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Inside vs. Outside: Haptic Perception of Object Size*

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***Abstract*— We have performed a psychophysical experiment to investigate differences in perceived object size when exploring the inside or outside of objects. The experiment consisted of five conditions, in which ten blindfolded subjects compared the size of circular disks and holes using either the index finger, two different probes, the finger-span method, or an infinitesimal virtual probe. The result showed significant negative biases for the conditions with the large probe and the finger-span method, meaning that an object felt on the inside should be larger than an object felt on the outside in order to be perceived as the same size. This indicates that subjects are unable to sufficiently correct for the diameter of the probe when exploring objects. At the same time, a general tendency was observed in all conditions that involved movement to feel the inside of objects as larger than the outside. This suggests that, in order to obtain a neutral estimate of object size in a virtual environment, one should use a virtual probe diameter of about 4 % of the size of the object to be explored.**

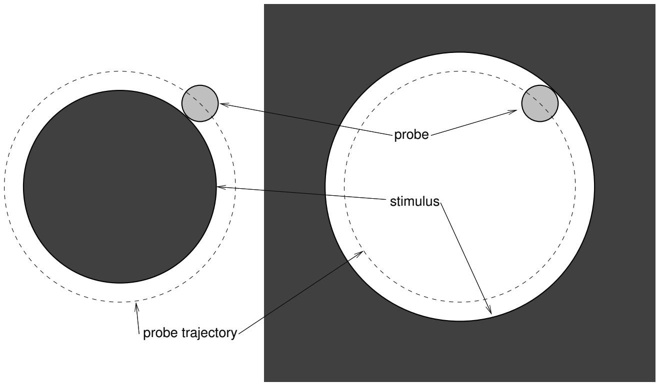

Fig. 1. Top view of circular stimuli (dark grey) being explored with a circular probe (light grey), on the outside (left) and on the inside (right). Due to the probe thickness, the stimulus on the right has to be larger than the one on the left in order to produce the same probe trajectory (dashed circles).

I. INTRODUCTION

THE development of haptic displays makes it possible to interact haptically with remote environments or to explore virtual objects. In these interactions, systematic distortions are observed, for instance in the perceived aspect ratio or orientation of objects [1]. At the same time, people are quite good at judging curvature of virtual objects [2]. When working with a haptic device, often a probe is used to interact with virtual objects. Depending on the software settings, the size of the virtual probe may not coincide with the size of the handle the user is holding: It may be of zero size or any finite size. This contrasts with the situation in real life, in which direct contact with the object is possible. Also, when a probe is used in real life, its size is often immediately known to the user. In order to understand the differences between interacting with real and virtual evironments, it is important to investigate how this probe affects the interaction with objects. In the present paper, we investigated the haptic perception of object size using cylindrical probes of different sizes, and using the fingers. In particular, our central question is, how feeling the inside and outside of objects depends on these different modes of exploration.

When exploring the outside of an object using a probe, the probe describes a larger trajectory than when exploring the inside of an object of the same dimension, due to the thickness of the probe and that of the object "hull". As shown in Fig. 1, in order for the probe to describe the same trajectory, the stimulus that is felt on the inside needs to be larger than that felt on the outside. If the perceived size of the object were based on the probe trajectory, an object felt on the inside should be larger than one felt on the outside in order to be perceived as the same size. However, since the user is holding the probe, s/he can form an estimate of the probe thickness and take this into account when estimating the size of the object. Our question therefore is: How well are people able to correct for different probe sizes when determining object size? Does the type of probe (or using the fingers) affect this ability?

The question can be framed as one of perceptual size constancy. In vision, it is known that equally-sized objects are perceived as such, even when viewed from different distances or orientations [3]. This is known as visual size constancy. In touch, however, it was found that the perceived size of objects depends on the distance or whether the arm was stretched or flexed [4], [5]. Also, perceived curvature was found to depend on distance [6]. Thus, in terms of distance, it appears that there is no haptic size or shape constancy. Still, it is unknown whether there is haptic size constancy for different types of probes or for exploring the inside or outside of shapes.

