controlled.

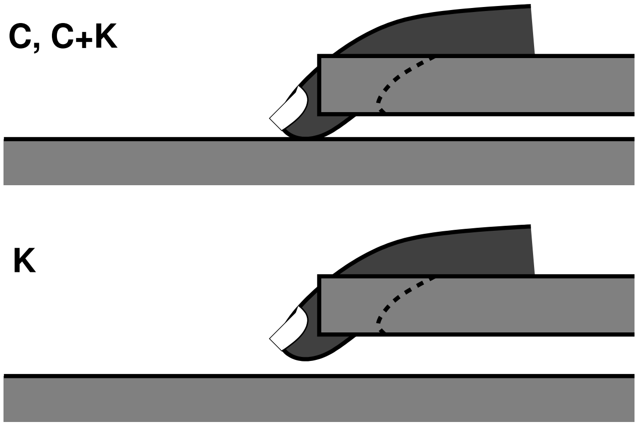

Figure 2: Illustration of the three conditions (side view). The index finger rests in an opening in the top board. Top: in the cutaneous condition (C), the finger stays still and the surface moves. In the combined condition (C+K), it is the other way around. Bottom: in the kinaesthetic condition (K), the finger moves but does not touch the surface.

In all conditions, a reference length of 80 mm was used. Each trial, this reference length was paired with one of 8 test lengths, which were 38, 50, . . . , 122 mm in the cutaneous condition, 45, 55, . . . , 115 mm in the kinaesthetic condition, and 52, 60, . . . , 108 mm in the combined condition. These step sizes (12, 10 and 8 mm) were chosen to provide the optimum range for determining discrimination thresholds, based on pilot experiments. The three conditions were performed in a pseudo-random, counterbalanced order (i.e. every possible ordering occured equally often).

2.4 Procedure

After receiving instructions, the subject was blindfolded and donned noise protection earmuffs (Gamma, −23 dB) to prevent the sound from the movement device to be used as a cue. In addition, s/he wore in-ear earphones on which white noise was played at a volume just below the irritation threshold to mask any remaining sound cues. For each condition, 80 trials were performed in random order, every test/reference pair occuring 10 times. In a trial, the test and reference lengths were presented one after the other, in pseudo-random, counterbalanced order (i.e. in half the trials, the reference was presented first and in the other half the test was presented first). The subjects were not told which was which. Presentation of a length consisted of the finger being moved first to the right and then the same distance to the left in the K and C+K conditions. In the C condition, the surface moved in the opposite directions. The start point was the same for all trials in all conditions. After a pause of 1.5 s, the second length was presented in the same way. The subject then had to say which of the two was the greater length. Then, the next trial began. In half the trials (randomly distributed), the two lengths were presented at the same speed (113 mm/s). In the other half, the two lengths were presented at the same duration (0.89 s), the speeds being dictated by the chosen test lengths. In this way, subjects could use neither speed nor duration alone as a cue for length perception, and had to rely on their tactual senses.

Each condition took about 10 minutes. Between conditions, there was a short break. The whole experiment took 30–40 minutes per subject.

2.5 Analysis

For every subject and every condition, the number of times that the test length was chosen to be the greater one was plotted as a function of the test length. An example is shown in figure 3. To

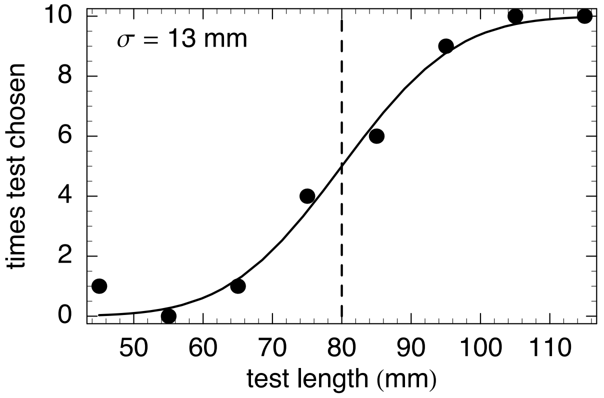

Figure 3: Example of a psychometric curve from one of the subjects in the kinaesthetic condtion. The dots are the measured data and the solid line is a fit. The dashed line indicates the length of the reference stimulus. The best-fit value of the fitting parameter σ is indicated.

