Title: Illusory visual completion of an object's invisible backside can make your finger feel shorter

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Summary

In a well-known magic trick known as multiplying balls, conjurers fool their audience with the use of a semi-spherical shell, which the audience perceives as a complete ball [1]. Here, we report that this illusion persists even when observers touch the inside of the shell with their own finger. Even more intriguingly, this also produces an illusion of bodily self-awareness where the finger feels shorter, as if to make space for the purely illusory volume of the visually completed ball. This observation provides strong evidence for the controversial and counterintuitive idea that our experience of the hidden backsides of objects is shaped by genuine perceptual representations rather than mere cognitive guesswork or imagery [2].

Results and Discussion

In a magic routine called multiplying balls, the magician starts by holding a ball between his thumb and index finger (Fig. 1A). Then, after a quick flick of the wrist, a second ball magically appears between his index and middle finger (Fig. 1B). The secret behind this trick is that the first "ball" is actually an empty semi-spherical shell in which the second ball is kept hidden [1]. During the flick of the wrist, this ball is simply flipped out of the shell. In line

24   with the perspective of considering magic as a means to study perception [3–5], we [1] have

25   recently argued that the surprising robustness of this magic trick [6] is due to visual

26   mechanisms creating perceptual representations of the invisible backsides of objects (amodal

27   volume completion [7–10]). Thus, the spectators do not merely entertain the intellectual belief

28   that the semi-spherical shell is a complete ball. Rather, their visual system creates an

29   immediate and compelling experience of a complete ball [1, 7–10], which effectively closes

30   the door to the actual solution before any intellectual problem solving process even starts

31   [11].

32   The notion that our experience of the hidden backsides of objects is based on genuine

33   perceptual representations rather than mere imagery [2, 8, 9, 12–14] is a rather counter-

34   intuitive claim that challenges conventional notions about what it means to see [15, 16]. Here,

35   we present a visuo-proprioceptive illusion ("shrunken finger illusion"), which provides

36   striking evidence for this controversial [17, 18] idea. Putting a semi-spherical shell on top of a

37   finger and viewing it directly from above (Fig. 1C), we observed that the illusion of a

38   complete ball produced the bodily experience of the finger being shorter, as if to make space

39   for the illusory volume of the "ball" (Fig. 1D). In Exp. 1, we estimated the illusory shortening

40   of the finger (see **Experimental Procedures**) by asking observers to point to the felt location

41   of their fingertip while balancing an empty shell on top of it and viewing it from above (see

42   Fig. 2). Using three empty shells with different diameters and a baseline condition without a

43   shell, we observed an illusory finger shortening that increases linearly with the diameter of

44   the shell (Fig. 3). The latter corresponds to the extent of illusory finger shortening necessary

45   to "make sufficient space" for the perceptual completion of the shell into a full sphere

46   (diagonal line). The size of the illusion is less than that, but nevertheless quite substantial.

47   When the observers instead had to point to the top of the shell, the effect was essentially

48   absent (Fig. 3). The difference between the slopes observed in the fingertip condition (0.27)

49   and the top-of-shell condition (0.02) was highly significant ($p < 0.0001$).

50   Additional observations (see **Supplemental Information** and **Figure S1**) indicate that,

51   although the tendency to perceive the shell as a complete ball is strong, the percept may not

52   be stable at all times. This is compatible with the somewhat larger estimates of the effect

53   obtained when ensuring that the shell was perceived as a ball during the measurement: The

54   slope difference was larger (by a value of 0.13, $p = 0.003$) when the observers waited until

55   they definitely perceived the semi-spherical shell as a full ball before pointing (Fig. 3).

56   To further test the explanation based on amodal volume completion, we performed Exp. 2. In

57   addition to an opaque semi-spherical shell, we used a transparent, but otherwise identical

58   shell, and a flat opaque disk. Here, the observers had to point to their fingertip using two

59   different criteria, namely (a) where they *think* it is located based on what they know and can

60   deduce (cognitive condition, CC) and (b) where they *feel* it is located independent of that

61   (perceptual condition, PC). Significant (at the 5% level) finger shortening effects (Fig. 4)

62   were only observed for the opaque shell (PC: $p = 0.00003$, CC: $p = 0.015$, both one-tailed),

63   and it was about 4 times larger in the perceptual than in the cognitive condition (the difference

64   was significant with $p = 0.001$, one-tailed). There were no significant effects for the

65   transparent shell (PC: $p = 0.09$, CC: $p = 0.41$, both one-tailed) or the flat disk (PC: $p = 0.43$,

66   CC: $p = 0.88$, both one-tailed). The latter finding indicates that amodal volume completion,

67   rather than occlusion in itself, is the critical factor.

