



Discrimination threshold for haptic volume perception of fingers and phalanges

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Abstract

Humans exhibit a remarkable ability to discriminate variations in object volume based on natural haptic perception. The discrimination thresholds for the haptic volume perception of the whole hand are well known, but the discrimination thresholds for haptic volume perception of fingers and phalanges are still unknown. In the present study, two psychophysical experiments were performed to investigate haptic volume perception in various fingers and phalanges. The configurations of both experiments were completely dependent on haptic volume perception from the fingers and phalanges. The participants were asked to blindly discriminate the volume variation of regular solid objects in a random order by using the distal phalanx, medial phalanx, and proximal phalanx of their index finger, middle finger, ring finger, and little finger. The discrimination threshold of haptic volume perception gradually decreases from the little finger to the index finger as well as from the proximal phalanx to the distal phalanx. Overall, both the shape of the target and the part of the finger in contact with the target significantly influence the precision of haptic perception of volume. This substantial data set provides detailed and compelling perspectives on the haptic system, including for discrimination of the spatial size of objects and for performing more general perceptual processes.

Keywords Haptic volume perception · Shape · Finger · Phalanx · Discrimination threshold

Introduction

General haptic perception is by far the most primitive and common recognition mechanism by which humans can learn about the world and bond with each other (Klatzky, Lederman, & Metzger, 1985). This perceptual system involves a combination

of somatosensory perception and proprioception derived from the skin and the body movement (Lederman & Klatzky, 2009). Additionally, humans can automatically choose the optimum type of manual exploration for haptic perception based on the nature of the body part touching the object for information. For example, grasping an apple to eat with the whole hand is different from pinching a grape to eat with the fingers. The best example of general haptic perception studies is Napier's remarkable work on power tasks and precision tasks (Napier, 1980). Napier pioneered the discussion of the concept that the intended activity determines what type of general haptic perception is used for any given action (Castiello, 2005). For the power task, participants performed an action for a large object using their whole hand (including the thumb, the surface of the palm and all other fingers). Meanwhile, for precision tasks, participants performed an action with a small object using only their fingers (between the index finger and thumb) (Begliomini, Wall, Smith, & Castiello, 2007). These two different types of haptic perception present enormous variability in parameters such as duration, posture, speed and discriminability. To date, there has been a substantial amount of research devoted to power tasks and using the whole hand experiment. In contrast, research related to precision tasks using the fingers and phalanges remains relatively uncommon.

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In the past decade, many psychophysical researchers have studied general haptic perception by using a regular solid object to determine humans' perception ability. When interacting with solid objects, humans can perceive information about the object's shape, material properties, and even how much size is spatial. In contrast to a large number of haptic perception studies of shape and material properties, perception of spatial sizes has not yet been studied in detail (Panday, Bergmann Tiest, & Kappers, 2014). In particular, volume, which is one of the most fundamental parameters of a solid object's spatial size, can be defined as the amount of spatial space that an object occupies or that is enclosed within a container (van Veen, Kappers, Koenderink, & Werkhoven, 1996). Studies have indicated that fundamental knowledge about haptic volume perception is necessary or at least useful for the development of bionic tactile skills, haptic interaction, and teleoperation (Scheibert, Leurent, Prevost, & Debregeas, 2009).

A recent psychophysical study revealed that haptic volume perception of solid objects was affected by physical shape. In an earlier study, the researchers examined relative biases in haptic volume perception for each shape-matched object pair when the solid objects were enclosed by the participant's whole hand, and they reported that changes in the object's shape significantly affected the participant's estimation of the volume (Kahrmanovic, Bergmann Tiest, & Kappers, 2010a). To date, such studies have paid little attention to the effect of the object's shape in precision haptic volume perception by fingers and phalanges. Another study investigated the ability of humans to discriminate variations in volume of solid objects, and researchers measured the barely noticeable differences for haptic volume perception of solid objects using the whole hand enclosure exploratory procedure (Kahrmanovic, Bergmann Tiest, & Kappers, 2011). Furthermore, another illustrative study by Kappers and her colleagues aimed at investigating the whole hand for a haptic volume perception task, i.e., the salient features of haptic volume perception, including the influence of the surface texture, the thermal conductivity, and the compliance (Bergmann Tiest, Kahrmanovic, Niemantsverdriet, Bogale, & Kappers, 2012). These studies provided an invaluable contribution by showing that a cube with a smooth surface, higher thermal conductivity, and composed of a hard material tends to seem significantly larger than an object with a rough surface, lower thermal conductivity, and composed of a soft material of equal physical volume. However, the salient properties related to precision haptic volume perception remain missing in their studies.

The goal of the current study was to investigate haptic volume perception in fingers and phalanges. In the current study, participants engaged in a haptic volume perception task in which a tiny object was enclosed with the phalanges of each of their fingers. By comparing the discrimination threshold of the index finger, middle finger, ring finger, and little finger, as well as the distal phalanx, the medial phalanx, and the proximal phalanx, for each participant, we determined whether the

influence of fingers and phalanges was a salient feature in haptic volume perception. In addition, it is notable that the distal phalanx of the index finger is the most sensitive for haptic volume perception, and this finding will be extensively analyzed in our future work.

