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Haptic perception of volume and surface area of 3-D objects

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Haptic perception of volume (Experiment 1) and surface area (Experiment 2) was studied with tetrahedrons, cubes, and spheres as stimuli (2–14 cm^3). The results of Experiment 1 showed that subjects perceived a tetrahedron to be larger in volume than either a cube or a sphere of the same physical volume and that they perceived a cube to be larger than a sphere. This pattern was independent of object size. The biases were smaller in conditions with mass information than in those without. The average biases in the different conditions ranged from 7% to 67%. Analyses revealed that the subjects apparently based their volume judgments on the surface area of objects. Experiment 2 showed that surface area itself could be perceived accurately, almost independently of the objects' shape. Experiment 3 investigated volume perception of objects in the absence of surface area (wire-frame objects) and showed larger biases than those observed with solid objects. With wire-frame objects, the maximal distance between two vertex points was probably the dimension on which the volume judgment was based. In conclusion, haptic volume perception of geometric objects has to be inferred from other object properties, but surface area can be perceived unbiased.

The most well-known example of a study on the perception of volume is probably Piaget's (1968) experiment on conservation of liquid volume with young children. In his experiments, liquid was poured from a tall cylinder into a shorter, wider one, so that the height of the liquid in the second cylinder was smaller. A young child who observes this action will most likely indicate that there is more liquid in the tall skinny cylinder. According to Piaget, this happens because the child tends to focus on just one dimension of the cylinder—that is, the height—in order to make the volume judgment. Studies performed with adult participants have also suggested that visual volume perception depends on the longest linear dimension of objects (Frayman & Dawson, 1981; Holmberg, 1975; Lauer, 1929; Raghubir & Krishna, 1999; Stanek, 1968, 1969; Wansink & Van Ittersum, 2003). This phenomenon has been termed the *elongation bias*.

Krishna (2006) showed that the extent and direction of this elongation bias is affected by sensory modality. She used two transparent plastic glasses, each with a volume of about 200 cm^3, with one glass taller than the other. Adult participants had to judge the volume of these glasses by use of visual cues alone, bimodal visual and haptic cues, and haptic cues alone. With visual cues alone and with bimodal cues, the elongation bias was obtained. With haptic cues alone, a reversal of the elongation bias occurred. Krishna suggested that this difference between the modalities occurs because the salience of a dimension may depend on sensory input. The height is salient for the visual sense, but the width for the haptic sense.

Objects can, however, differ along more geometric dimensions than only the height-to-width ratio. When a long and a short cylinder or a cube and an elongated rectangular cuboid are compared by touch, the most obvious difference between the compared objects is indeed the height-to-width ratio. On the other hand, a cube and a sphere differ along more geometric properties that can be salient for the haptic sense—for example, curvature, edges, and number of flat surfaces. The important question we will address in this article is, can we generalize the influence of the longest linear dimension on haptic volume perception to objects that differ along more geometric dimensions?

In the first experiment, blindfolded subjects handled tetrahedrons, spheres, and cubes of varying volume and matched them according to their perceived volume. The stimuli were perceived by enclosure, since that has been shown to be the stereotypical exploratory procedure for haptic volume judgment (Lederman & Klatzky, 1987). We measured the tendency to over- or underestimate the volume of an object with respect to the volume of objects of different geometric shapes. Since significant biases occurred, we also examined the influence of diverse geometric properties, such as elongation and surface area, on haptic volume perception. An additional purpose of the first experiment was to examine the importance of mass information during haptic volume perception. Subjects performed the volume discrimination task either by unsupported holding of the object (i.e., with mass information) or by handling objects that were placed on stands (i.e., without mass information). The mass of the objects covaried consistently

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with their volume, and, therefore, both cues could be used for the volume judgment. The small Weber fractions for weight perception, ranging from 0.02 to 0.13 (for a review, see Jones, 1986), indicate that mass differences can be perceived accurately and that mass information is likely to be used when it is available. In the present experiment, the subjects may base their volume judgment primary on the available mass information, ignoring the geometric cues. However, Amazeen (1999) showed that both physical mass and physical volume contribute to perceived volume. Mass information may, then, be used as a second dimension to adjust the initial volume judgment.

The results from this first experiment showed large effects of geometric shape on volume perception, in both the conditions with and those without mass information, and revealed that haptically perceived volume was apparently based on the surface area of objects. This raised the question of whether surface area itself could be matched for objects of different geometric shapes. This was addressed in Experiment 2. Another question, which was the focus of Experiment 3, was whether the effect of shape on haptic volume perception would change when objects were explored without surface information.

EXPERIMENT 1
Volume Perception

Method

Subjects. Nine students from Utrecht University (6 of them female and 3 male; mean age, 21 years) participated in this experiment. Data from 1 of these subjects were excluded from the analysis, because she indicated afterward that she was not performing the required task. All the subjects were right-handed, as established by Coren's (1993) handedness questionnaire. All were naive as to the purposes of the experiment, and they were paid for their participation. Before starting the first session of the experiment, they provided written informed consent.

Stimuli. Tetrahedrons, cubes, and spheres were used as stimuli. They were made of brass, and their volumes ranged from 2 to 14 cm^3, in steps of 1 cm^3. Two different sets were used for each of the three geometric objects. The first set consisted of 13 completely solid objects (see Figure 1A). The mass of the objects covaried consistently with their volume (i.e., the mass ranged from 16.8 to 117.6 g). For the second set, objects identical to those in the first set were used, but in each of them, a small cylindrical hole was made in the center of one plane. This hollowing caused no changes to the global geometric shape or volume of the objects. These objects could be placed on stands to eliminate mass information (see Figure 1B). Two 12-cm-high stands were used, and they were placed at a center-to-center distance of 10 cm.

Conditions. The experiment was divided into two main exploration blocks; in one block, the mass information was available during the exploration of the stimuli (*mass*), and in the other, the mass cues were eliminated by placing the objects on stands (*no mass*). Each exploration block consisted of three different object pair conditions: tetrahedron–sphere, tetrahedron–cube, and cube–sphere. Furthermore, for each object, a small, medium, and large reference volume was used.

When two different objects are compared with each other, it is important to test whether the comparison is independent of the choice for one or the other object as the reference. That is, if a reference tetrahedron of 2 cm^3 is matched to a sphere of 4 cm^3, a reference sphere of 4 cm^3 should be matched to a tetrahedron of 2 cm^3. In the present experiment, the different reference values per object were selected in such a way that this consistency could be tested afterward. The selection was based on results from a pilot study, showing that, in general, a tetrahedron was matched to both a larger cube and a larger sphere and that a cube was matched to a larger sphere. Therefore, the selected tetrahedron references should be smaller than the cube and the sphere references, and the cube references should be smaller than the sphere references. On the basis of these assumptions, the following reference volumes were used: tetrahedrons of 3, 5, and 7 cm^3, cubes of 4, 6, and 8 cm^3, and spheres of 5, 7, and 9 cm^3. This means that each object comparison consisted of six references—that is, three for each object. Taken together, there were 36 different conditions—that is, exploration manner (2) × object pair (3) × reference size (3) × reference object (2).

