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Tool use produces a size illusion revealing action-specific perceptual mechanisms

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ABSTRACT

In four experiments, participants estimated the sizes of target objects that were either out of reach, or that could be reached by a tool (a stylus or laser pointer). Objects reachable with the aid of a tool were perceived to be smaller than identical objects without a tool. Participants' responses to questioning rule out demand characteristics as an explanation. This new size illusion may reflect a direct impact of tool use on perceived size, or it may stem from the effects of tool use on perceived distance. Both possibilities support action specific accounts of perception.

Our perceptual systems serve the primary purpose of providing information about the environment in order to allow us to effectively navigate through it and interact with the objects that are in it. There are numerous examples that show that perception is affected by the perceiver's physical abilities to act on the environment. For example, hills look steeper when wearing a heavy backpack (Proffitt, Stefanucci, Banton, & Epstein, 2003), softball players that are hitting better perceive the ball to be bigger (Witt & Proffitt, 2005), and apertures to be walked through look smaller to people who are holding a rod that increases their overall width (Stefanucci & Geuss, 2009; for reviews see Brockmole, Davoli, Abrams, & Witt, 2013; Witt, 2011a). According to the action-specific account of perception (Proffitt, 2006; Witt, 2011a) this scaling of the environment serves the purpose of taking into account the costs (e.g., metabolic demands) or dangers (e.g., risk of injury) of a contemplated action. Indeed, participants who are glucose-depleted judge distant targets to be further away than participants who are not (Schnall, Zadra, & Proffitt, 2010; Taylor-Covill & Eves, 2016; Zadra & Proffitt, 2016; Zadra, Schnall, Weltman, & Proffitt, 2010).

One interesting finding that supports the action-specific perception account is a *tool use effect*. For example, Witt, Proffitt, and Epstein (2005) had participants estimate the distance to a target that was beyond reach. Participants either used a tool (a conductor's baton) to reach out to the target or they pointed to the target by hand. The target appeared to be closer when participants wielded the tool. A similar tool use effect has been shown when the tool used to "reach" the target is a laser pointer (and only the projected laser can reach the target; Davoli, Brockmole, & Witt, 2012), and when a person merely observes an actor use a tool but does not have a tool of their own (Bloesch, Davoli, Roth, Brockmole, & Abrams, 2012; see also Abrams & Weidler, 2015). These results show that visual processing can change when one's action capabilities are enhanced by a tool. Presumably, targets that are out of reach would appear further away to reflect the increased costs of interacting with such targets.

Nevertheless, these interpretations have not been without their critics. In particular, it has been suggested that action capabilities may sometimes influence only an individual's *responses* in an experiment, but not their perception (Durgin et al., 2009; Woods, Philbeck, & Danoff, 2009). In support of this, Durgin et al. (2009) showed that people reported an inclined ramp to be steeper when wearing a heavy backpack, but only when they believed that the backpack was a critical manipulation of the experiment. Based on this, Durgin et al. (2009) argued that demand characteristics of an experiment can bias participants' responses to mimic an effect of action capabilities on perception. Firestone (2013) has also argued that action capabilities influence response bias, but not perception per se.

In order to minimize the influence of demand characteristics on assessment of the effects of tool use, some researchers have asked participants to make judgments that are only indirectly connected to the perceptual dimensions that are thought to be affected. For example, Witt (2011b) used a shape-matching task instead of the distance estimation tasks that often had been used in earlier studies. In her study, participants viewed three circles in a triangular shape projected onto a table as shown in Fig. 1. Participants were asked to adjust reference circles presented on a separate display to reproduce the shape of the triangle on the table. When a tool was used to touch the distant circle at the top of the triangle on the table, the response triangle had a

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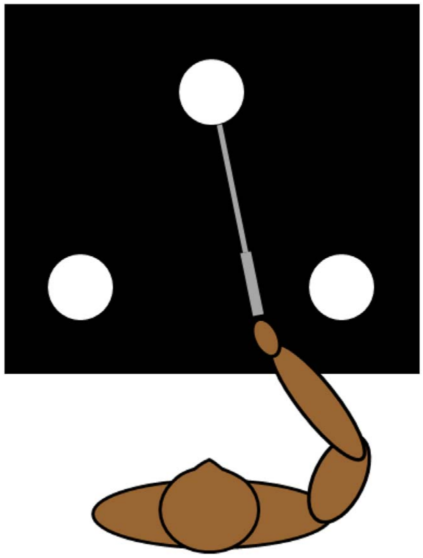