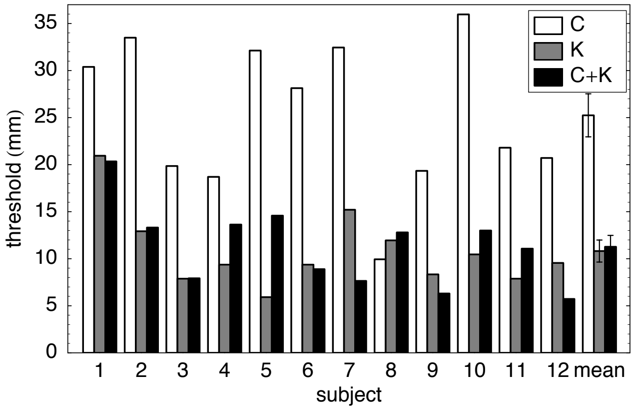

Figure 4: Discrimination thresholds for traversed distance in cutaneous (C), kinaesthetic (K) and combined (C+K) conditions. The last set of bars shows the average over subjects. The error bars indicate the standard error of the sample mean.

these data, a psychometric function of the form

$$f(x) = 5 + 5\mathrm{erf}\left(\frac{x - l_{\mathrm{ref}}}{\sqrt{2}\sigma}\right) \tag{1}$$

was fitted, where $l_{\mathrm{ref}} = 80$ mm is the reference length. The parameter σ corresponds to the 84 % discrimination threshold. In this way, three thresholds per subject were determined, corresponding to the three conditions. In addition, the data from the equal-speed and equal-duration trials were also analysed separately to check for possible effects.

When multiple cues are combined to form a single percept, the information from those cues is weighted with a certain weight factor w_i. These weight factors should add up to 1. The variance σ_i^2 that is present on these cues is also combined into the final percept. When the variances can be assumed to be independent, the combined variance is given by:

$$\sigma_{\mathrm{total}}^2 = \sum_i w_i^2 \sigma_i^2. \tag{2}$$

In the case of combining cutaneous and kinaesthetic cues, with $w_c + w_k = 1$, we can write

$$\sigma_{c+k}^2 = w_c^2 \sigma_c^2 + (1 - w_c)^2 \sigma_k^2. \tag{3}$$

Solving for w_c yields

$$w_c = \frac{\sigma_k^2 \pm \sqrt{\sigma_{c+k}^2 \sigma_k^2 + \sigma_c^2 \left(\sigma_{c+k}^2 - \sigma_k^2\right)}}{\sigma_c^2 + \sigma_k^2}. \tag{4}$$

Using this equation and the measured discrimination thresholds in the three conditions, we can calculate the weight factors for each subject.

From the MLE model of cue combination follows that the best result (lowest variance of the combined percept) is obtained when the weight factor for a particular cue is inversely proportional to its variance:

$$w_{j,\mathrm{MLE}} = \frac{\sigma_j^{-2}}{\sum_i \sigma_i^{-2}} \tag{5}$$

For combining cutaneous and kinaesthetic cues, this yields

$$w_{c,\mathrm{MLE}} = \frac{\sigma_k^2}{\sigma_c^2 + \sigma_k^2} \tag{6}$$

as the optimal weight factor for the cutaneous contribution. When we substitute this in equation (3), we obtain a value for the predicted discrimination threshold in the combined condition, based on the MLE model and the measured discrimination thresholds in the two separate condtions:

$$\sigma_{c+k,\mathrm{MLE}} = \sqrt{\frac{\sigma_c^2 \sigma_k^2}{\sigma_c^2 + \sigma_k^2}} \tag{7}$$

By comparing this to the actual measured threshold in the combined condition, we can check whether the MLE model applies to perception of traversed distance and whether the cues are combined in a statistically optimal fashion.

3 RESULTS

The thresholds for all subjects in the three conditions are shown in figure 4. On average, the thresholds are 25 ± 2 mm, 11 ± 1 mm and 11 ± 1 mm for conditions C, K, and C+K, respectively (value±SE). A repeated-measures ANOVA shows an effect of condition: $F_{2,22} = 35,\ p = 1.5 \times 10^{-7}$. Bonferroni-corrected pairwise comparisions show that the thresholds in the kinaesthetic and combined conditions are significantly lower than the threshold in the cutaneous condition ($p = 1.6 \times 10^{-4}, 2.0 \times 10^{-4}$, respectively). There is no significant difference between the kinaesthetic and combined conditions.