Experiment 1

Method

Participants This research was approved by the local ethics committee at the Capital Medical University, Beijing, China. All of the subjects were recruited from the student body of Capital Medical University. The number of subjects required for the experiment was determined by a priori power analysis using G*Power based on the assumption of a general linear model, detection of medium effect sizes = 0.25, a type I-error probability of $\alpha = 0.05$ and an analytical power of $(1-\beta) = 0.95$ (Faul, Erdfelder, Lang, & Buchner, 2007). Overall, 18 right-handed ranging in age from 21 to 29 years (ten female, eight male), with a mean age of 24 years, consented to participate in this experiment. They were all right-handed as confirmed by the Edinburgh Handedness Inventory (Oldfield, 1971). In addition, all subjects declared they had no loss of haptic sensation or any unusual experiences with haptic input. They all were naïve to the purpose of the experiment and were compensated for taking part in the experiment.

Stimuli Two sets of tetrahedrons, cubes, and spheres were made from plastic (acrylonitrile-butadiene-styrene, ABS) and used as stimuli. They were manufactured on a milling machine controlled by a high-speed computer and had an accuracy range of volume at $\pm 0.003 \text{ cm}^3$. Each of the stimuli could be enclosed in each subject's fingertips and had volumes of 0.200, 0.250, 0.300, 0.350, 0.400, 0.450, or 0.500 cm^3 (steps of 0.050 cm^3) as well as volumes of 0.275, 0.300, 0.325, 0.350, 0.375, 0.400, and 0.425 cm^3 (steps of 0.025 cm^3) (Fig. 1). The 0.350 cm^3 object was used as the reference stimulus for each set of object shapes. Additionally, to eliminate the availability of weight information, a small cylindrical hole (diameter of 2 mm) was made so that the objects could be placed on a stand.

Conditions A 3 (shape) \times 4 (finger) within-subjects design was used, resulting in 12 conditions. The three different shape conditions were tetrahedron, cube, and sphere. The four different finger conditions were the thumb (fingertip) with the index finger (fingertip), middle finger (fingertip), ring finger (fingertip), and little finger (fingertip), respectively. All 12 conditions were performed within six sessions. Shape and finger factors were randomized between sessions, and the order of the tests and reference stimuli within each trial was also randomized. The subjects performed no more than two sessions per day, in a

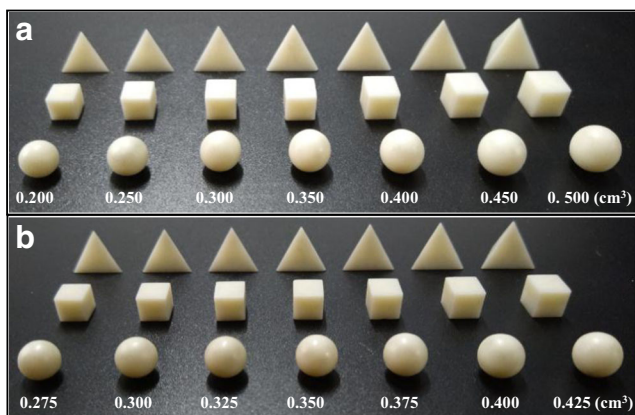


Fig. 1 The sizes and shapes of the stimuli for the experiment. The two ranges of tetrahedrons, cubes, and spheres from the stimulus set of completely solid objects. **(a)** From left to right, the volumes were 0.200, 0.250, 0.300, 0.350, 0.400, 0.450, and 0.500 cm^3 (in steps of 0.050 cm^3). **(b)** From left to right, the volumes were 0.275, 0.300, 0.325, 0.350, 0.375, 0.400, and 0.425 cm^3 (in steps of 0.025 cm^3)

counterbalanced order, and a break time of at least 10 min between two sessions was required. Each session lasted for approximately 50 min, resulting in a total time of approximately 6 h for each participant to complete the experiment.

Method As shown in Fig. 2, we designed a haptic-volume presentation device for this behavior experiment. The chair and screen were adjusted to fit each participant, and the right hand of the participant was placed in a comfortable position during the experiment. A stand (12 cm

high) was fixed in front of the device on which the stimuli could be placed without providing weight information. Each of the objects included a small cylindrical hole, which allowed them to be placed on the stimulus stand to prevent subjects from obtaining weight information. From this experimental setup, subjects needed to rely on the central part of each fingertip and rotate the object back and forth with two fingertips to perceive volume (Fig. 2). After receiving these instructions, the participants received an eye mask to prevent them from using visual information, and no feedback was given during the experimental trials.

In this study, the two-alternative forced-choice technique was used to measure the discrimination threshold. Subjects were asked to choose which they perceived as the larger of two volumes, even if they could not detect a difference. To start a trial, the experimenter provided a vocal cue to indicate that the participant could explore the first stimulus for 4 s, and the stimulus was then enclosed with the thumb and other fingers as thoroughly as possible. After a 3-s inter-stimulus interval in which the experimenter changed the stimuli, the participant explored the second stimulus in the same fashion for 4 s. Then, the participant had to declare which of the two stimuli was larger by oral communication within 3 s. The two stimuli were the reference and the test, and they were presented in a pseudo-random order. No other information was given concerning the volume of the objects during haptic volume judgment.