For answering these questions, we have chosen to use the simplest two-dimensional form: a circular disk. The most natural way of haptically determining the size of such an object is to use the finger-span method, in which the object is held between thumb and index finger. Humans are exceedingly good at discriminating object size using this method, with reported Weber fractions in the order of 0.02

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Fig. 2. Photograph of the stimuli used in the experiment.

for sizes of around 50 mm [7], [8]. Durlach et al. found that for greater lengths (∼ 80 mm), the discrimination thresholds do not continue to increase with stimulus size, as predicted by Weber's law, but level off to a constant value of ∼ 2.5 mm [9]. However, the finger-span method is not suitable when only a single probe or finger is available, as is often the case when interacting with a haptic device. In that case, (a part of) the object's circumference should be explored. Then, both the size and the curvature of the exploration trajectory provide information about the size of the object, and these sources of information can be effectively combined [10]. The fact that with circular forms, strictly speaking, not only object size, but also object curvature contributes to the perception of size, is not a confounding factor, because the two sources of information are affected by probe size in identical ways, as can be seen in Fig. 1. To determine the effect of probe size, we asked subjects to explore the inside and outside of objects using two different probe diameters. For the sake of completeness, we have also included a two-fingered (bidigital) condition which uses the finger-span method, in which only size information is available, and no curvature information. We could have eliminated curvature information entirely by using square shapes, but it was found in pilot experiments that it proved difficult to keep the probe in contact with such objects as it tended to slip off the corners. With circular objects, this problem was avoided.

It has been suggested that people tend to feel the inside of objects as bigger than the outside when the touched surfaces have the same dimensions, and this has been dubbed the *Tardis effect* [11], [12]. This is opposite to what one would expect based on the assumption that size perception were based on probe trajectory: In that case, the inside of an object would feel *smaller* than the outside by the probe diameter. However, there have been found many other sources of information on object shape that influence or override proprioception, for example slip information (movement over the skin) or surface slope [13], [14]. For this reason, it is interesting to see how this effect depends on whether or not a probe is used. Thus, we have included a condition in which only the index finger is used to explore the edge of the object.

Finally, there may be many differences between exploring virtual and real objects with a probe. To assess these differences in the context of comparing the inside to the outside of objects, we have included a condition in which the objects were rendered using a haptic device. This also enabled us to use a probe diameter of zero. All in all, five conditions were included in the experiment: using only the finger, a small-diameter probe, a large-diameter probe, the finger-span method, and a haptic device. The experiment was a guided matching experiment, designed to find the dimensions of the inside and outside of stimuli that were perceptually the same size.

II. METHODS

A. Subjects

Ten naïve subjects participated in the experiment, three males and seven females, aged 21 ± 3 years. Three were left-handed and seven were right-handed, according to Coren's handedness questionnaire [15]. All used their dominant hand in the experiment. After having been given instructions, but before the experiment started, they provided written informed consent. They were paid € 8 for their time. The experiment was approved by the Ethics Committee of the Faculty of Human Movement Sciences, VU University Amsterdam.

B. Materials

The stimuli were seven circular disks, laser-cut from 7.5 mm thick smooth acrylic sheet material, and the seven sheets from which they were cut, 20×20 cm squares with the circular hole in the centre. The disks were 69.5, 79.6, 89.5, 99.6, 109.5, 119.7, and 129.7 mm in diameter, while the holes were 70.4, 80.5, 90.5, 100.5, 110.4, 120.6, and 130.6 mm in diameter. The differences in sizes between the two stimulus types reflect the width of the cut, ∼ 0.9 mm. Since the actual stimulus diameters are used in the analysis, this has no impact on the measured biases. The edges of the stimuli were lightly sanded to avoid damaging the skin when touched. The stimuli are shown in Fig. 2. There were two cylindrical wooden probes, 16.5 cm in length, and 2.5 and 12.0 mm in diameter, respectively. The stimuli were presented on an anti-slip mat on a table in front of the subject.