68   That the effect is only a fraction of the diameter of the "ball" (22% in the "spontaneous"

69   condition of Exp. 1 and 30% with the opaque shell and PC in Exp. 2) may be taken to suggest

70   that the shell is not completed into a full sphere, but rather a smaller object, such as a solid

71   semi-sphere. Such a percept was, however, not reported by any of our observers. Therefore,

72   we regard it as more likely that this reduced effect is due to the conflict with the observer's

73   knowledge about the actual state of affairs. All observers were familiar with the shell before

74   the measurements commenced, which presumably made it obvious to them that the true

75 position of their fingertip was essentially identical to the top of the shell. Thus, in order to

76 report the true extent of the illusion, the observers were required to completely disregard this

77 knowledge. This is a difficult task, making it likely that the measurements obtained here

78 *underestimate* the actual extent of the perceptual illusion. Indeed, some of the observers

79 reported that they had noticed the illusory finger shortening and tried to compensate for it.

80 The observation that the illusory effect in the perceptual condition of Exp. 2 was larger than

81 in Exp. 1 is consistent with this line of reasoning. The fact that we found a small (4 mm) but

82 significant ($p = 0.015$) finger shrinking effect in the cognitive condition, suggests that the

83 observers were not completely successful in separating their cognitive judgments from their

84 perceptual experience. Conversely, it may well be that their settings in the perceptual task

85 were, to some extent, influenced by their knowledge of the real position of the fingertip.

86 Accordingly, even the settings in the perceptual task may underestimate the true size of the

87 effect. Importantly, though, an effect as large as the diameter of the ball is only to be expected

88 if visual mechanisms suggesting a complete ball override the available proprioceptive

89 information about the position of the fingertip *entirely*. Based on common notions about cue

90 integration, the intermediate result we observe here is what one would expect: a compromise

91 between the two contradictory sources of information [19] (visual cues to amodal volume

92 completion and proprioceptive information).

93 Could the observed effect be due to demand characteristics [20]? Several observations speak

94 against this. First, the observed effect is highly counter-intuitive, making it unlikely that

95 subjects would be able to figure out the hypotheses/ predictions. Even to a subject able to

96 correctly guess that the experiment was about visuo-proprioceptive conflict and amodal

97 completion, it would presumably appear more likely that the hypothesis is that the conflict is

98 resolved by perceiving the finger veridically and the "ball" closer. This is essentially the

99 opposite of the observed effect. Secondly, neither (a) the predicted (and observed)

100 presence/absence and directions of the effects in the three conditions, nor (b) the essential

101 aspects of the true hypothesis, were correctly identified by any of the observers of Exp. 2 in

102 post-experimental debriefing sessions.

103 The present findings unequivocally show that our experience of the hidden backsides of

104 objects is sometimes based on genuine perceptual representations rather than mere cognitive

105 guesswork or imagery [2, 8, 9, 12–14, 21], despite the lack of any direct sensory stimulation

106 reaching the eye from the hidden backsides themselves [16]. The effect can be understood as

107 resulting from a process of multisensory integration [22, 23], involving a percept-percept-

108 coupling [24–28], where not only proprioceptive information (as well as assumptions about

109 object solidity/penetrability and the linking of touch sensations to a specific object), but also

110 visual information influences the perceptual representation of body shape. It is well known

111 that somatosensory representations of the size, shape and position of our body parts are highly

112 flexible [29, 30] and that vision often dominates over other modalities in resolving cross-

113 modal cue conflict [19]. As mentioned earlier, the perceptual system could, a priori, equally

114 well have resolved the conflict between vision and proprioception produced in our experiment

115 by making the "ball" appear closer rather than by making the finger feel shorter.

116 Theoretically, one would expect that this alternative resolution of the conflict should be more

117 likely to occur if the reliability of the visual depth cues are sufficiently reduced relative to the

118 reliability of the proprioceptive cues [19]. As can be seen in Fig. 3, the pointing errors in the

119 "point to shell" condition were slightly higher when the observers waited until they were

120 certain that they experienced a complete ball. Although not significant at the 5% level, this

121 may reflect a slight tendency towards this alternative resolution of the conflict.