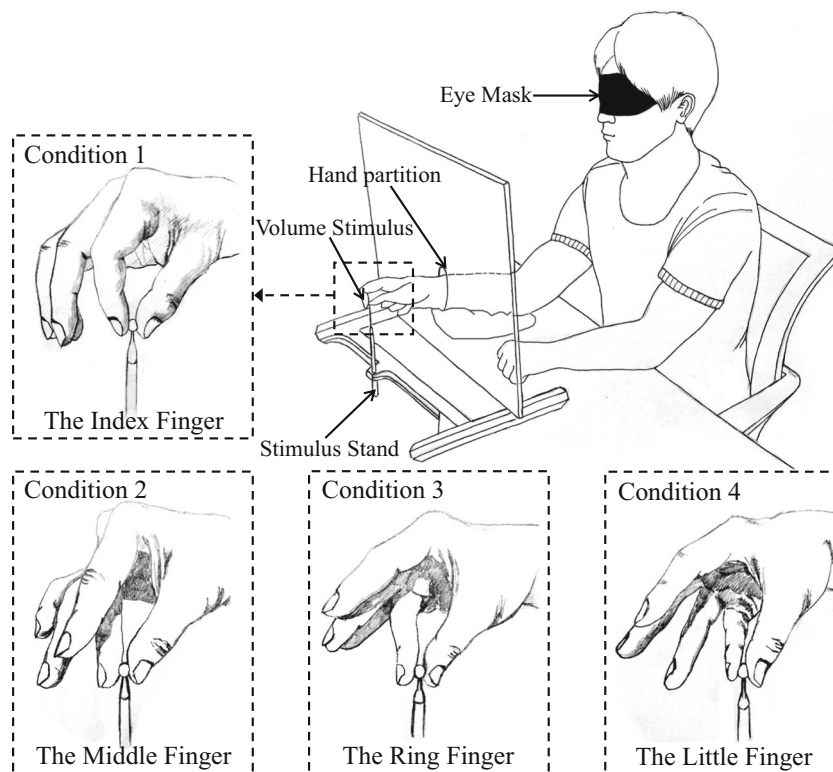


Fig. 2 A detailed depiction of the experimental apparatus and the position of the participant

Data collection The experimental data were collected from constant stimuli that consisted of two parts. The first part was the same for all participants, and the test stimuli differed in steps of 0.050 cm^3 from the reference stimulus, up to the outer range of the stimulus sizes ($0.200, 0.250, 0.300, 0.400, 0.450,$ and 0.500 cm^3). Each pair of reference and test stimuli in the first part was tested four times. In the second part, the stimulus range was based on the percentage of correct responses in the first part. If the performance on the first part was worse than a specified criterion, the same set was used as in the first part. Each combination of reference and test stimuli was repeated six more times to end up with ten repetitions for each combination. On the other hand, if the performance of the first part was better than this criterion, the second part used a set of test stimuli with a narrower size range ($0.275, 0.300, 0.325, 0.375, 0.400, 0.425 \text{ cm}^3$, differing in steps of 0.025 cm^3), and each stimulus was presented for either six or ten trials, such that the total number of trials was ten per stimulus value (Fig. 3). To define a specific criterion, we used a Monte Carlo simulation to generate 100 data sets based on a binomial distribution and calculated the discrimination threshold for each data set. In this study, the difference between the specified and the calculated discrimination thresholds was smallest when the criterion was approximately 0.84, which indicated that the appropriate criterion was 84 % (Kahrimanovic, Bergmann Tiest, & Kappers, 2011). The data from both parts were considered together for the subsequent analyses.

Data analyses These data were used to calculate the fraction of trials in which the subject selected the test stimulus as being larger in volume than the reference stimulus. Subsequently, a weighted cumulative Gaussian distribution (f) as a function of the volume of objects (V) was fitted to the data with a maximum-likelihood procedure (Wichmann & Hill, 2001a, 2001b), using the following equation:

$$f(V) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{V - V_{ref}}{\sigma\sqrt{2}} \right) \right]$$

where σ in this equation is a parameter that describes the steepness of the curve and can also be taken as a measure of the discrimination threshold and where the parameter V_{ref} corresponds to the volume of the reference stimulus that was used. Note that the volume of an object was used as the unique feature in all conditions. In addition, the coefficient of determination, R^2 , is a measure used in statistical analysis that assesses whether each psychometric function truly conforms to a cumulative Gaussian distribution. Then, the data were analyzed by repeated-measures analysis of variance (ANOVA) with factors of different conditions as the within-subjects factors. For factors with more than two levels, P -values were corrected for non-sphericity using the Greenhouse–Geisser correction (Greenhouse & Geisser, 1959). When a significant effect was found, the Bonferroni-corrected t-test for multiple comparisons was applied.