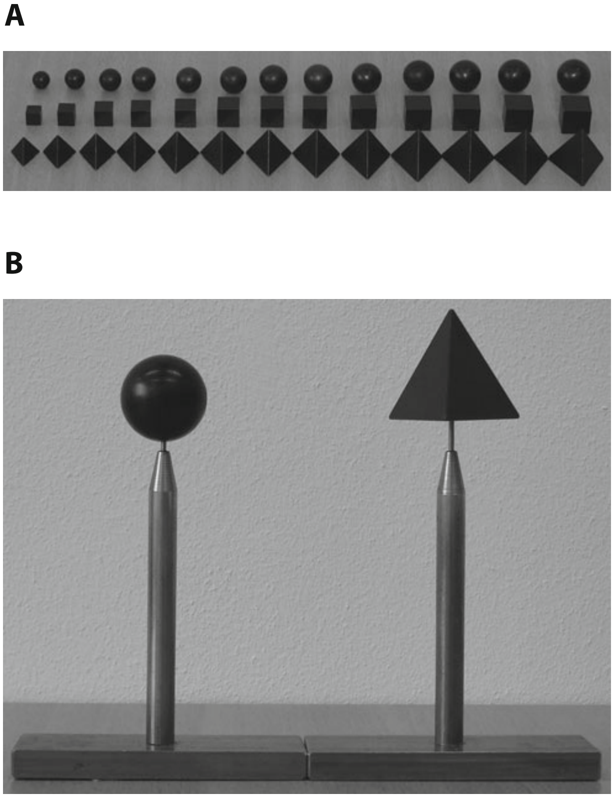

Figure 1. (A) The stimulus set with the completely solid objects. (B) Example of the setup in the no-mass condition.

Procedure. The stimuli were covered before the subjects entered the experimentation room, and the subjects were blindfolded to prevent them from using visual information. For the mass blocks, the elbow of the right arm rested on the table, and the forearm was shifted upward so that the angle between the forearm and the upper arm was about 90º. The hand was positioned horizontally. The experimenter could place the stimuli in the center of the hand palm (see Figure 2A). After the first stimulus was placed in the hand, the subject enclosed the stimulus and, thereby, maximized contact with it. The period of exploration was not restricted but was often just a few seconds. The first stimulus was then replaced by a second stimulus, which was explored in the same way as the first one. The order of the reference and comparison stimuli was randomized. The subject judged which of the two explored stimuli was larger in volume. In these conditions, mass information was available, but no information was provided about the relationship between volume and mass. The subjects were instructed that the objects would vary in mass but that their task was to compare the objects according to their volume.

During the no-mass block, the stimuli were presented on stands. Several practice trials were necessary to familiarize the subject with the exact position of the stands and the stimuli on them. After practicing, the subject could locate the stimuli with just one smooth arm

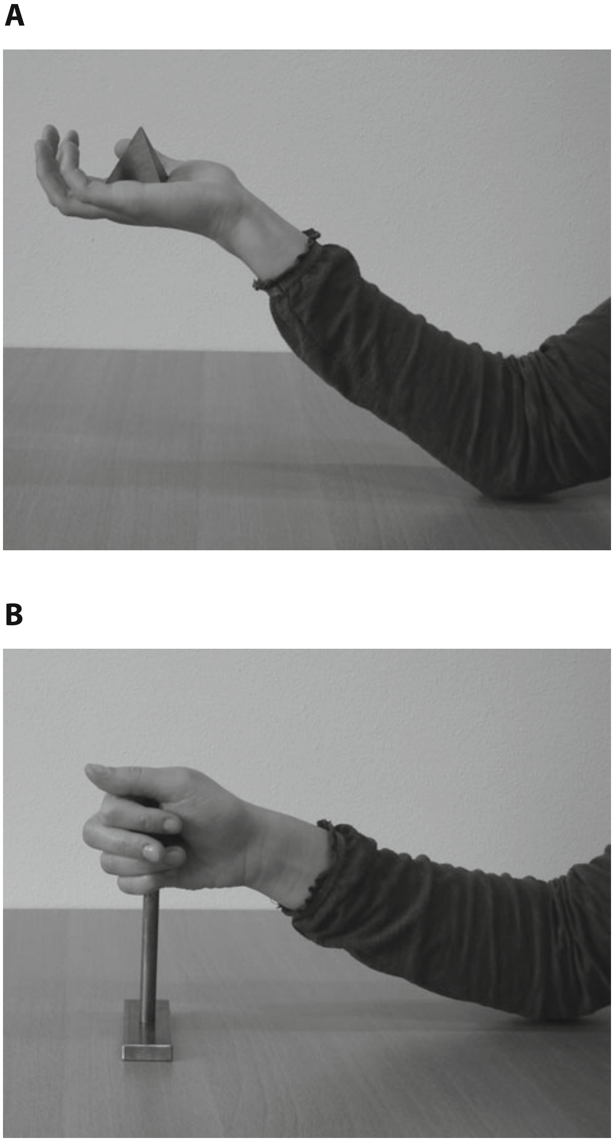

Figure 2. (A) The way in which stimuli were presented during the mass conditions. (B) The exploration manner of the stimulus during the no-mass conditions.

movement. The exploration of the stimuli was the same as during the mass block, except that the hand palm was now turned sideways (see Figure 2B). To start a trial, the experimenter gave a vocal signal to indicate that the subject could move his/her hand toward the first stimulus, which was always the stimulus on the right side with respect to the subject. The fingers enclosed the stimulus surface after the hand palm had touched one side of the stimulus. In this way, exploration was as similar as possible to that in the mass conditions. Moving the stimulus was not allowed; otherwise, mass information would become available. After exploration of the first stimulus, the subject moved his/her hand toward the second stimulus, explored it in the same way, and judged which of the two stimuli was larger in volume.

Data collection. The stimuli were presented by means of a one-up–one-down staircase procedure. The staircases were computer driven. The complete experiment consisted of six sessions, with exploration manner and object pair being randomized between sessions. For each combination of exploration manner and object pair, the six different references (i.e., three for each object) were tested within one session. Sets consisting of trials belonging to the six different references were presented successively. Within a trial, the presentation order of the reference and the test stimulus was randomized. The data for one reference were collected during 35 trials, with two staircases intermingled and each starting at one side of the stimulus range—that is, at 2 and 14 cm^3 (see Figure 3A for an example). A pilot study showed this number to be enough to reach a constant threshold level in all conditions. The subjects performed no more than two sessions per day, and a rest period of at least 20 min between two sessions was required. One session lasted for approximately 40 min, resulting in 4 h per subject for the total experiment.