Fig. 1. Setup used by Witt (2011b) to study the tool use effect.

compressed shape compared to when the tool was not used, suggesting that the top of the triangle appeared closer with the tool. Witt argued that this finding is unlikely to reflect demand characteristics because participants would be unlikely to predict that tool use should change the perceived shape of the triangle. Instead, the findings are consistent with a truly perceptual effect of tool use.

Nevertheless, it is not inconceivable that a participant might infer the hypothesized change in shape. For example, if one thought that a tool would cause a touched object to appear closer, then it is not too difficult to create a shape that fulfills that expectation in much the same way that some have argued that distance judgments fulfill participant expectations (e.g., Durgin et al., 2009). Thus, in the present study, to learn more about the perceptual consequences of tool use we employed a judgment that not only is an indirect consequence of a distance change as are the shape judgments used by Witt (2011b), but which also typically leads to an inverted effect when people reason about it. In particular, we asked people to make judgments about the *sizes* of objects that were either reached or not reached by a tool. Perceived size depends upon perceived distance due to size-distance invariance (Epstein, 1963). As illustrated in Fig. 2, given two objects with equal retinal sizes, the one that is closer must also be smaller. So if use of a tool to reach an object that is beyond one's unaided reach causes the object to appear closer, the object should also appear smaller.

Size-distance invariance provides a partial explanation for many common size illusions, such as the moon illusion or the Ponzo (railroad tracks) illusion. In these illusions, one of two equal-sized objects is perceived to be larger than the other due to the (incorrect) perception that the object is further from the viewer. Importantly, when asked to reason about the size-distance relationship, many observers make the opposite prediction. We present support for that in Experiments 2b and 3, below. Anecdotally, many undergraduate students exhibit confusion about the reasoning underlying one explanation of the moon illusion: “The moon looks bigger when near the horizon because it appears *further* away there? Shouldn't it look smaller if it was further away?”. Given this sort of reasoning, a change in perceived size in the hypothesized direction would be unlikely to stem from demand characteristics. Size judgments have been used as an indirect measure of perceived distance (specifically height) in several studies and the patterns of results correspond closely to results obtained using explicit estimates of distance (Stefanucci & Proffitt, 2009; Stefanucci & Storbeck, 2009).

In the present study participants viewed target circles of various sizes with or without a reach-extending tool (a stylus in Experiments 1,

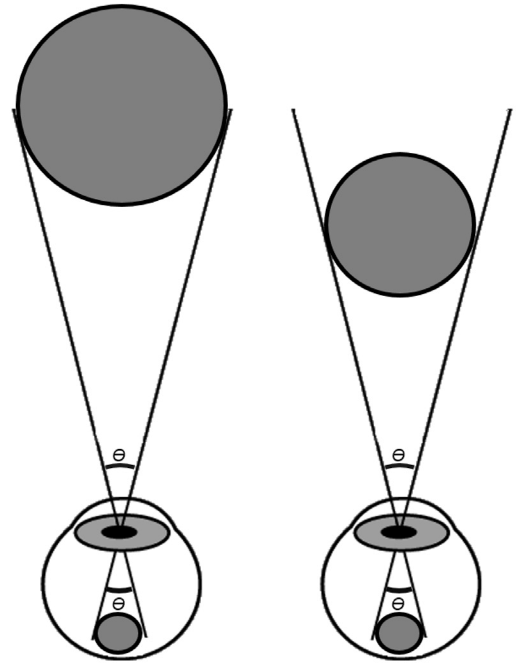

Fig. 2. Effect of perceived distance on perceived size, based on size-distance invariance. The proximal size of the target (θ) is identical in both cases, so the closer object must also be smaller.