The virtual stimuli were rendered using a Haptic Master (Moog, Inc.), a very stiff admittance-control haptic device, capable of generating forces up to 250 N. It has a 5 cm diameter spherical handle as an end effector. The stimuli were rendered as the inside or the outside of virtual cylinders (stiffness 20 kN/m, zero friction) with their axis in the horizontal sagittal direction. The diameters were 70.0, 80.0, 90.0, 100.0, 110.0, 120.0, and 130.0 mm. They could be explored between two frontoparallel virtual walls, 50.0 mm

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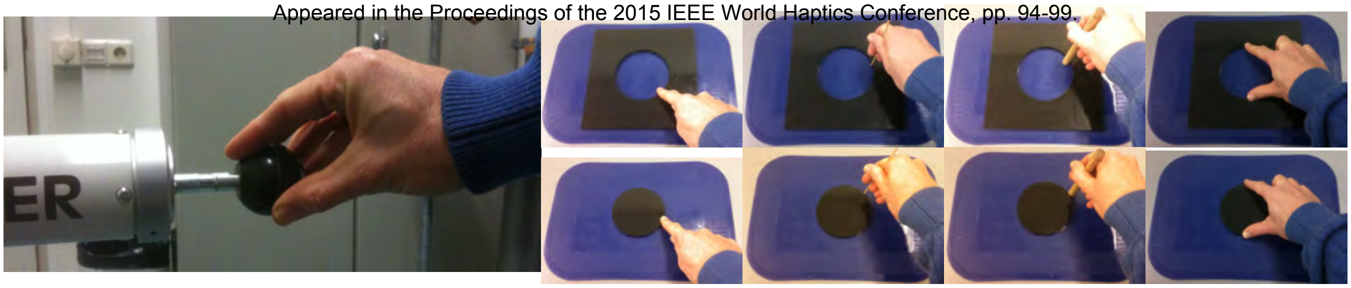

Fig. 3. The five conditions of the experiment: from left to right: the *haptic device* condition, the *finger* condition, the *small probe* condition, the *large probe* condition, and the *bidigital* condition. For the four conditions on the right: the top row shows the *inside* stimuli, while the bottom row shows the *outside* stimuli.

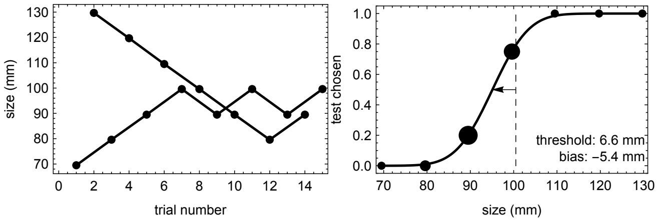

Fig. 4. Example of data from a single subject in the *bidigital* condition with the *inside* reference. Left: the test sizes presented in two interleaved staircase procedures. Right: the psychometric curve fitted to the data. The size of the dots corresponds to the number of times a test stimulus was presented. The dashed vertical line indicates the size of the reference stimulus. The discrimination threshold and bias are indicated. A negative bias in this case means that the stimulus felt on the inside should be larger than one felt on the outside in order to feel equal.

from each other, using a virtual probe of zero dimensions and a virtual mass of 2.0 kg. It is noted that the virtual stimuli were presented in the vertical plane, whereas the real stimuli were presented on a table, in the horizontal plane. This distinction has been made because it felt more “natural” to explore the virtual stimuli in the vertical plane, using a comfortable grip on the handle.

C. Procedure

The experimental task was a two-alternative forced-choice discrimination task. On each trial, the subject was presented with two stimuli, one inside (hole) and one outside (disk), and had to choose the larger of the two. Each trial consisted of one reference stimulus, with a fixed size, and a test stimulus of variable size. A one-up-one-down staircase procedure was used to “zoom in” on the stimuli that were perceptually equal: Whenever the reference stimulus was chosen as the larger one, the test stimulus in the next trial was one step larger. Conversely, whenever the test stimulus was chosen as the larger one, the test stimulus in the next trial was one step smaller. In fact, for each condition, there were four interleaved staircase procedures: two staircases starting from the low end of the test stimulus range, and two starting from the high end. Of these two, one used the hole of 100.5 mm as a reference and the disks as test stimuli (reference: inside), while the other used the disk of 99.6 mm as a reference and the holes as test stimuli (reference: outside). For the virtual stimuli, the 100.0 mm stimulus was used as the reference, both inside and outside. The staircase procedures were interleaved, and the presentation order of test and reference randomised in each trial, so as not to introduce a recognisable pattern for the subject, which might otherwise bias his/her responses. For each condition, 30 trials were performed.