122 Although the present findings show that visual completion can override proprioception to an

123 impressive extent, modifying the demonstration by balancing the shell on a pencil rather than

124 one's own finger makes it clear that proprioceptive input is a fundamental ingredient in the

125 shrunken finger effect. In this case, the task of reporting the felt (or "perceived") position of

126 the tip of the pencil becomes meaningless and cannot be performed without recurring to

127 explicit knowledge and guesswork rather than immediate perceptual experience.

128 Whilst previous research has shown modification of somatosensory perceptual experience in

129 response to visual stimuli [30], the shrunken finger illusion goes further by demonstrating that

130 purely subjective mental representations of the invisible backsides can have comparable

131 causal powers: Although amodally volume-completed percepts refer to the hidden backsides

132 of objects, our findings show that they are "real" in the sense that they can – even against

133 better knowledge – affect the experience of our own body in a dramatic and almost bizarre

134 way.

135 **Experimental procedures**

136 Detailed descriptions of the experiments are given in the **Supplemental Experimental**

137 **Procedures**.

138 **Stimuli and procedure** In both experiments, the observers were asked to sit as shown in Fig.

139 2 viewing the object (shell or disk) on their middle finger directly from above (binocularly)

140 and point either to (a) where they felt the tip of their finger was located or (b) the top of the

141 shell (only in Exp. 1) using a knitting needle (length 40 cm, diameter 3 mm). The observers

142 were asked to point as if the needle were a laser pointer, while keeping its tip about 10 cm

143 away from the shell. The position pointed to and the true position of the fingertip were

144 estimated based on a semi-automated analysis of photographs made during the pointing (see

145 **Supplemental Experimental Procedures**).

146 Immediately prior to the experiments, the observers participated in related experimental

147 sessions, which are described in the **Supplemental Experimental Procedures**. In total, each

148 experiment lasted about 45 minutes per subject.

149   **Observers** The 22 observers in Exp. 1 were fellow researchers and/or students at KU Leuven,

150   and the 18 observers in Exp. 2 were all students. All observers were naïve regarding the

151   research hypothesis. The students were compensated with course credit or € 8.

152   **Statistical analysis** We performed a linear mixed-effects analysis of the pointing data (Fig. 3)

153   using *R* [31], *lme4* [32, 33] and the *afex* package [34]. See **Supplemental Experimental**

154   **Procedures** for details.

155   All methods and procedures were approved by the Ethical Committee of the Faculty of

156   Psychology and Educational Sciences at The University of Leuven (KU Leuven) and written

157   informed consent was obtained prior to the experiments.

158

Author Contributions

160   V.E. and B.S. designed the experiment, performed the research, analyzed the data and wrote

161   the manuscript. R.V.d.H. performed the research and wrote the manuscript. J.W. designed the

162   experiment and wrote the manuscript.

Acknowledgements

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246 **Figure Legends:**
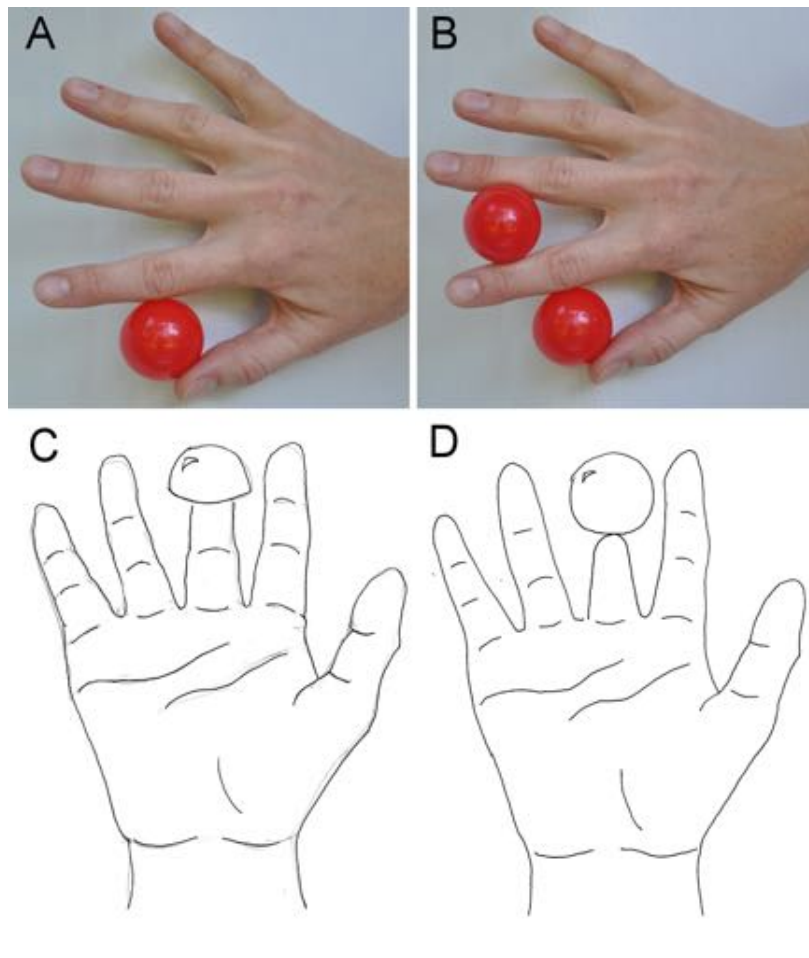
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248 **Figure 1**: **A well-known magic trick and the shrunken finger illusion**. Top: The