Psychometric data. An example of the data collected with the staircases can be seen in Figure 3A. From these data, the fraction was calculated with which the subject selected the test stimulus to be larger in volume, as compared with the reference stimulus. This calculation was performed for all test volumes (see Figure 3B). Subsequently, a cumulative Gaussian distribution (f) as a function of the volume (x) was fitted to the data with the maximum-likelihood procedure (Wichmann & Hill, 2001), using the following equation:

$$f(x) = \frac{1}{2}\left[1+\operatorname{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right],$$

where the parameter σ is a measure of the discrimination threshold—that is, the sensitivity of the subjects in perceiving volume

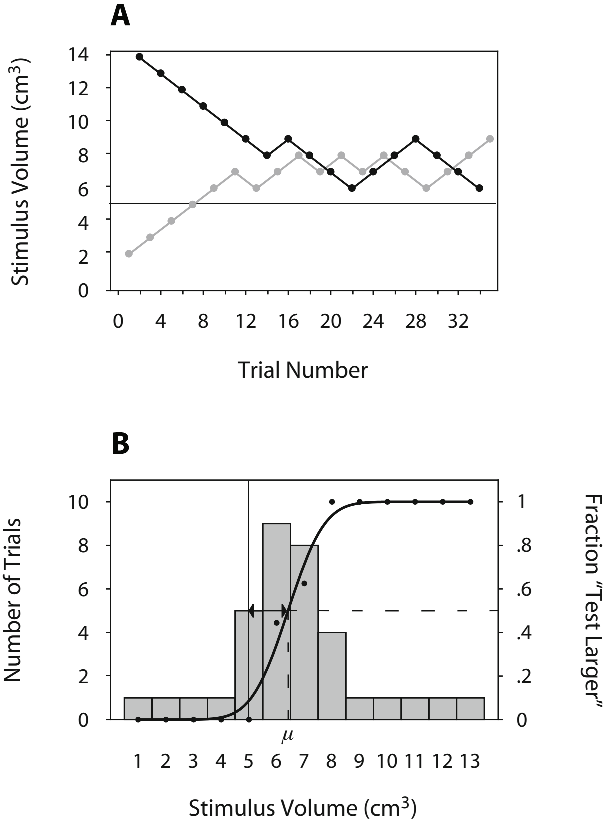

Figure 3. (A) Example of the two staircases from one condition, each starting at different points. The horizontal line at the stimulus volume of 5 cm^3 indicates the volume of the reference stimulus. (B) Example of the corresponding psychometric curve. The bar chart shows the number of repetitions at each test volume (left scale), and the curve shows the fitted function through the measured data points (right scale). The vertical line at the stimulus volume of 5 cm^3 indicates the volume of the reference stimulus. The dashed line specifies the place of the point of subjective equality, μ. The arrow shows the absolute bias.

differences when comparing two objects—and μ represents the volume at which, 50% of the time, the test stimulus was selected to be larger in volume than the reference. This indicates the volume of the test stimulus that was perceived to be equivalent to the reference stimulus, also known as the point of subjective equality (see Figure 3).

Relative biases were calculated from these data. For each matched object pair (tetrahedron–sphere, tetrahedron–cube, and cube–sphere), the volume of the object mentioned first was subtracted from that mentioned second and was expressed as a percentage of the volume of the first-mentioned object. In this way, the biases obtained with the first object as reference could be compared directly with those obtained with the second object as reference. Statistical ANOVAs tested for the effect of four within-subjects factors on these relative biases. The first within-subjects factor (two levels) was the reference object, with the first level indicating the biases when the first object from an object pair was the reference, and the second level indicating the biases with the second object being the reference. The remaining within-subjects factors were object pair (tetrahedron–sphere, tetrahedron–cube, cube–sphere), reference size (small, medium, large), and exploration manner (mass, no mass). The same statistical analyses were also performed on the discrimination thresholds.

Results

Effect of reference. The ANOVA revealed that, for each combination of objects, both references resulted in biases of similar magnitude [$F(1,7) = 0.11, p = .75$]. For example, if a reference tetrahedron of 2 cm^3 is perceived to have the same volume as a sphere of 5 cm^3, a reference sphere of 5 cm^3 will be perceived to be identical to a tetrahedron of 2 cm^3. In the subsequent analyses, the biases for the two references from each object pair will be averaged.

Effect of shape. Figure 4 shows the relative biases in the different conditions. The expected biases would be around 0% if geometric shape had no influence on haptic volume perception. On the other hand, if geometric shape exerted an influence on volume perception, positive or negative biases would occur. For each matched object pair, a positive bias indicates an overestimation of the volume of the object mentioned first, and a negative bias indicates an underestimation of the volume of the first-mentioned object. As the figure shows, the observed biases were all much larger than zero. The overall average was 31% (*SE* = 3%). The positive biases indicate that a tetrahedron was perceived to be larger in volume than both a cube and a sphere of the same physical volume and that a cube was perceived to be larger than a sphere of the same physical volume. As an example, a tetrahedron of 3 cm^3 was perceived to be the same in volume as a sphere of about 5 cm^3. The ANOVA showed that the effect of object pair was highly significant [$F(2,14) = 25, p < .001$]. Post hoc tests revealed that the biases in the tetrahedron–sphere condition—on average, 48% (*SE* = 4%)—were significantly larger ($p < .05$), as compared with the biases in the other two object pairs, which were 26% and 20% (*SE* = 3% and 5%, respectively). However, these biases from the tetrahedron–cube and the cube–sphere conditions did not differ significantly ($p = .73$).

Effect of size. Figure 4 also shows the biases for the different reference sizes. The use of a small, medium, or large reference resulted in average bias of 34% (*SE* = 4%), 30% (*SE* = 3%), and 28% (*SE* = 3%), respectively. Linear regression analyses, with the size as a continuous variable, were performed for the different conditions. The slopes of the regression lines were not significantly different from zero ($p > .05$). This indicates that the relative bias for perceived volume was not affected by the size of the objects, at least not within the range of object size that was used in this experiment. Note that for the relative bias to be constant for different sizes, the absolute bias has to increase proportionally with the size of the reference.