There were one virtual and four real conditions. The conditions are illustrated in Fig. 3. In the *haptic device* condition, the subject held the handle of the haptic device and was instructed to remain in contact with the inside or outside of the virtual cylinder. It was stated that the virtual probe was infinitesimal and that the size of the handle was of no consequence. The subject was allowed to become familiar with the haptic device while not yet blindfolded. Then, the subject donned the blindfold and was allowed one practice trial, before the experiment proper started. In the four real conditions, the subject was shown the stimuli and how to explore them before the start of each block. In the *finger* condition, the subject was to trace the inside or outside edge with the fingerpad of the index finger. In the *small probe* and *large probe* conditions, the subject was to hold the probe in a pen-like grip and follow the inside or the outside of the stimulus. S/he was instructed to keep the probe approximately upright. In the *bidigital* condition, the subject placed two fingers (thumb and index finger) on the inside or outside edges of the stimulus, to statically assess its size (without moving). The experimenter helped the subject to position the fingers correctly. It was always stressed that the comparison should refer to the size of the actual stimulus. The ordering of the four real conditions was different for each subject (using ten randomly chosen permutations of the possible 24), but for practical reasons, the *haptic device* condition was always performed first. The total experiment took one hour per subject to complete.

D. Analysis

For each subject, condition, and reference (inside or outside) separately, the proportion of times that the test stimulus was chosen as the larger one was plotted as a function of the test stimulus size. An example is shown in Fig. 4. A psychometric curve of the form

$$f(x) = \tfrac{1}{2} + \tfrac{1}{2}\mathrm{erf}\left(\frac{x-\mu}{\sqrt{2}\sigma}\right)$$

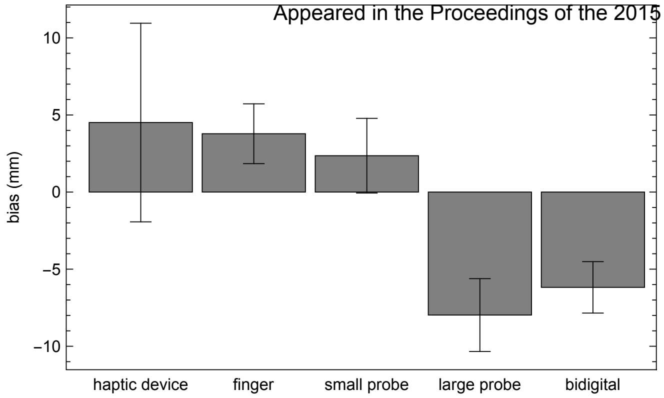

Fig. 5. Average biases found in the five experimental conditions. A positive value means that the stimulus felt on the inside should be smaller than one felt on the outside in order to feel equal. The error bars indicate the standard error of the sample mean.

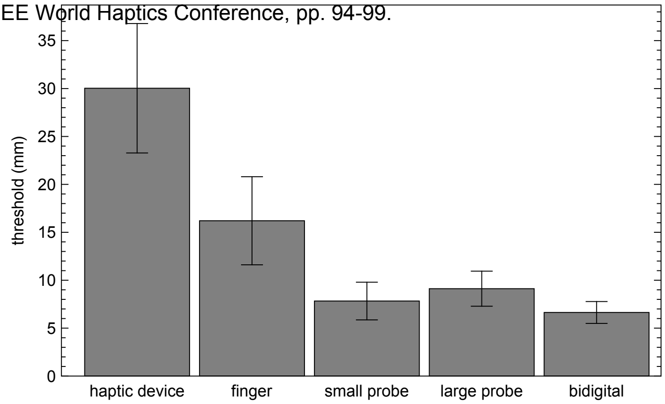

Fig. 6. Average discrimination thresholds found in the five experimental conditions. The error bars indicate the standard error of the sample mean.