249 multiplying balls routine. (a) The magician first holds what seems to be a single ball between

250 his fingers. (b) After a quick flick of the wrist, a second ball seems to materialize. In reality,

251 the lower "ball" is a hollow semi-spherical shell, from which the real ball is pulled out.

252 Bottom: Schematic illustration of the shrunken finger illusion. When a semi-spherical shell is

253 balanced on the observer's finger as shown in (c) and viewed from above, the observer often

254 reports perceiving the shell as a complete ball (d), while his or her finger is felt to be

255 unusually short, as if to make space for the illusory volume of the complete ball. Note that

256 this drawing is an exaggerated caricature of the perceptual experience. In particular, the real

257 effect may be smaller than depicted here. In the experiments, only the middle finger was

258 extended, while the other fingers were closed to a fist (see Fig. 2). Top row adapted from ref.

259 1, licensed under CC BY 2.0 .
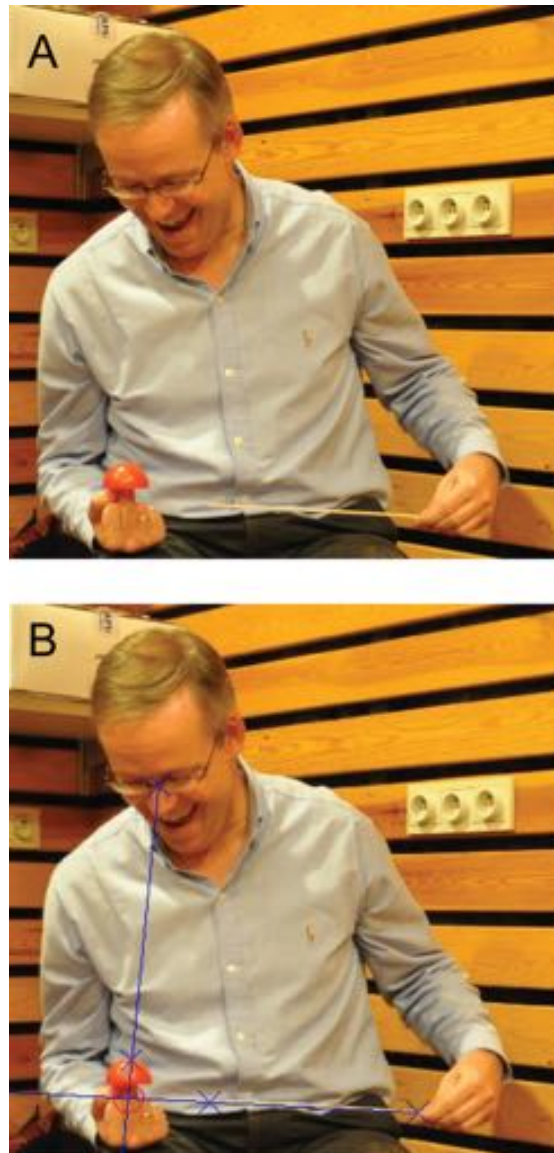
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261 **Figure 2**: **Illustration of the experimental pointing task.** (a) In Exp. 1, the observers

262 viewed the semi-sphere balancing on their extended middle finger from above and indicated

263 the felt position of their fingertip by pointing with a stick held with the free hand. (b) In order

264 to estimate the deviation of the observers' pointing from the true position of the fingertip, four

265   points in the image (blue crosses) were manually identified. The distance from the

266   intersection of the two resulting lines (red circle) and the top of the shell was taken as a