Effect of mass. The biases in the no-mass conditions ($M = 41\%$, *SE* = 3%) were significantly larger [$F(1,7) =$

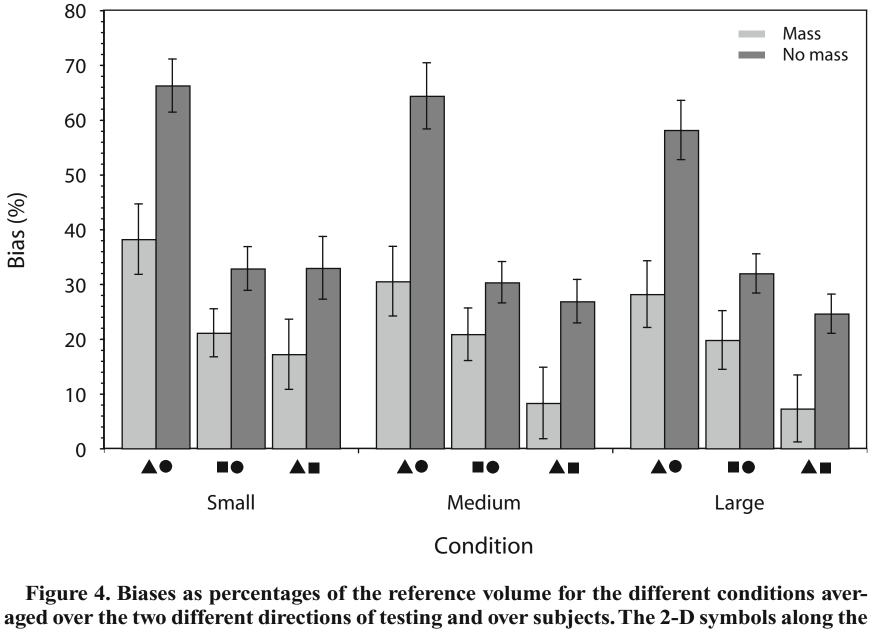

Figure 4. Biases as percentages of the reference volume for the different conditions averaged over the two different directions of testing and over subjects. The 2-D symbols along the categorical axis stand for their 3-D counterparts. Error bars represent the standard errors of the means.

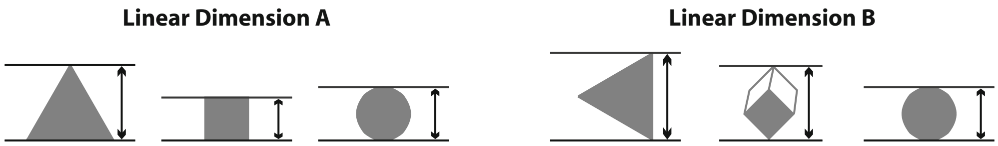

Figure 5. Representation of the smallest (left) and the largest (right) distance between two parallel planes with the objects in between them. The depicted distance is based on an example of objects of equal volume.

Table 1
Formulas Used to Describe the Different Factors

	Tetrahedron	Cube	Sphere
Volume	V	V	V
Linear Dimension A	$\frac{2V^{1/3}}{3^{1/6}}$	$V^{1/3}$	$\left(\frac{6}{\pi}\right)^{1/3} V^{1/3}$
Linear Dimension B	$\sqrt{2}\ 3^{1/3}\ V^{1/3}$	$\sqrt{3}\ V^{1/3}$	$\left(\frac{6}{\pi}\right)^{1/3} V^{1/3}$
Circumsphere radius	$\frac{1}{2}\ 3^{5/6}\ V^{1/3}$	$\frac{1}{2}\sqrt{3}\ V^{1/3}$	$\frac{\left(\frac{3}{\pi}\right)^{1/3} V^{1/3}}{2^{2/3}}$
Surface area	$6\ 3^{1/6}\ V^{2/3}$	$6\ V^{2/3}$	$6^{2/3}\ \pi^{1/3}\ V^{2/3}$

Note—The formulas are expressed as a function of the volume (V) of the objects. Linear Dimension A corresponds to the smallest distance between two parallel planes that can enclose the object, and Linear Dimension B to the largest distance between two planes that still contact the object.

39, $p < .001$] than those in the mass conditions (M = 21%, SE = 4%). This means that the availability of mass information contributed to a more accurate volume judgment and resulted in a decrease of the volume biases. Note, however, that these biases were still significant.

Discrimination thresholds. The average discrimination threshold derived from the psychometric curves was 0.97 cm^3 (SE = 0.07 cm^3). The fact that the discrimination threshold was smaller than the absolute average bias of 1.5 cm^3 (SE = 0.15 cm^3) indicates that the biases were of substantial magnitude. The lack of a significant effect of object pair on the discrimination thresholds [$F(2,14) = 0.01$, $p = .99$] revealed that the sensitivity in perceiving differences between objects was independent of the specific geometric objects that were compared. There was no significant difference in discrimination thresholds between the mass and no-mass conditions [$F(1,7) = 0.15$, $p = .71$]. The main effect of reference volume was significant [$F(2,14) = 24, p < .001$]. However, the linear regression analysis showed that the discrimination thresholds increased with an increase of the reference volume only when tetrahedrons and cubes were compared. The slope of that regression line was 0.072 ($p = .04$).

Analysis of the Influence of Geometric Properties

At this point, we can conclude that the physical and the perceived volumes of differently shaped objects are not the same when subjects explore those objects by touch. Which property of the objects is mainly involved in the occurrence of this effect? As was suggested in the introduction, haptic volume perception of different geometric objects may depend on elongation. The geometric objects in the present experiment did not differ only along this linear dimension. Therefore, we also analyzed the possible involvement of some other geometric dimensions that were shared by the objects in the present experiment. To explore some relevant possibilities, the raw data set was expressed in terms of four different values.

1. Linear dimension defined as follows (see Figure 5):
   A. Smallest distance between two parallel planes that can enclose the object. This equals the height of the tetrahedron and the cube and the diameter of the sphere.
   B. Largest distance between two parallel planes that still contact the object. This equals the edge length of the tetrahedron, the space diagonal of the cube, and the diameter of the sphere.
2. Circumsphere radius. This is the radius of the smallest sphere that can contain the geometric object.
3. Surface area.

Table 1 represents the formulas that describe these factors. If the data expressed in any of these parameters do not show significant biases, it would be reasonable to assume that the objects were matched according to that corresponding dimension, although the task was to compare the objects according to their volumes.

Results. Figure 6 displays the average biases for each possible determining factor. The biases for the different reference objects and reference sizes are taken together, since the previous analysis on the volume data did not reveal a significant effect of these variables. The biases expressed in terms of Linear Dimension A ranged from about −38% to 35%, with an average of −6% (SE =