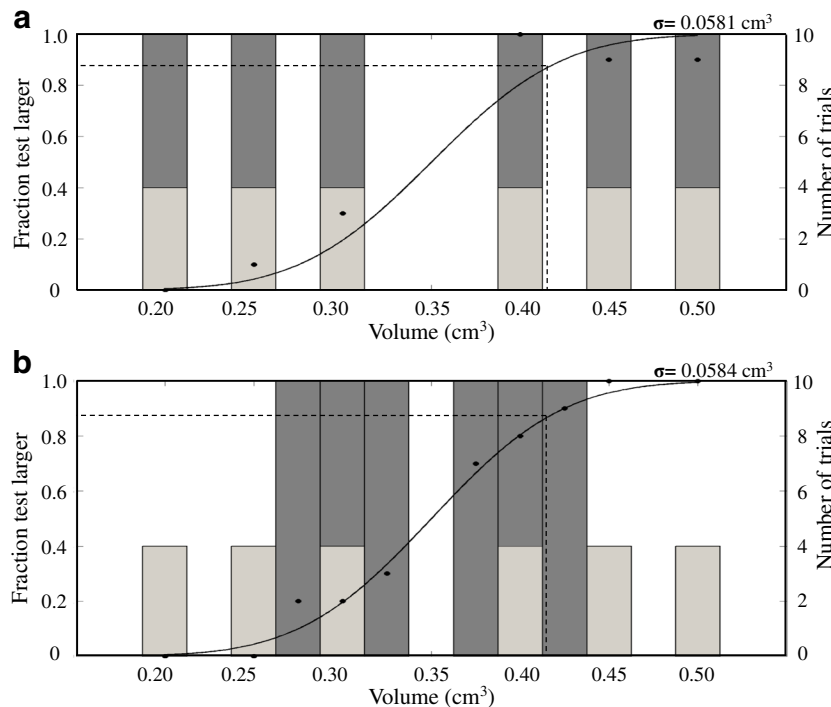


Fig. 3 An example of a data set for which the second part used a wide range (a) or a narrow range (b). The bar chart shows the number of repetitions for each test volume (right scale). The light-gray bars indicate the trials from the first part of the data collection procedure. The dark-gray bars indicate the trials from the second part. The curve shows the fitted

function through the measured data points (left scale). The vertical line at 0.35 cm^3 indicates the volume of the reference stimulus. The dashed line specifies the position of the 84 % threshold. The value of this discrimination threshold, σ , is shown in the upper right corner of the figure

Table 1 Mean coefficient of determination (R^2) of the psychometric functions for experiment 1

Finger	Shape		
	Tetrahedron	Cube	Sphere
Index finger	0.96 (0.02)	0.97 (0.02)	0.98 (0.02)
Middle finger	0.96 (0.03)	0.96 (0.02)	0.97 (0.02)
Ring finger	0.94 (0.05)	0.95 (0.03)	0.94 (0.05)
Little finger	0.93 (0.05)	0.94 (0.03)	0.95 (0.04)

Standard deviations are given in parentheses

Results

In Experiment 1, the mean coefficient of determination ranged from 0.93 (SD = 0.05) for the tetrahedron in the little finger condition to 0.98 (SD = 0.02) for the sphere in the index finger condition (Table 1). Therefore, all the psychometric functions truly conform to a cumulative Gaussian distribution ($R^2 \geq 0.88$). Figure 4 shows the average discrimination thresholds for the three different shapes and four different fingers. The average discrimination thresholds ranged from 0.040 cm³ (standard error of the mean (SEM) = 0.002 cm³) for the sphere in the index finger condition to 0.071 cm³ (SEM = 0.005 cm³) for the tetrahedron in the little finger condition (Fig. 4). Further analysis revealed that in the haptic volume discrimination task, the mean discrimination threshold for a tetrahedron was higher than that for a cube and much higher than that for a sphere (Fig. 5a). We also observed that haptic volume discrimination thresholds varied significantly across the fingers. The thresholds were the highest for the little finger condition and the lowest for the index finger condition (Fig. 5b). Furthermore, these data were analyzed using a 3 (shape) \times 4 (finger) repeated-measures ANOVA performed on the

discrimination threshold, which revealed no significant interaction effect between shape and finger ($F(6, 102) = 0.991, p = 0.412$), but there was a main effect for shape and finger condition ($F(2, 34) = 7.314, p < 0.01$ and $F(3, 51) = 20.338, p < 0.01$, respectively).

The main effect of shape revealed that the discrimination thresholds for the tetrahedral stimuli were significantly larger than those for the spherical stimuli, averaging 0.057 cm³ (SEM = 0.002 cm³) and 0.049 cm³ (SEM = 0.002 cm³), respectively ($p < 0.01$), but the cube stimulus failed to reach a significant difference from the tetrahedron ($p = 0.283$) or the sphere ($p = 0.136$). The significant main effects of fingers indicated that the discrimination thresholds differed depending on the different fingers that were compared. The average discrimination thresholds for the index finger, middle finger, ring finger, and little finger were 0.044 cm³ (SEM = 0.001 cm³), 0.047 cm³ (SEM = 0.001 cm³), 0.057 cm³ (SEM = 0.002 cm³), and 0.063 cm³ (SEM = 0.003 cm³), respectively. Additionally, Bonferroni-corrected pairwise comparisons showed that the discrimination thresholds for the index finger ($p < 0.01$) or the middle finger ($p < 0.01$) were significantly lower than the thresholds for the ring finger or the little finger conditions. In other words, the sphere shape and the index finger produced the best haptic volume perception among the different shape and finger conditions.