267   measure of the illusion. See **Supplemental Experimental Procedures** for further details.
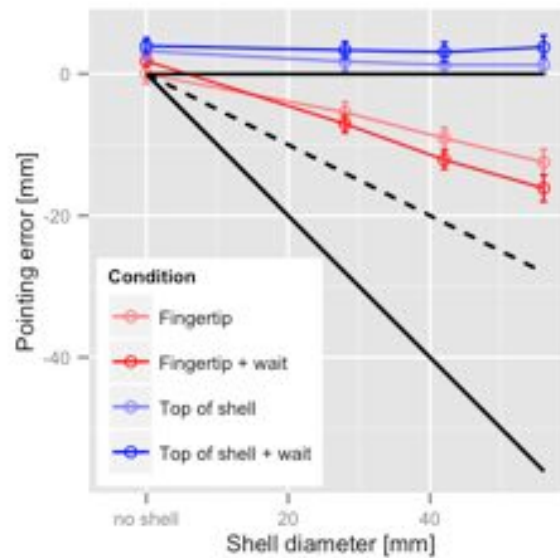
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269   **Figure 3**: **Errors made when pointing to the fingertip increase linearly with the diameter**

270   **of the semispherical shell**. Results from Exp. 1. Average errors made by the observers when

271   pointing to the tip of their fingers (red symbols) or to the top of the shell (blue symbols)

272   plotted against the diameter of the shell. A shell diameter of zero means that observers just

273   pointed to their fingertip without any shell on it, so in this case the task was identical in all

274   four conditions. The black horizontal line represents the true position of the fingertip/top of

275   the shell and the solid diagonal line indicates the theoretical extent of the illusory finger

276   shortening necessary to "make sufficient space" for the perceptual completion of the shell into

277   a full sphere. The dashed oblique line shows the pointing error necessary to "make space" for

278   a solid half-sphere. The strongly colored data point refer to the conditions where the observers

279   were asked to wait until they were sure that they experienced the shell as a complete ball

280   before performing the pointing task. The pale data points refer to the conditions where no

281   such additional instruction was given. Each data point shows the average of 66 settings (22

282   observers x 3 repeated measurements). Error bars represent +- 1 SEM of the pooled data.

283   Where invisible, they are smaller than the symbol size. See also Figure S1.
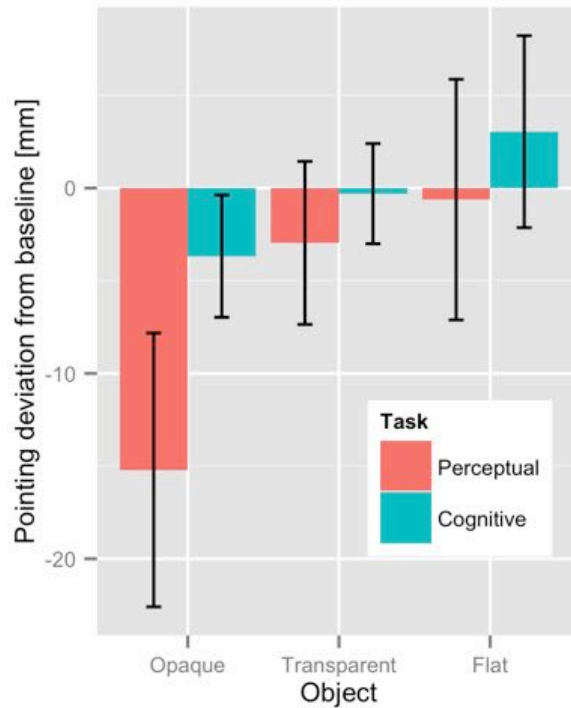
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285   **Figure 4**: **The shrunken finger effect only occurs with an object supporting amodal**

286   **volume completion.** Results from Exp. 2. Average pointing deviations relative to the baseline

287   bias (observed when the observers pointed to the directly visible fingertip without any shell).