As for the separate analysis of the equal-speed and equal-duration trials, it must be noted that those thresholds are less reliable because in that situation, each point of the psychometric curve is only based on 5 trials instead of 10. That said, it was found that in the K and C+K conditions, the thresholds were approximately the same for the equal-speed and the equal-duration trials. However, in the C condition, the thresholds were significantly higher for the equal-duration trials than for the equal-speed trials ($t_{11} = -3.5,\ p = 0.0045$).

Using equation (7), we can calculate a predicted value of the thresholds in the combined condition from those in the two separate conditions, based on the MLE model. These predicted threshold values are plotted as a function of the actual measured values in figure 5. The correlation between measured and predicted values is not significant ($R = 0.44,\ p = 0.15$). This means that on the level of the individual subjects, the MLE model is not a good predictor of the thresholds in the combined condition.

If the weight factors are not based on the MLE model, then what are they? Using equation (4), we can calculate the weights that have

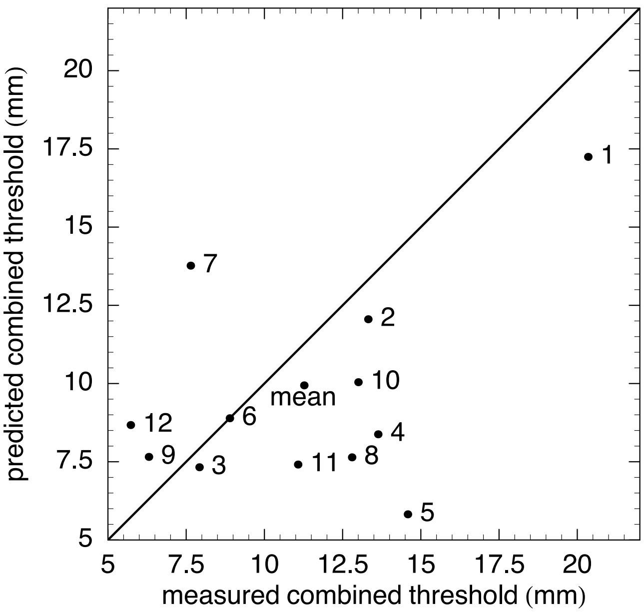

Figure 5: Predicted threshold values for the combined condition as calculated from the measured data in the other two conditions, plotted as a function of the measured thresholds in the combined condition. The numbers refer to the subjects. The calculation is also performed on the mean of the data. The straight line indicates a perfect match.

been used in the cue combination. These are plotted in figure 6. For subjects 6, 7, 9, and 12, equation (4) did not yield a (real) outcome (although the imaginary part for subject 6 is very small). Note that most weights are negative, meaning that for those subjects, the addition of cutaneous information has a detrimental rather than a beneficial effect on haptic length perception. The cutaneous weights are overall low, meaning that length perception in the combined condition must be primarily based on kinaesthetic cues. Therefore, one might expect a strong correlation between the thresholds in the kinaesthetic condition and the combined condition. However, this correlation is not significant: $R = 0.51,\ p = 0.092$.

4 DISCUSSION AND CONCLUSIONS

The main result of this experiment is that for a reference length of 80 mm, the discrimination threshold for passive tactual perception of traversed distance is about 11 mm, or about 14 %. This is quite a bit higher than the Just Noticeable Differences (JND) of 2.2 mm [7] or 3.1 mm [20] reported for the same distance with the finger-span method. Although these JNDs were measured in a different way from the thresholds in the current experiment, they should be quite comparable within a factor of ~ 1.5. In the present experiment, the cutaneous information did not contribute significantly, so this threshold must be mainly based on kinaesthetic cues. In the finger-span method, cutaneous cues also do not play a role, and the information is purely proprioceptive. Apparently, the accuracy of the proprioceptive perception of the position of the thumb and fingers is about 2–3 times better than the kinaesthetic perception of the movement of the hand. It is noted that in the present experiment, the whole hand was moved. It could be that when the hand is kept still and only the index finger is moved, lower thresholds are found. Of course, this is viable only up to distances of about 60 mm, depending on finger length.

A second result is that purely cutaneous perception of the length of an object sliding over the finger is possible, with an accuracy of about 25 mm or 32 %. This is a novel and interesting result, that opens up possibilities for ungrounded haptic displays.