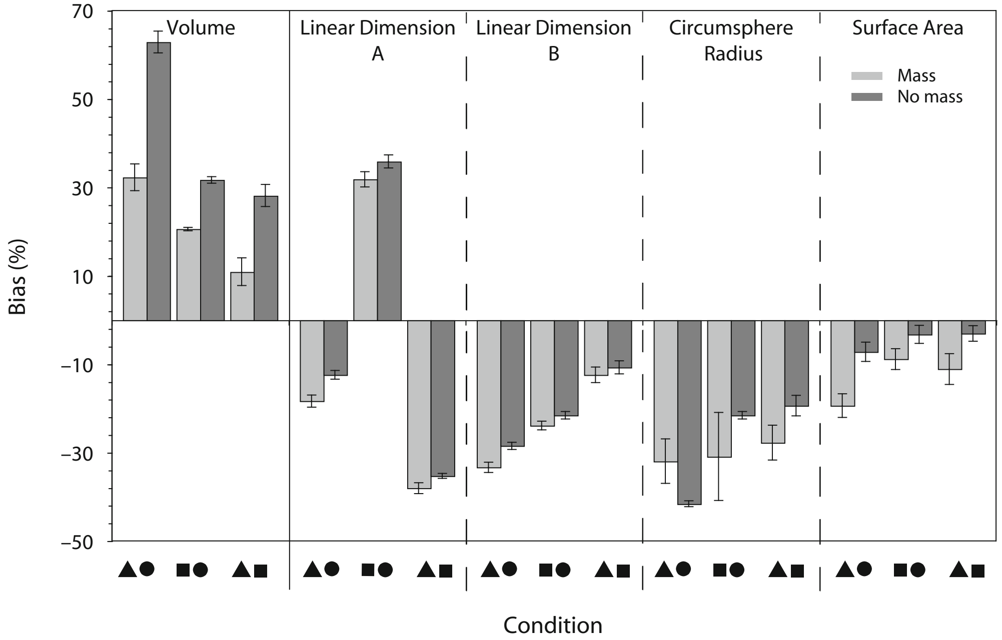

Figure 6. The average biases per condition for the volume data and the data expressed in terms of the longest Linear Dimensions A and B, radius of circumsphere, and surface area. For definitions see the text and Table 1. The error bars represent the standard errors of the means.

11%). Note that the average absolute value of the bias was 29% (*SE* = 11%). The biases expressed in terms of Linear Dimension B ranged from −11% to −33%, with an average of −22% (*SE* = 3%). These biases are still large with respect to the already presented biases expressed in volume, with an average of 31% (*SE* = 3%). Also, the biases expressed in terms of the radius of circumsphere are large—on average, −23% (*SE* = 5%). Hence, it is not likely that any of these dimensions were used for volume judgment by touch.

On the other hand, the biases expressed in terms of surface area resulted in an average bias of −9% (*SE* = 1.4%), as shown in the last column of Figure 6. This figure also shows that the surface area biases in the no-mass conditions are very small, on average −4.5% (*SE* = 1%), whereas those in the mass conditions are somewhat larger, with an average bias of −13% (*SE* = 2%). Statistical analyses performed on these biases showed that the surface area biases are still significantly different from zero ($p < .05$) and that a significant effect of object pair was still present [$F(2,14) = 8.4, p < .005$]. Nevertheless, the surface area biases in both the mass and the no-mass conditions are much smaller than the biases expressed in terms of volume or in terms of any of the other relevant dimensions. This suggests that, in all conditions, surface area information is used as the main factor to determine volume but that the dependence of haptic volume perception on surface area information decreases when mass information becomes available during the task.

Discussion

This first experiment demonstrates the occurrence of large perceptual biases during haptic volume comparison of different 3-D objects. These results support Krishna's (2006) finding that the shape of objects has an influence on their haptically perceived volume. However, her study was concerned with the influence of only one simple dimension of objects: the elongation—or more precisely, the height or width—of two transparent plastic glasses. If the objects from the present experiment are compared according to their height, the height of a cube is almost the same as that of a sphere, and the height of both of them is smaller than that of a tetrahedron. From this, it can be deduced that if elongation were the main factor influencing the volume judgment, the biases for a tetrahedron, as compared with a cube, should be almost as large as the biases for a tetrahedron, as compared with a sphere. The present results showed that comparison of a tetrahedron with a sphere resulted in significantly larger biases than did a tetrahedron–cube or a cube–sphere comparison and that comparison of a tetrahedron with a cube and of a cube with a sphere resulted in almost the same biases. This suggests that linear dimension was not the influential factor for haptic volume perception. This conclusion is supported by the biases from the psychometric data expressed in terms of the linear dimensions: The absolute values were not smaller than the biases from the data expressed in terms of volume.

The contribution of two other dimensions was also analyzed: the radius of circumsphere and the surface area. The first dimension did not show a decrease of the biases. Expressing the data in terms of surface area resulted in much smaller biases. It seems that the subjects' decisions were based on, or at least strongly influenced by, the surface area of objects when they were, in fact, asked to match the volume of these objects. This finding could be related to the cutaneous stimulation that is received when solid objects are explored. Cutaneous stimulation is probably a salient object feature during enclosure of objects. This salience may be analogous to the salience of the longest linear dimension during visual perception of area and volume. It has been theorized that the visual percept of area and volume depends on the most salient dimension, which has been shown to be the elongation of objects (Anastasi, 1936; Frayman & Dawson, 1981; Holmberg, 1975; Raghubir & Krishna, 1999; Stanek, 1968, 1969; Wansink & Van Ittersum, 2003). Along the same line, the most salient dimension of 3-D objects for the haptic volume task was probably the surface area, and that dimension therefore biased the judgment.

The biases expressed in terms of surface area were larger in conditions with mass information than in those without. However, they were still smaller than the biases expressed in any of the other parameters. This suggests that the dependence of volume perception on surface area information decreases when mass information becomes available. Amazeen (1999) already showed that both physical mass and physical volume contribute to perceived volume. In the present study, the additional mass cue may direct attention away from the salient surface area information. The mass cue is then probably used as a second dimension to adjust the initial volume judgment. This adjustment is apparently not sufficient to eliminate the biases, since significant volume biases occurred also with mass information.

Summarizing, the present experiment revealed large effects of shape on haptic volume perception, which decreases somewhat when mass information becomes available. Surface area is probably the geometric dimension that is used to infer haptically perceived volume. This raises two important questions. First, if one uses information about the surface area when judging volume, is haptic perception of surface area itself independent of the shape of 3-D objects? Second, if cutaneous stimulation by the surface area indeed biases volume perception, will the biases decrease when the surface of the objects is removed? The following two experiments focused on each of these questions separately.

EXPERIMENT 2

Surface Area Perception

Studies from the visual domain have shown that shape has a large influence on the perceived area of 2-D figures. It has been shown that triangles are perceived to be larger than circles and squares (e.g., Anastasi, 1936; Fisher & Foster, 1968; Warren & Pinneau, 1955). Furthermore, some studies have concluded that a square is perceived to be larger than a circle (Anastasi, 1936), whereas others concluded the reverse (Fisher & Foster, 1968) or even showed no differences (Warren & Pinneau, 1955). The relative biases found in these experiments ranged from about 6% to about 28%, depending on the nature of the stimuli and on the specific figures that were compared. These studies concluded that the maximum linear dimension of the figures was used as the dependent factor for visual perception of 2-D area. Stanek (1968, 1969) found that this dimension also has an influence on visual surface area perception of 3-D objects. He showed that the surface area of a thin square plate was underestimated, as compared with the surface area of a cube.