288   Negative values indicate a finger shortening effect. The labels on the x-axis refer to the

289   opaque semi-spherical shell, the transparent semi-spherical shell and the flat disk. The error

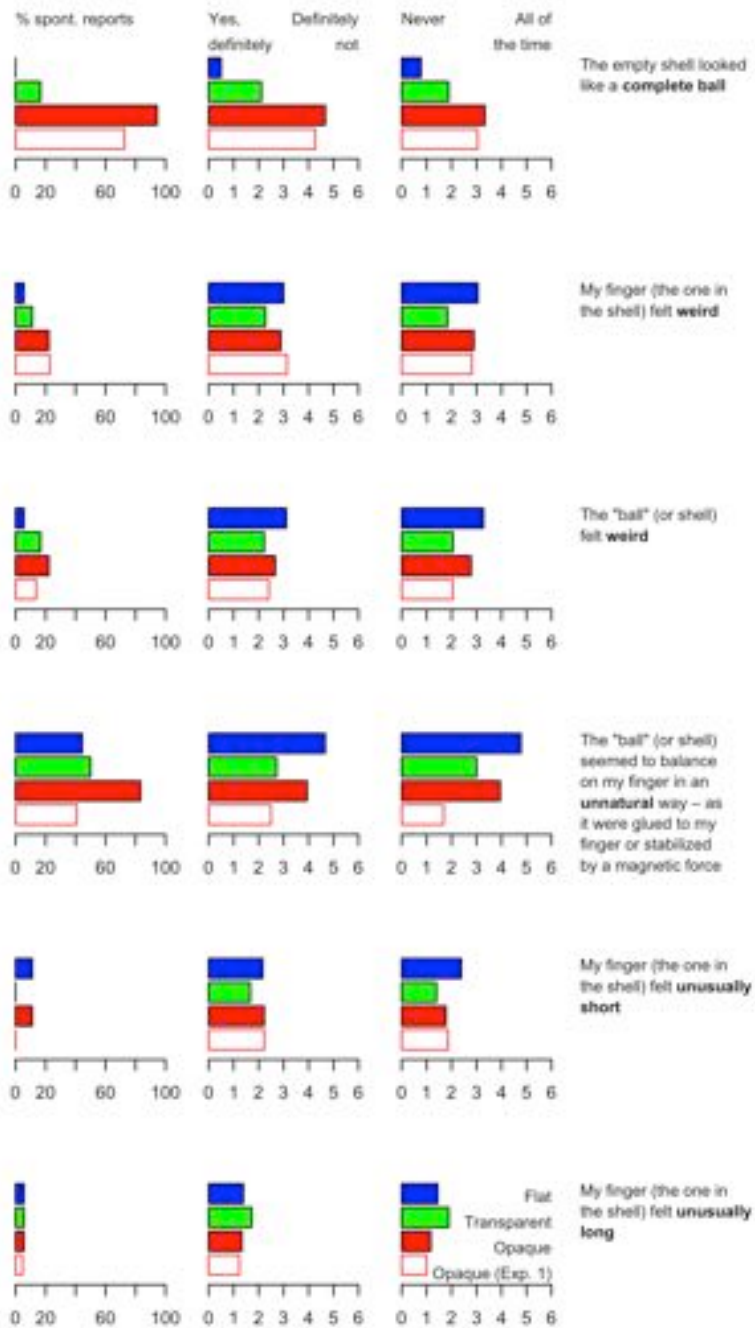290   bars represent 95% confidence intervals. See also Figure S1.

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292   **Graphical abstract:** A graphical abstract is provided separately

293

294   **Supplemental Information:** Supplemental information is provided separately

Supplemental Information

Figure S1: Results from the additional tasks. Related to Figures 3 and 4. Average responses to the items in the structured questionnaire administered in Task 2 of Exp. 1 and 2. The white bar with the red outline shows data from Exp. 1 obtained with the red opaque shell. The other bars show data from Exp. 2 for each of the three objects used. The second column shows responses to the statement "During the experiment, there were times when …" followed by the statements in the right-hand column. Answers were given on a 7-point scale from 0 ("Definitely not") to 6 ("Yes, definitely"). The third column shows responses when asked to "Please indicate roughly how much of the time during the experiment you had the following experiences:" followed by the same statements. Here, the endpoints of the scale were "Never" and "All of the time". The left column shows the percentage of observers who made statements during the free report period that were essentially equivalent to the statements in the questionnaire.

Supplemental Experimental Procedures

The subjects were free to hold the stick with the right hand or the left hand according to their own preference, while pointing to the other hand.

Experiment 1

Stimuli and procedure When the observers signaled that they were pointing to the requested location, a photograph was taken. Each subject completed four blocks of 12 trials, each consisting of trials (3 repetitions) involving three different shell diameters (28, 42 and 56 mm) or no shell at all. The trials were presented in random order. The task of the observers was to point to the position where they felt the tip of their finger to be located ("fingertip condition", blocks 1 and 3) or to point to the top of the shell ("top-of-shell condition", blocks 2 and 4). After blocks 1 and 2 ("spontaneous condition"), the observers were told that the shell may sometimes look like a complete ball, and sometimes just as a semi-spherical shell. In blocks 3 and 4, they were asked to wait until they perceived the shell as a complete ball before pointing to the requested locations ("wait condition"). After completion of all 48 trials, we engaged the observers in a brief informal conversation about their experience of the experiment and, at the end, we informed them about our research hypothesis.