Experiment 2

Experiment 1 revealed significant differences in the discrimination thresholds in inter-finger conditions and showed that the index finger or middle finger could discriminate smaller volume variations than the ring finger or little finger. However, the latest study from a two-point

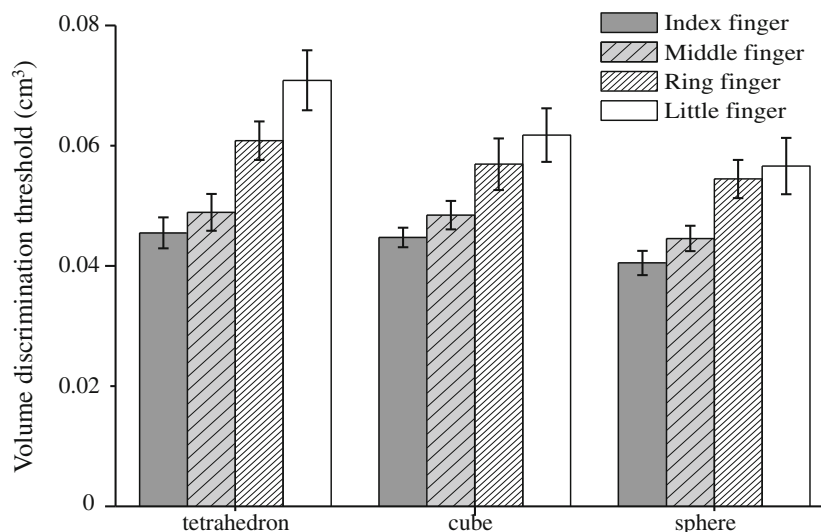


Fig. 4 The average discrimination thresholds for the different conditions, with the standard errors of the means (SEMs) indicated by the error bars. Each panel shows data for tetrahedron, cube and sphere stimuli for the index finger, the middle finger, the ring finger and the little finger

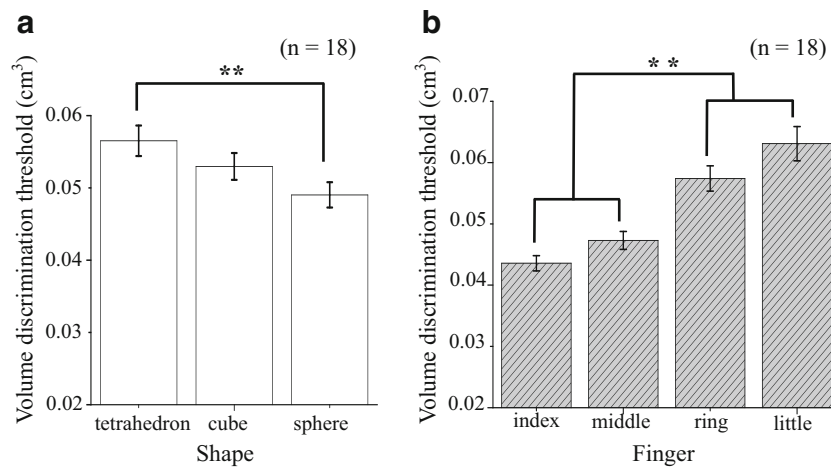


Fig. 5 The average discrimination thresholds for three shapes of stimuli (a) and four finger conditions (b) with the standard errors of the means (SEMs) indicated by the error bars (* $p < 0.05$, ** $p < 0.01$)

orientation discrimination task has shown that different phalanges of each finger also have a high influence on the tactile spatial resolution (Tong, Mao, & Goldreich, 2013). It has been demonstrated that the spatial resolution at the fingertip (1.20 mm) was significantly superior to that at the finger base (1.77 mm) (Johansson & Vallbo, 1979a, b). Although this effect of different phalanges on tactile spatial resolution measurement has been widely investigated, research linking different phalanx conditions to haptic volume perception remains unknown. In

addition, experiment 1 also indicates that a sphere is the best shape for haptic volume perception among tetrahedron, cube, and sphere shape conditions (Kahrimanovic, Bergmann Tiest, et al., 2011; Kahrimanovic, Bergmann Tiest, & Kappers, 2010b). To explore the ability of the distal, medial, and proximal phalanges of the index, middle, ring, and little finger to perform haptic volume perception, experiment 2 was performed, and the participants were asked to discriminate the volume of spheres in the inter-phalanx of each finger condition.