Although these effects of geometric shape on visual perception of area have been widely investigated, research linking these effects to haptic perception of surface area is missing. The results from Experiment 1 suggested that surface area information is used to make a distinction between volumes of 3-D objects when they are explored by touch. Therefore, the present experiment examined the effect of 3-D shape on haptic surface area perception.

Method

The setup for this experiment was highly comparable to that in the no-mass conditions in Experiment 1. The main difference was that, in Experiment 1, the subjects had to indicate the objects with the larger volume, whereas in this second experiment, the objects with the larger surface area had to be selected.

The experiment was performed with 8 university students (5 of them male and 3 female; mean age, 20 years), who had not participated in Experiment 1. All the subjects were right-handed, as established by Coren's (1993) handedness questionnaire, and provided written informed consent. The experiment lasted for approximately 2 h, divided into three sessions of about 40 min each. No more than two sessions per day were performed, with a rest period of at least 20 min between them.

Results

Figure 7A shows the surface area biases measured in the present experiment. The overall average bias was 2.4% (*SE* = 2%). The ANOVA performed on these biases revealed no significant effects of reference object [$F(1,7) = 0.58, p = .47$], reference size [$F(2,14) = 0.25, p = .78$], or object pair [$F(2,14) = 3.5, p = .06$]. Although the effect of object pair is not significant, Figure 7A suggests the occurrence of a trend. In all reference size conditions, there seems to be a trend from positive biases in the tetrahedron–sphere condition toward negative biases in the tetrahedron–cube conditions, with the cube–sphere biases in between. Inspection of the individual data reveals that only 4 out of 8 subjects followed this pattern, indicating that this trend is apparently not so strong. Hence, we cannot draw hard conclusions concerning the effect of object pair on surface area perception. Nevertheless, a more important notion is that all these biases are very small, indicating that haptic surface area perception of 3-D objects was quite accurate. Therefore, the relevance of resolving the question concerning a possible effect of object pair on these small surface area biases is negligible. More interesting to the present study is how these surface area biases are related to the volume biases measured in Experiment 1.

In Figure 7B, the surface area biases in the present experiment are plotted next to the volume biases in the no-mass conditions of the volume judgment task. The volume biases in the first experiment—on average, 41% (*SE* = 3%)—were significantly larger than the small surface area biases measured in the present experiment [$F(1,14) = 93, p < .001$]. Hence, the subjects could match the surface area of objects more accurately than their volumes.

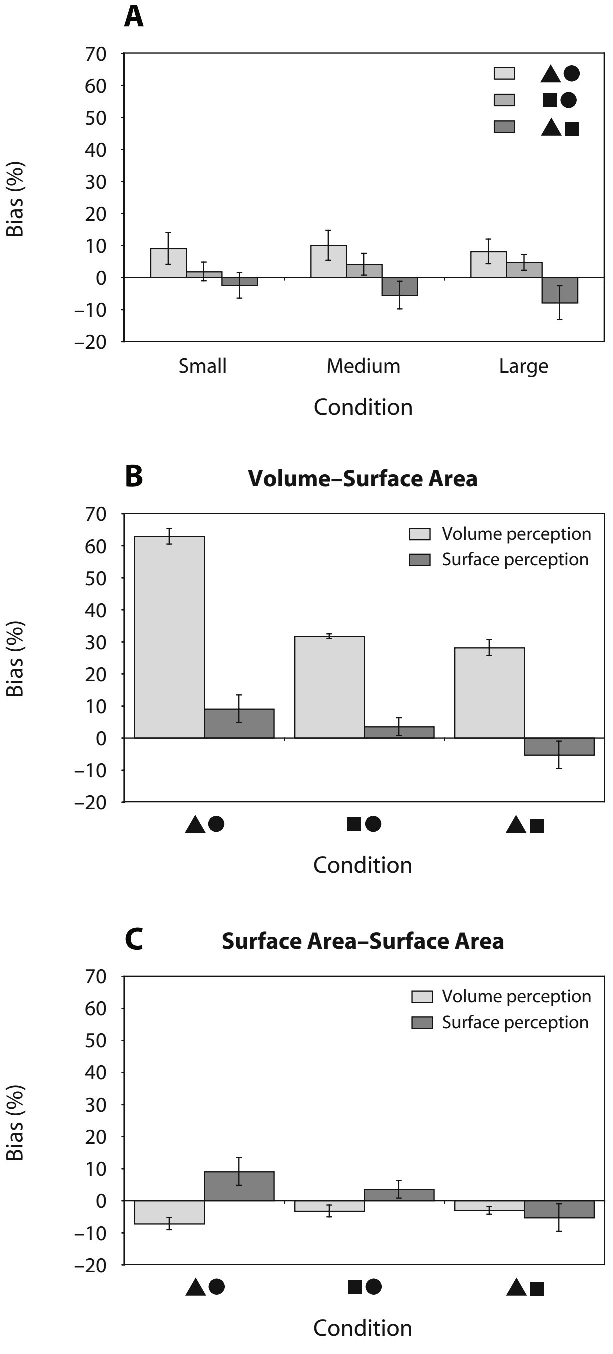

Figure 7. (A) The biases for the different conditions in the surface area judgment task, averaged over the different directions of testing and over subjects. (B) The average biases in the volume and the surface area judgment tasks. (C) The same biases, but now with those from Experiment 1 expressed in terms of surface area. The error bars are the standard errors of the means.

In addition, Experiment 1 has already shown that the biases decreased when the data were expressed in terms of surface area, indicating that the subjects used surface area information in order to judge volume. Figure 7C reveals that the surface area biases in Experiments 1 and 2 were of comparable magnitude. The statistical analysis showed a significant object pair × experiment interaction [$F(2,28) = 5.2, p < .05$]. The post hoc analysis exploring this interaction effect showed that the surface area biases in Experiments 1 and 2 differed only in the tetrahedron–sphere conditions: average biases of −7.2% and 9.0%, respectively.

Discussion

The main conclusion that can be drawn from these results is that the surface area of different 3-D objects can be judged fairly well by touch. The biases for the surface area comparison were much smaller than the biases for the comparison of volume, which were observed in Experiment 1. Subjects are apparently better at comparing surface areas by touch than at comparing volumes. Furthermore, results from Experiment 1 showed that the subjects probably used surface area information to match the volume of objects. The present results support this suggestion by showing that the surface area biases derived in Experiment 1 were of a magnitude comparable to the measured surface area biases in Experiment 2.

Previous studies in the visual domain have shown that the shape of figures has an influence on their apparent area (e.g., Anastasi, 1936; Anderson & Cuneo, 1978; Fisher & Foster, 1968; Warren & Pinneau, 1955). These studies showed that the largest biases occurred when the area of triangles was compared with that of circles. The overestimation of the triangles ranged from 14% to 28% (Anastasi, 1936; Fisher & Foster, 1968; Warren & Pinneau, 1955). These visual biases are larger than the average haptic surface area bias of 9%, which was measured in the present experiment for a tetrahedron–sphere comparison. It seems that surface area of 3-D objects can be perceived more accurately and more independently of other factors by touch than 2-D area by vision.