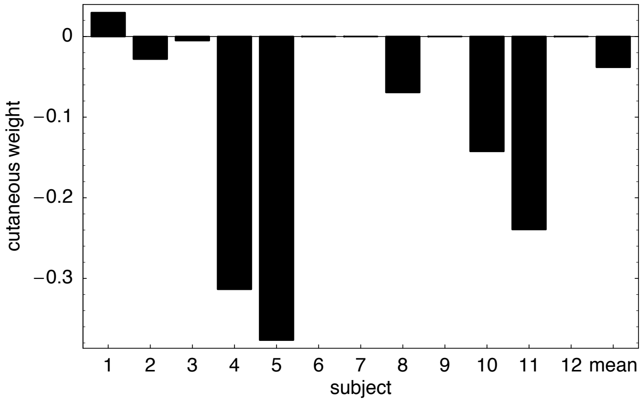

Figure 6: Calculated weight factors for the cutaneous cue in the combined condition. For subjects 6, 7, 9, and 12, no value could be calculated. The last bar is not the average of the others, but the cutaneous weight factor calculated from the average over subjects.

Although length perception with the movement method is mainly based on kinaesthetic cues, no significant correlation was found between the thresholds in the K and C+K conditions. This might be due to a disruptive effect of the cutaneous information in the C+K condition. Although cutaneous length perception was found to be possible and this information could potentially contribute to length perception in the combined condition, the cutaneous stimulation might have drawn attention away from the kinaesthetic perception. The severity of this effect could be different for different subjects, resulting in a loss of correlation between the thresholds in the K and C+K conditions. For 5 of the 12 subjects (nos. 1, 6, 7, 9, and 12), a more or less beneficial effect was found of having cutaneous information present in the combined condition. However, for only one of these (no. 1) could separate weights be calculated: 3 % cutaneous and 97 % kinaesthetic. For the other 4, the cutaneous-only threshold is so high compared to the other two that its contribution cannot account for the difference between the kinaesthetic and combined thresholds. It is not clear why this is. It must be that in the combined condition, more information is available than just the cutaneous and kinaesthetic information, but it is unknown what this information is. There might be some effect of the fact that the starting position was the same for all trials, so that in the K and C+K conditions, the task could be performed by just perceiving the end positions. If this were the case, then the task in the C condition was somewhat different than that in the K and C+K condtions. Future research with randomised starting positions should provide more clarity in this respect.

Other cues were present in the stimuli, such as speed cues and duration cues. Care was taken to eliminate the usefulness of these cues by randomly switching between equal-speed and equal-duration trials. But even if subjects still managed to somehow use these cues, the effect of this would be the same in the three conditions. The conclusions about the relative roles of cutaneous and kinaesthetic information would not change. In the separate analysis, it was found that in the K and C+K conditions, the thresholds were approximately the same for the equal-speed and the equal-duration trials. However, in the C condition, the thresholds were significantly higher for the equal-duration trials than for the equal-speed trials. This would suggest that in this condition, in which it is harder to determine the traversed distance, subjects may have used the duration of the movement as an additional cue, but not so much the speed of the movement. In the conditions with kinaesthetic information present (K and C+K), they probably did not need any additional cues.

The MLE model does not seem to correctly predict the thresholds in the combined condition from the measured thresholds in the separate conditions, judging by the low correlation coefficient. However, the model cannot be rejected, because a paired-samples t-test between predicted and measured thresholds did not show a significant difference ($t_{11} = 1.5,\ p = 0.17$). It appears that the variance over subjects is too large to draw such a conclusion. (Also with the data of subject 1 removed, who might have been an outlier, was this difference not significant). Although the correlation between kinaesthetic and combined thresholds is also not significant, it might be that this correlation became significant if it were based on more subjects. A model in which the most accurate source of information alone determines the percept in the combined situation can be characterised as a winner-take-all model. The predictive power of the two models can be compared by looking at the RMS difference between the predicted and measured thresholds for the two models. The RMS deviation from the measured thresholds for the winner-take-all model (4.0 mm) is slightly smaller than for the MLE model (4.2 mm). Therefore, it seems that a winner-take-all model of cue combination (i.e. combined perception equals kinaesthetic perception in this case) is more applicable to this situation. However, in a situation of magnitude estimation in which conflicting information was present, it was found that the combined percept was determined by the information source that provided the greater length, not necessarily the greater accuracy [22]. This is another clue that the MLE model does not apply to haptic length perception.

In conclusion, we have shown that cutaneous length perception is possible, and in some cases contributes a little to perception of traversed distance, but on average, perception of traversed distance is based on kinaesthetic information, whereas cutaneous information can even have a disruptive effect. The MLE model does not seem to apply to this type of cue combination, although an outright rejection of this model is not possible.

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