was fitted to the data, with μ and σ as free parameters. A weighted least-squares fitting procedure was used, where the weights corresponded to the number of times a test stimulus was presented (indicated by the size of the dots in Fig. 4). The parameter μ corresponds to the Point of Subjective Equality (PSE). The bias is found by subtracting the size of the reference stimulus from the PSE. For each subject and each condition, two bias values were determined: one for the *inside* reference and one for the *outside* reference, usually with the opposite sign. Since the task for the subject was identical for the two reference types, the two biases were combined (averaged) by subtracting the *outside* bias from the *inside* bias and dividing by 2.

To determine whether the biases deviated significantly form zero, Student's t-tests were used. To assess differences between the biases in the four real conditions, a repeated-measures ANOVA was used, with Bonferroni-corrected pairwise comparisons. The *haptic device* condition was not included in the ANOVA because the set-up was different, not allowing for a fair comparison.

The fitting prcedure also yields discrimination thresholds (the parameter σ in the equation) for every condition and subject. These are indicative of the relative task difficulty. It should be noted that, while the chosen staircase method and stimulus values are very suitable for estimating biases, they may be less suited for the precise estimation of discrimination thresholds, so these outcomes should be treated with care.

III. RESULTS

The biases averaged over subjects are shown in Fig. 5. Of the five conditions, only the biases for the *large probe* and *bidigital* conditions are significantly different from zero ($t_9 = -3.4,\ p = 0.0082$ and $t_9 = -3.7,\ p = 0.0049$). They are both negative, indicating that in those conditions, the stimulus felt on the inside should be larger than one felt on the outside in order to feel equal. In the *haptic device* condition, a large range of both positive and negative biases was found, as indicated by the large error bar. As shown below, this condition also had the highest discrimination thresholds, on average 30 ± 7 mm.

When looking at the four conditions involving real stimuli, it is found in the ANOVA that there is a significant effect of condition on the biases ($F_{3,27} = 13,\ p = 0.000021$). Bonferroni-corrected pairwise comparisons show that the bias in the *finger* condition is significantly different from the *large probe* and *bidigital* conditions ($p = 0.011$ and $p = 0.0012$, repectively). Similarly, the bias in the *small probe* condition is also significantly different from the *large probe* and *bidigital* conditions ($p = 0.043$ and $p = 0.0044$, repectively).

Since biases for different subjects seem to be spread out considerably, it is of interest to look at the correlations between the different conditions. Significant correlations were found between the *haptic device* and *large probe* conditions ($R = 0.64,\ p = 0.044$), and between the *small probe* and *bidigital* conditions ($R = 0.71,\ p = 0.019$). Note that these are positive correlations, while the averages in the involved conditions have opposite signs, as visible in Fig. 5. This suggests that although different subjects have different biases, the shift in bias due to the different conditions is fairly consistent over subjects.

Although the biases are of our greatest interest, the measured discrimination thresholds also provide some information: they indicate the relative difficulty of the tasks in the different conditions for the subjects. The average discrimination thresholds are shown in Fig. 6. A repeated-measures ANOVA on the four conditions involving real stimuli shows an effect of condition ($F_{3,27} = 3.1,\ p = 0.044$), but no significant differences were found using Bonferroni-corrected pairwise comparisons.

IV. DISCUSSION AND CONCLUSIONS

In the *haptic device* condition, with an infinitesimal probe, no bias between inside and outside was expected. Indeed, on average the bias was not significantly different from zero. On an individual level, the biases show a large spread and this suggests that subjects have an arbitrary internal model of the dimensions of the probe. However, it seems reasonable to expect that subjects would use an internal model with a *non-negative* probe size, which would result in a negative bias between inside and outside. Still, seven out of ten subjects showed a positive bias, meaning that a shape explored on the inside feels bigger to them than the same shape explored on the outside. This could be consistent with the Tardis effect noted earlier [11], [12]. However, the large value of the discrimination threshold in this condition indicates that subjects found this condition difficult, and the reliability of the biases may be limited. Still, in the *finger* condition, the direction of the effect is confirmed, with eight out of ten subjects showing a positive bias. On average, the bias was 3.8 ± 1.9 mm (or percent), but this was not significantly different from zero. We can say that most, but not all people show a bias consistent with the Tardis effect when exploring a shape with a virtual probe or their finger.