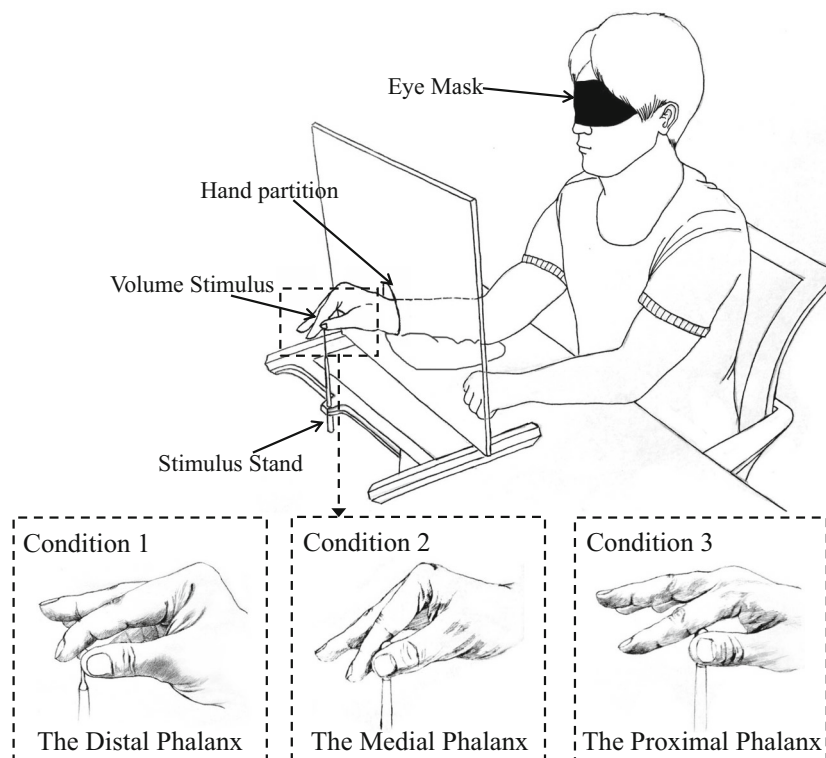


Fig. 6 A detailed depiction of the experimental apparatus and position of the participant

Table 2 Mean coefficient of determination (R^2) of the psychometric functions for experiment 2

Finger	Phalanx		
	Distal phalanx	Medial phalanx	Proximal phalanx
Index finger	0.98 (0.02)	0.98 (0.02)	0.96 (0.04)
Middle finger	0.97 (0.02)	0.95 (0.04)	0.95 (0.05)
Ring finger	0.94 (0.05)	0.93 (0.03)	0.95 (0.02)
Little finger	0.95 (0.04)	0.93 (0.06)	0.93 (0.05)

Standard deviations are given in parentheses

Method

The procedure for the effect of phalanx on the volume discrimination task was similar to that of experiment 1. The main difference was that the participants in this experiment were asked to perceive volume depending on the medial and proximal phalanges of their index, middle, ring, and little finger enclosed with their fingertip and thumb as much as possible (Fig. 6). Participants needed to rely on the central part of each phalanx and rotate back and forth with two fingers to perceive volume. However, the data related to the distal phalanx (fingertip) of each finger were collected in experiment 1. In particular, it is worth mentioning that the sphere was the most sensitive shape condition, and it was the only shape used in Experiment 2. This experiment was performed with 16 participants who took part in Experiment 1. They also provided informed written consent and were paid for their participation.

Results

In Experiment 2, the mean coefficient of determination ranged from 0.93 (SD = 0.06) for the medial phalanx in the little finger condition to 0.98 (SD = 0.02) for the distal phalanx in the index finger condition (Table 2). Therefore, all the psychometric functions truly conformed to a cumulative Gaussian distribution ($R^2 \geq 0.87$). Figure 7 shows the average discrimination thresholds measured in Experiment 2. For haptic volume perception of a spherical stimulus, the average discrimination thresholds ranged from 0.040 cm³ (SEM = 0.002 cm³) for the distal phalanx of the index finger to 0.073 cm³ (SEM = 0.008 cm³) for the proximal phalanx of the little finger (Fig. 7). ANOVA revealed that the main effects of the finger and phalanx were significant ($F(3, 45) = 11.184, p < 0.01$ and $F(2, 30) = 7.227, p < 0.01$, respectively), but there was no significant interaction effect between the finger and phalanx ($F(6, 90) = 2.285, p = 0.089$). A post hoc test suggested that the discrimination threshold averaged 0.044 cm³ (SEM = 0.002 cm³) for the index finger and 0.048 cm³ (SEM = 0.001 cm³) for the index finger, and these values were significantly lower ($p < 0.05$) than those for the ring finger and little finger, which were 0.057 cm³ (SEM = 0.002 cm³) and 0.063 cm³ (SEM = 0.003 cm³), respectively (Fig. 8a). However, the differences between the index finger and middle finger ($p = 0.481$) and between the ring finger and little finger ($p = 1.000$) were not significant. Furthermore, the average discrimination threshold for the proximal phalanx was 0.057 cm³ (SEM = 0.003 cm³), which was much larger than that for the distal phalanx at 0.048 cm³ (SEM = 0.002 cm³). A Bonferroni-corrected pairwise