Data extraction The deviation of the observers' pointing from the true position of the fingertip/shell was obtained using a semi-automated procedure, where a colleague who was unaware of the experimental conditions yielding the images inspected each image and manually clicked on four critical points in the image (Fig. 2b). Two points were placed close to the end-points of the pointing stick, thus defining a line along its direction. One point placed midways between the observer's eyes and another one placed at the top of the shell/fingertip defined the line of sight as well as the position of the top of the shell/fingertip. The signed distance from the latter point along the line of sight to the intersection with the pointing line was taken as a measure of the effect in pixels. This measure was converted to absolute displacement in space by multiplication with a factor obtained from a calibration photo of a ruler of known length taken from the same distance. The thickness of the surface of the shells (1.35 mm for the largest and smallest shells and 1.6 mm for the medium-sized shell) was taken into account when computing the actual position of the fingertip.

Statistical analysis We performed a linear mixed effects analysis of the pointing data (Fig. 3) using *R* [S1] and *lme4* [S2, S3]. P-values were calculated using the *afex* package [S4] (function "mixed", with Kenward-Roger approximation for degrees of freedom). The model included ball diameter, task and experimental phase (spontaneous pointing vs. wait-for-ball-percept) and all their interaction terms as fixed effects. The random effects included random intercepts and random slopes for all main effects. An initial modeling attempt included random slopes for all interaction terms as well but this model produced convergence warnings. Therefore, the interaction terms for the by-subject random effects were left out in the final model. It should be noted that all conclusions about statistical significance on the fixed effects (at the 5% significance level) were the same for both models considered.

Experiment 2

Stimuli and procedure As in Exp. 1, the observers participated in related experimental sessions immediately prior to the experiment, which are described in the Supplemental Information. In addition to an opaque, red semi-spherical shell similar to the ones used in Exp. 1, we also used a transparent, but otherwise identical shell, and a flat disk (opaque and red). All three objects had a diameter of 51 mm. The flat disk was attached to the observer's fingertip using a small piece of adhesive gum. Because is difficult to keep the disk perfectly level, the true position of the finger is difficult to ascertain based on a photo taken while the disk is balancing on the observer's fingertip. For this reason, each measurement was based on two photos. When the observer indicated that he or she was pointing to the fingertip, the first photo was taken. The observer then remained immobile for a few seconds, while the experimenter removed the object, such that a second photo could be taken with the finger in full view. For consistency, this procedure was employed in all conditions. Three blocks of measurements, one for each of the three objects, were completed in counterbalanced order across observers. In the first and second half of each block, the observers were asked to indicate the position of their fingertip according to the cognitive and perceptual criteria, respectively (see main text). Each half-block consisted of 6 trials: 3 repeated measurements using the target object, each preceded by a "baseline" measurement where no object was used.

After completion of the experimental session (36 trials) we informed the observer that the experiment was now completed, but that we were curious to know what he or she thought the purpose of the experiment might be. We laid all of the three objects on the table in front of the observer and asked them to tell us what they thought (a) our hypothesis was and (b) what kind of result we expected to obtain.

Data extraction The deviation of the observers' pointing from the true position of the finger was obtained using essentially the same semi-automated procedure as in Exp. 1. As explained above, however, the true location of the fingertip was obtained from a second photograph in which the finger was not occluded by any object.

Statistical analysis We analyzed the pointing data (Fig. 4) with a linear mixed model including fixed and by-subject random effects using R [S1] and lme4 [S2, S3].

Additional tasks

Prior to each of the two pointing experiments described above, all observers performed two related experimental tasks. In the case of Exp. 1, these tasks were only performed with a red, opaque semi-spherical shell. In Exp. 2, they were also performed with two additional objects: a transparent semi-spherical shell and a flat (red and opaque) disk.