EXPERIMENT 3
Volume Perception Without Surface Information

In the introduction, we suggested that the influence of surface area on volume perception might be caused by the salience of the cutaneous stimulation by the surface area during enclosure. In that case, elimination of this stimulation should change the observed effect. Attention will then not be captured by the salience of the surface area and, therefore, can be directed more toward the volume itself.

The last experiment in this study investigated this possibility. The stimuli used were a set of tetrahedrons and cubes that were described only by their edges. Hence, there was no physical surface area. The stimuli were compared with each other according to their perceived volume or, more correctly, the volume that is suggested by the wire-frame models.

Method

Nine right-handed subjects participated in this experiment (4 of them male, 5 female; mean age, 22 years), after they had provided written informed consent. None of them had participated in the previous experiments of this study. One of these subjects did not perform the required task, and therefore, it was decided to exclude her data from the analysis.

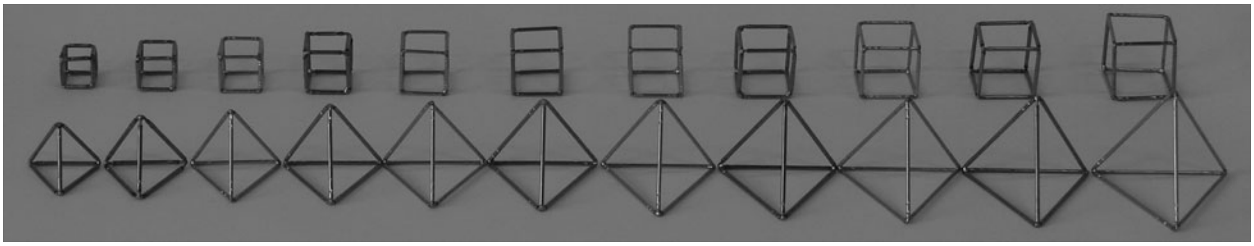

Figure 8. The stimulus set used in Experiment 3.

The setup of this experiment was the same as that for the Experiment 1 block with mass cues. The main difference was the stimulus set. Whereas the stimuli in the previous experiments were solid objects, the ones used in this experiment were wire-frame objects. Furthermore, only tetrahedrons and cubes were used. The sphere could not be used because it does not have edges. The wire-frame objects were constructed by connecting tubes of stainless steel (diameters of 1.6 mm) to each other by corner elements. These were three short pieces of brass wire, which were placed in a fixture to braze them to each other with the proper angle. Subsequently, they were inserted into the tubes, which formed the edges of the objects (see Figure 8). Due to manufacture by hand, not all edges were of exact length. However, this was not an obstacle, because the actual lengths were used for the analysis. Each edge of each stimulus was measured, and the volume of the objects was calculated by taking the average of the edge lengths for each stimulus. The volume[1] of the set ranged from 2 to 13 cm^3, and a small, medium, and large reference volume was used for each object. These references corresponded to the tetrahedron and cube references used in Experiment 1. The total mass of the individual objects in the set ranged from 1.09 to 3.12 g. The mass of the stimuli was determined by the total length of the tubes, the corner elements, and also the amount of brass that was used. This amount of brass and the length of the corner elements could differ independently of the volume of the objects. The difference in mass of subsequent volume stimuli was positive in only about half of the cases. Therefore, we doubt that the mass could be used accurately for the volume judgment.

The experiment consisted of one session, lasting for approximately 40 min. The same procedure was used as during the mass conditions in Experiment 1. The present data were compared with those from both the mass and the no-mass conditions in Experiment 1.

Results

Figure 9 shows the average biases in each of the three reference conditions, measured with the wire-frame objects. The overall average bias of 69% (*SE* = 16%) indicates that a tetrahedron is perceived to be much larger in volume than a cube of the same physical volume. The statistical analysis showed no significant effect of reference object [$F(1,7) = 7.7$, $p = .24$]. The effect of reference size was significant [$F(1,14) = 21$, $p < .001$]. Figure 9 shows that the biases decreased when the size of the objects increases. A regression analysis with the size of objects being a continuous variable showed that this decrease was indeed significant ($p < .05$). The average discrimination threshold for this experiment was 1.1 cm^3 (*SE* = 0.2 cm^3). The discrimination threshold was similar for the two reference objects [$F(1,7) = 0.35$, $p = .57$], and it was not significantly influenced by the size of the references ($p = .09$).

The dashed lines included in Figure 9 represent the biases in the Experiment 1 tetrahedron–cube mass and no-mass conditions. A comparison between Experiment 1 and the present experiment could provide additional insight into the effect of surface area removal on haptic volume perception. The analysis showed that the mass and the no-mass biases measured with the solid objects were significantly smaller [$F(1,14) = 7.2$, $p < .05$, and $F(1,14) = 5.8$,

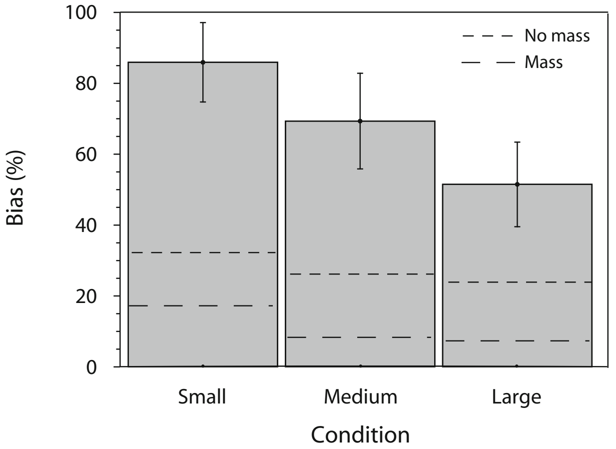

Figure 9. Average biases for the comparison of a wire-frame tetrahedron and cube. The dashed lines indicate the average biases in the Experiment 1 tetrahedron–cube mass and no-mass conditions (with the solid objects). The error bars represent the standard errors of the means.