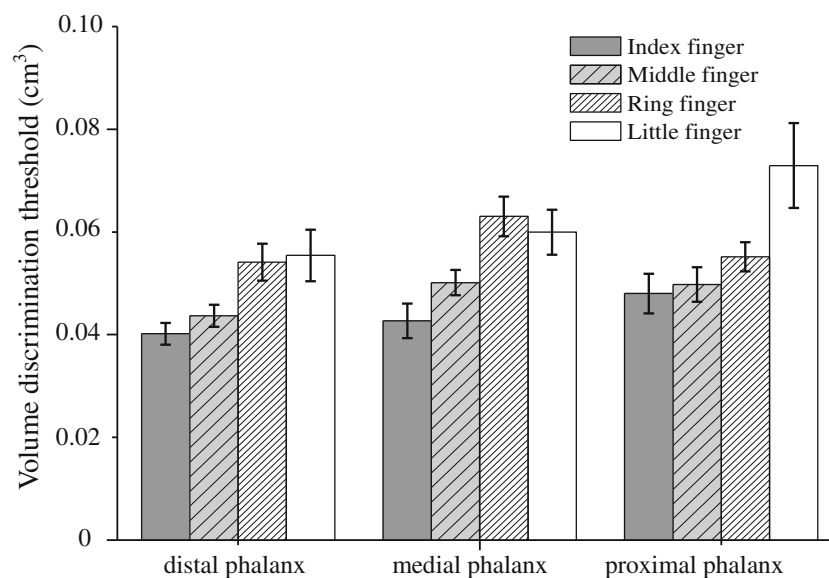


Fig. 7 The average discrimination thresholds for the different conditions, with the standard errors of the means (SEMs) indicated by the error bars. Each panel shows data for the distal phalanx, the medial phalanx and the proximal phalanx of the index finger, middle finger, ring finger and little finger

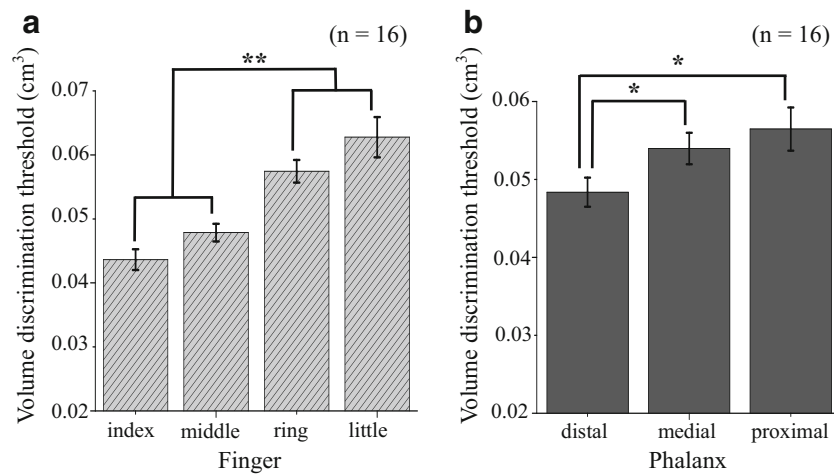


Fig. 8 The average discrimination thresholds for four fingers (**a**) and three phalanges (**b**) with the standard errors of the means (SEM) indicated by the error bars. (* $p < 0.05$, ** $p < 0.01$)

comparison between the discrimination thresholds of the distal phalanx and the medial phalanx was significant ($p < 0.05$), and a similar comparison between the distal phalanx and the proximal phalanx was significant ($p < 0.05$), but the medial phalanx and the proximal phalanx were not significantly different (Fig. 8b).

General discussion

The set of current psychophysical experiments shows significant effects of shape, finger, and phalanx on haptic volume perception while varying the shape of the stimulus and the part of the participant's finger in contact with the stimulus and comparing the volume discrimination thresholds. The effects of shape and finger on the discrimination threshold were investigated in Experiment 1, whereas the discrimination thresholds for the different phalanges of each finger were investigated in Experiment 2. In the following sections, we will discuss the observed effects.

The effects of shape on haptic volume perception

In the first experiment, the volume discrimination threshold for a tetrahedron was much larger than that for a sphere in the haptic volume discrimination task. A previous study revealed that the estimated volume tended to be larger for a tetrahedron than a cube or a sphere of the same physical volume when using whole-hand haptic volume perception, which was consistent with the results of the present study (Kahrmanovic et al., 2011). Therefore, it is possible that the shape of solid objects also influences the magnitude of the estimated volume in finger haptic volume perception.

One straightforward interpretation of this result might be that the surface area dimension plays an important role in haptic volume perception. Thus, possibly the participants'

judgments were influenced by the surface area of the solid objects. Obviously, a tetrahedron or a cube is far more difficult to manipulate and enclose than a sphere because a sphere has a smoother, curved surface, unlike that of a cube or a tetrahedron. The spherical stimuli could be completely enclosed by two fingers, thus allowing the perception of the entire stimulus at once. In contrast, the explorations of the tetrahedral and cubic stimuli are more sequential. Even with an optimal enclosure of the stimulus with two fingers, the stimulus was still not completely in contact with the fingers. Consequently, in the haptic volume discrimination task, the information about the objects' surface area might be more complete for the spherical objects than for the tetrahedral and cubic objects.