Task 1 In the first part of the experiment, the observers were asked to sit as shown in Fig. 3 with one of their hands resting on their lap, extending their middle finger upwards and viewing it straight from above. They were then told that the experimenter would put a small and harmless plastic object on their finger while they kept their eyes shut. Their task was to report, as quickly as possible, after being told to open their eyes, what kind of object it is. The responses of 17 of the 22 subjects (77 %) in Exp. 1 and 10 of the 18 subjects (56%) in Exp. 2 indicated that they spontaneously mistook the opaque shell for a complete ball. None of the observers mistook the flat disk for a ball, but one of the 18 observers mistook the transparent shell for a (transparent) ball. Note that, in cases where the observers' responses did not literally refer to a ball or a semi-sphere, we categorized them according to the typical shape of the named objects. For instance, "a tomato" was coded as a complete ball, while "a clown's nose" was not, as it typically has an opening at the back.

Task 2 After having stated their response, the observers were allowed to inspect and manipulate the object freely, seeing that it was in fact just a hollow shell (or flat disk). They were then asked to put the object back on their finger and experiment freely with it for two minutes while reporting on any unusual or interesting aspects of how the object looked or how their finger felt. It was suggested that they could wiggle their finger as well as look at their finger from different angles. All responses ("free reports") were recorded on audio for later analysis. After the two-minute period, the observers completed a questionnaire referring to the six statements shown in **Figure S1**. On the first page of the questionnaire, the general form of the question was "During the experiment, there were times when …" followed by each of the six statements. Answers were given on a 7-point scale from 0 ("Definitely not") to 6 ("Yes, definitely"). The second page of the questionnaire was identical to the first, except for the general form of the question ("Please indicate roughly how much of the time during the experiment you had the following experiences:") and the definition of the 7-point scale (0="Never", 3="Half of the time" and 6="All of the time"). The average responses are shown in the second and third column of **Figure S1**. The left column of **Figure S1** shows the percentage of observers that made spontaneous statements during the free report period that were essentially equivalent to the statements used in the structured questionnaire.

As can be seen in the left column of **Figure S1**, very few of the subjects spontaneously reported the finger shortening during the free report phase using the opaque shell (None of the 22 subjects in Exp. 1 and only 2 of the 18 subjects in Exp. 2). There was a small tendency to report finger shortening in response to the explicit questions of the questionnaire, but comparable small tendencies were also observed for the transparent shell and the flat disk. Viewed in connection with the results from the pointing experiments (see Figs. 3 and 4 in the main text), where we observed a substantial finger shortening effect that was unique to the opaque shell, this may be taken to suggest that although the effect can be quite stunning once one attends to it, it does not have any attention-grabbing pop-out quality. Normally, one does not attend to how long one's limbs feel, so the observers may simply not notice it unless they are explicitly asked about it. Note that the explicit question in Task 2 was only asked after termination of the observation phase. Thus, if the observers had failed to attend to their finger length, they had no chance to do so retrospectively.

Baseline bias

In the pointing data of both Exp. 1 and Exp. 2, we observed a baseline bias in the sense that the observers tended to point slightly above their fingertip when they viewed their finger directly (without any shell). While this baseline bias was small (2 mm) in Exp. 1, it was substantially larger (7 mm) and clearly not a random deviation from zero in Exp. 2 ($p = 0.00002$, two-tailed). This difference may be explained as follows: It seems that the observers exhibit (a) a general tendency to hold the stick slightly slanted upwards toward the tip, and (b) a general tendency to underestimate the amount of deviation from the horizontal (which taken together produces an upward bias). The latter tendency seems to be stronger in Exp. 2 due to a slight difference in posture, which made it more difficult to perceive the true slant of the stick, which would explain why the upward bias is stronger in Exp. 2. While the average horizontal distance between the fingertip and the tip of the pointing stick

was comparable in both experiments (Exp. 1: 88 mm, Exp. 2: 90 mm), the horizontal distance from the eyes (their midpoint) to the pointing stick (its tip) was substantially larger in Exp. 2 (80 mm) than in Exp. 1 (38 mm), which can be expected to make it more difficult to perceive the slope of the stick accurately. The average slope with which observers actually held the stick was not much larger in Exp. 2 (0.073) than in Exp. 1 (0.059). In both experiments, a linear regression analysis of the data from the baseline conditions (where no object occluded the finger) indicated that the upward bias increased with the slope of the stick and was close to zero when the stick was actually horizontal. Compared to the regression line obtained in Exp. 1 ($b = 45s - 1.3$, where b is the upward bias in mm and s is the slope of the stick), however, the one observed in Exp. 2 ($b = 69s - 2.4$) was steeper by a factor of 1.5, which is consistent with the idea that it was more difficult to perceive (and to take into account) the actual slope of the pointing stick in Exp. 2 due to its more peripheral position in the observer's field of view.

Supplemental References List

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