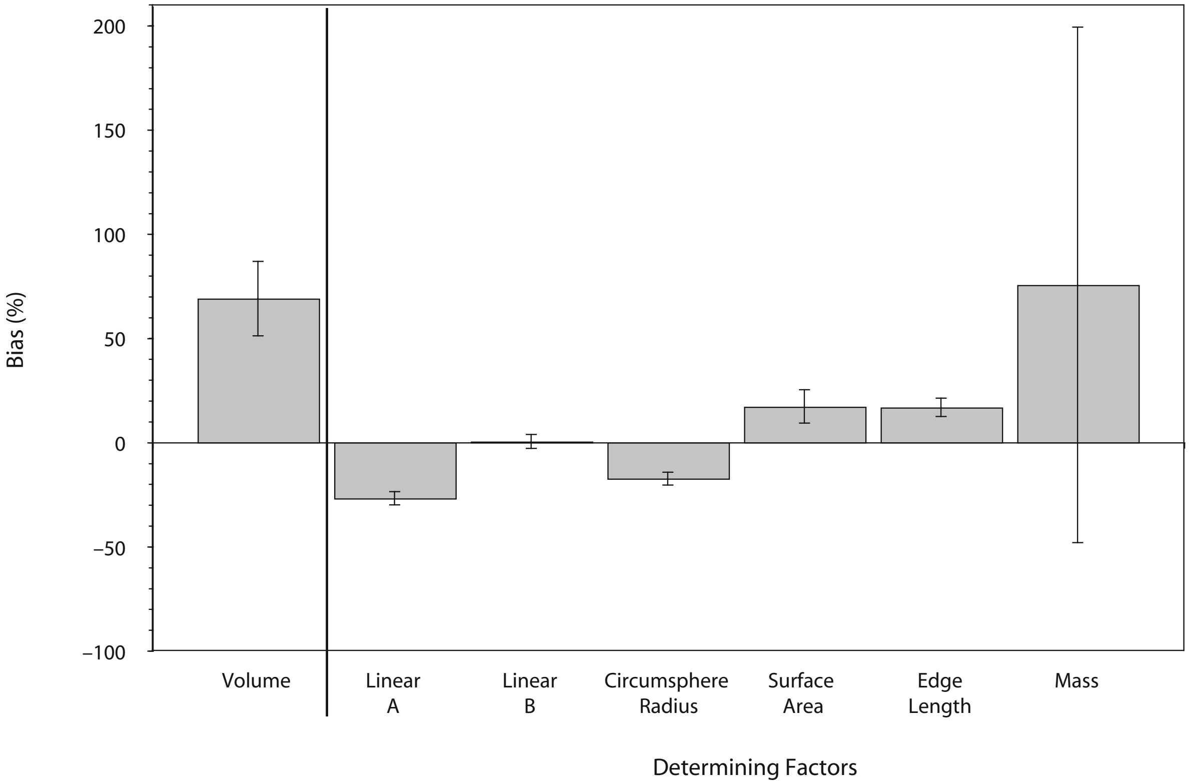

Figure 10. The average bias for the volume data when wire-frame objects were used and the data were expressed in terms of the longest linear dimensions, radius of circumsphere, and surface area. The longest linear dimension was defined as the smallest distance between two parallel planes that can enclose the object (A) and the largest distance between two parallel planes that still contact the object (B). The surface area is the surface area as suggested by the wire-framed models. The edge length is the total length of all edges of an object, and the mass is the total mass of each object. The error bars represent the standard errors of the means.

$p < .05$] than the biases observed with the wire-frame objects, as can be seen in the figure. Hence, removal of surface area information resulted in an increase of the biases. The discrimination thresholds did not differ between the two experiments.

In Experiment 1, we showed that the large volume biases could be explained by the dependence of volume perception on the surface area of objects. The biases measured with the wire-frame objects were also further analyzed to reveal the determining factor on which haptic volume comparison was based when objects without surface area information were handled. Figure 10 shows the biases when the data were expressed in terms of six different factors. The first four factors were the same as those in Experiment 1. Two additional factors may also be relevant when exploring wire-frame objects by touch: the total edge length and the mass.

The figure clearly demonstrates that the maximal distance between two vertices was the factor with the smallest biases. Consequently, this factor was apparently used to compare the volumes of differently shaped wire-frame objects. A one-sample multivariate *t* test showed that the biases expressed in terms of this maximal elongation did not differ significantly from zero ($p > .05$). Furthermore, the large bias and standard error for the mass factor reveal that mass information of the wire-frame objects was indeed not used for the volume judgment.

Discussion

This last experiment in the present study demonstrated that removal of surface area does not result in a more accurate volume judgment. Instead, there is an overall increase of the biases. In contrast to the experiment with the solid objects, the biases for the wire-frame objects are also influenced by the size of the objects. They decrease when the size of the objects increases. Furthermore, the results showed that the maximal elongation of the objects seems to be used during volume comparison in cases in which no surface area information is available. This maximal elongation is defined as the greatest distance between two vertices and corresponds to the edge length of the tetrahedron and the length of the space diagonal of the cube (see Figure 5). Hence, haptic volume perception is still not veridical even in the absence of the salient surface area information.

CONCLUSIONS

The set of experiments presented in this article shows large effects of geometric shape on haptic volume perception of 3-D objects. Large biases are observed when the volumes of a tetrahedron, a cube, and a sphere are compared with each other. The average biases in the different conditions ranged from 7% to 67%. These biases seem to be caused by the subjects' tendency to base the volume comparison on the surface area of objects, and not on their physical volume. Therefore, when one handles objects of the same physical volume, a tetrahedron is perceived to be larger in volume than both a cube and a sphere, and a cube is perceived to be larger in volume than a sphere. These conclusions extend the findings from a study by Krishna (2006), who used objects that differed mainly along their height-to-width ratio and who showed that the determining factor for volume perception is the width of objects. Furthermore, the volume biases decreased when mass information was available during the task—that is, when the objects were held unsupported in the hand. The mass information was probably used as a second dimension in order to adjust the initial volume judgment.

The present study is also the first one to show that one is able to match the surface area of 3-D objects by touch, almost irrespectively of their shape. This almost unbiased haptic perception of 3-D objects' surface area differs from visual 2-D area perception, which is influenced by the geometry of figures (e.g., Anastasi, 1936; Anderson & Cuneo, 1978; Fisher & Foster, 1968; Warren & Pinneau, 1955).

Finally, the present study demonstrates that biases during haptic volume perception increase when the surface area is removed by use of wire-frame objects. This suggests that, although surface area biases haptic volume perception when solid objects are used, perception is not improved by removal of this salient information. Haptic volume perception is still not veridical and is biased by other salient object properties, such as the maximal elongation of objects.

Until now, haptic research has concentrated mainly on object properties, such as shape, length, and diverse material properties (see the review by Klatzky & Lederman, 2002). These dimensions are indeed important, but a complete understanding of the perception of objects requires investigation of all their properties. The present study makes a step in that direction by investigating haptic perception of volume and surface area, properties that have not been studied extensively until now.

AUTHOR NOTE

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NOTE

1. The volumes are in cm^3. The bold numbers indicate the references.

Nominal:	2	3	4	5	6	7	8	9	10	11	13
Tetrahedron:	2.0	**3.1**	3.9	**4.9**	6.1	**7.3**	8.1	9.2	10.3	11.1	13.2
Cube:	2.0	3.1	**3.9**	5.0	**5.6**	7.1	**7.8**	9.1	10.1	10.7	13.1

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