On the other hand, this effect of shape may also be related to the properties of edges and vertices. Researchers have proposed that haptic volume perception is affected by the salient features of the object and that edges and vertices are likely salient features during exploration. Note that the tetrahedron and the cube have sharp edges and vertices, but the sphere has fewer salient features. Attention will therefore be captured by the salience of the edge and vertex cues, which could direct attention away from the volume itself. Therefore, the presence of the sharper edges and vertices probably disrupted the participants' ability to perceive volume (Panday, Bergmann Tiest, & Kappers, 2012; Plaisier, Bergmann Tiest, & Kappers, 2009). Additionally, the participants used the size of pinch grasp as a cue to decide object volume. Pinch grasp is invariant with object orientation (low-variance cue) for a spherical object. However, distinct surface angles (60° or 90°) may disrupt the utility of size of pinch grasp as a cue for perceiving volume in the tetrahedral and cubic objects. Thus, our results suggest that the different shape conditions also disrupt volume discrimination in finger haptic perception.

The effects of fingers and phalanges on haptic volume perception

For the main objective of this study, we determined which phalanx and finger combinations were the most sensitive in haptic volume perception. The results indicated that volume discrimination thresholds for the index finger and the middle finger were significantly lower than those for the ring finger and the little finger, and the distal phalanx had significantly lower volume discrimination thresholds than the middle phalanx and the proximal phalanx. This is a plausible result because the highest density of mechanoreceptors is found in the distal phalanges of fingers, especially those of the index and middle fingers (Johansson & Vallbo, 1979a). In addition, Johansson and Vallbo calculated the densities of four different types of highly sensitive mechanoreceptive units, including Rapidly Adapting (RA), Pacinian corpuscle (PC), Slowly Adapting type I (SA I), and Slowly Adapting type II (SA II) mechanoreceptors, that were related to tactile input, and they showed that the overall density increased abruptly from the proximal phalanx to the distal phalanx (Johansson & Vallbo, 1979b). For example, the relative densities of these mechanoreceptive units in the proximal phalanx and the distal phalanx were reported to be 1.0 and 4.2, respectively. The distribution of the RA and SA I units ranged from 40 units cm⁻² and 38 units cm⁻² in the proximal phalanx to 140 units cm⁻² and 70 units cm⁻² in the distal phalanx, respectively (Johansson & Vallbo, 1980). Moreover, RA and SA I units as well as their receptive field properties make them particularly suitable for haptic spatial perception. Thus, the distal phalanges of the index finger and the middle finger have an outstanding capacity in the perception of volume through touch.

Another possibility is that the discrimination threshold would be influenced by synergies. Haptic perception results from the integration of cutaneous stimulation in skin and proprioception generated by finger movement. Sensory and motor synergies are two key points for acquiring a certain type of information in the haptic perception. Precision haptic perception between the index and thumb finger also occurs frequently (postural synergies), whereas it is uncommon between the index and little fingers. In contrast to the distal phalanx, the medial and proximal phalanges seem to use unnatural finger movement to make contact with the target. This unnatural finger movement would drastically reduce the free movement of the finger. In contrast, the natural finger movement would facilitate or optimize the sensorimotor system to identify common objects by the coordination of sensory and motor synergies, thereby facilitating volume perception (Santello, Bianchi, Gabiccini, Ricciardi, Salvietti, Prattichizzo, Ernst, Moscatelli, Jörntell, Kappers, Kyriakopoulos, Albu-Schäffer, Castellini & Bicchi, 2016). Thus, the distal phalanx has a greater capacity for volume perception than do the medial phalanx and the proximal phalanx, as one might predict based on the enclosure exploratory procedure. Additionally, this superiority in the performance of the distal phalanx of index finger in the haptic volume

perception task appears to match the function of this skin area as the best sensory region. When the human hand was used to explore the properties of an object with fine manipulation movements, it was necessary for the distal phalanx of the thumb finger, the index finger, and the middle finger to make contact with the object. However, our results only reflected how the volume-perception ability between fingers and phalanges differed in normal subjects and indicated that these parts were probably necessary to perform volume perception tasks. It would be worthwhile for future studies to further investigate the ability of other body parts in people or individuals with long-term training for haptic volume perception.

Conclusion

In summary, the present study sheds new light on haptic volume perception under different finger and phalanx conditions. These findings indicate that the distal phalanx of the index finger is the most sensitive for discriminating variations in volume, while the proximal phalanx of the little finger is the least sensitive for discriminating variations in volume. Our results also confirmed that the haptic volume perception decreases from the index finger to the little finger and also decreases from the distal phalanx to the proximal phalanx. Our results are important for precision haptic perception, but a complete understanding of the precision haptic perception of human fingers requires additional investigation. Our findings provide an important step toward the further understanding of the neural mechanisms underlying precision haptic perception, which have not previously been studied extensively.

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Compliance with ethical standards

Conflict of interest The author(s) have no potential conflicts of interest to declare with respect to the research, authorship, and/or publication of this article.

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