The cause of the described effect can only be speculative at this point. The possible causes would fall into three, non-mutually-exclusive categories. The first category would include top-down effects, where the brain, having no global information about the shape being explored would rely on an internal model that would be updated from highly localised, thus unreliable, sensory information in time and in space. The differential reliability of that information could explain the global perceived size differences. The second category would be related to bottom-up effects where the differences in localised information integrate to different global shapes. The third category could attribute the perceived differences to differences in the sensorimotor task. In effect, exploring a shape from the outside is a mechanically unstable task to which the brain is known to respond by modifying the impedance of the limb(s) by co-contraction [16]. Exploring the same shape on the inside is an inherently stable task, providing the brain with very different sensorimotor information than in the former case.

Regarding the role of the size of a hand-held probe, we note that with an increase of the probe diameter of 9.5 mm between the *small probe* and *large probe* conditions, the average bias shifts towards a negative value by 10 ± 3 mm, a very comparable amount (average±SEM). This suggests that this shift is almost entirely (for $9.5/10 \times 100\,\% = 92\,\%$) due to the probe diameter, and that subjects base their judgement for the most part on the probe trajectory. Apparently, people are largely unable to correct sufficiently for the probe diameter, even though they have the probe in their hand and can thus perceive its size quite easily. This leads to a breakdown of the size constancy principle for haptic exploration with a probe. When compensating for the probe size effect by adding 92 % of the respective probe diameters to the biases found in the *small probe* and *large probe* conditions, values of 5 ± 2 and 3 ± 2 mm are found (average±SEM). These are very comparable to the average bias of 3.8 ± 1.9 mm in the *finger* condition, without any probe, and also consistent with those using the zero-sized probe in the *haptic device* condition. Taken together, the observed biases in these conditions suggest that when the effect of probe size is compensated for, a "natural" overestimation of the inside size of objects of around 4 % remains.

That leaves the *bidigital* condition, in which also no probe was involved, but which shows a significant negative bias. As no movement was involved, this condition is somewhat different from the others. This task boils down to just comparing the distance between the edges felt by thumb and index finger, and is thus not really concerned with the perception of the inside or outside of a shape. Therefore, no inside/outside effect is to be expected. Given that no probe was used, one would also not expect to find a bias caused by the probe diameter. It could be that the observed bias is the result of the way the hand is positioned when touching the edges. To feel the inside edges, the distal phalanges of the fingers may have been tilted slightly more inwards than when feeling the outside edges. The direction of the effect may be then explained by assuming that people base their judgement on the locations of the distal inter-phalangeal joint, rather than the fingertip. Whether this is truly the case should be investigated by further research.

Regarding discrimination performance, the lowest threshold was found in the *bidigital* condition, indicating that the finger-span method (when feasible) is the most precise method for determining object size. The value of the discrimination threshold found here (~ 0.07 mm) is somewhat larger than found in earlier studies [7], [8], [9], but this may be attributed to the unfamiliarity with the task of having to compare an inside edge with an outside edge. The presence of curvature information in the other conditions, which may contribute to size discrimination in circular objects, was not sufficient to get the discrimination threshold below that of the *bidigital* condition.

All in all, we can conclude that haptic size constancy is violated, at least with respect to different probe sizes. The inside/outside effect may have been present in individual cases, but did not reach significance on average. If present, this effect and the probe size effect combine to determine how object size is perceived: With small probe diameters ($<$ 4 mm) or no probe, the inside/outside effect dominates and objects explored on the inside will feel somewhat larger than objects explored on the outside. With larger probe diameters, the probe size effect dominates and objects explored on the outside will feel larger than objects explored on the inside. This is useful information for designers of haptic interfaces: in order to obtain a neutral estimate of object size, they should employ a virtual probe diameter of about 4 % of the size of the object to be explored.

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