2a and 2b, and a laser pointer in Experiment 3). The target circle was presented at a fixed location during the experiment. In a *tool* condition, participants had to briefly tap (with a stylus) or illuminate (with a laser pointer) the target circle at the beginning of each trial. In a *no tool* condition, they were asked to point toward the target circle using their hand or a non-functional laser pointer. Following the pointing, participants were asked to estimate the size of the target circle by matching the size of an adjustable reference circle.

1. Experiment 1

1.1. Method

1.1.1. Participants

Twenty-four participants (14 females) from Washington University in St. Louis participated to fulfill a partial requirement for course credit. All of them had normal or corrected-to-normal vision.

1.1.2. Apparatus

Fig. 3 shows the experimental setup. All stimuli were projected onto a screen (158 cm × 187 cm) on the floor of a dimly lit room. Stimuli were presented, and responses recorded using Psychopy software (Peirce, 2007). Participants sat on a chair positioned on one side of the short edge of the screen. A wireless keyboard was placed on a table on the side of the participant's non-dominant hand for recording responses.

1.1.3. Stimuli and procedure

Each trial began with the appearance of a yellow circle (the *target circle*) on the screen (see Fig. 3). The circle was aligned to the participant's midline, and was 99 cm away–beyond the reach of the hand. The target circle was shown in one of four sizes (31.0 mm, 38.7 mm, 46.4 mm, or 54.2 mm in diameter). In the *tool* condition, participants were asked to briefly tap the target circle with a stylus (65 cm long) held in their dominant hand. In the *no-tool* condition, they were asked to simply point at the target circle with their index finger. In both conditions, participants had to reach their arms toward the target circle, thus the only difference between two conditions was whether they

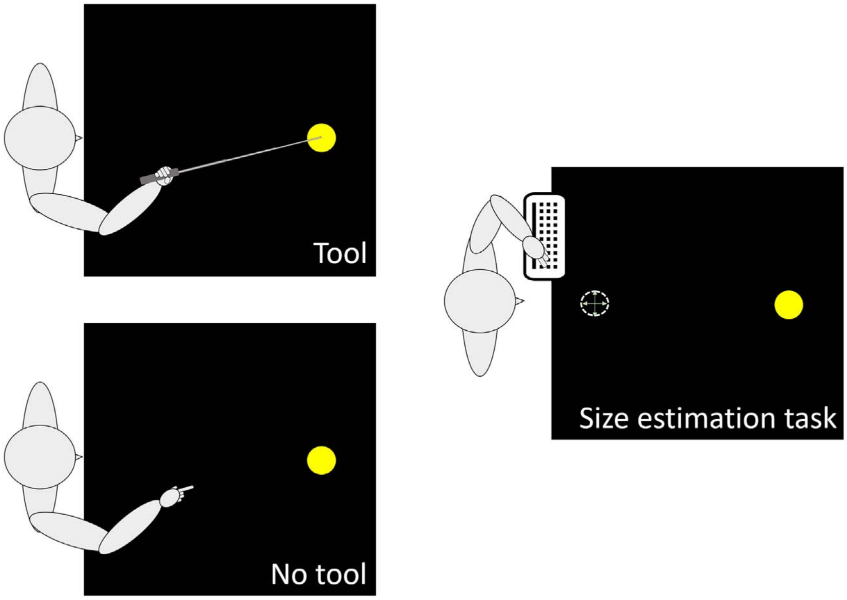

Fig. 3. Schematic illustration of tool and no tool conditions in Experiments 1 and 2. In the tool condition, participants were required to briefly tap the target circle using a stylus. In the no tool condition, they were asked to simply point at the target with their index finger. Following the pointing, a response circle (dashed circle in the right panel) appeared and they had to adjust the size of it to match the size of the target circle.

could physically touch the target circle or not. One second after target presentation, a response circle appeared 21.75 cm from the participant. The response circle was unfilled, with a dashed white border, and its initial diameter varied randomly between 7.74 mm and 77.39 mm. Participants were asked to adjust the size of the response circle to match the size of the target circle by pressing the up and/or down arrow keys on the keyboard (each key press increased or decreased the diameter of the response circle by 4.6 mm); they pressed the spacebar to register their response. The target circle remained visible during the adjustment of the reference circle.

1.1.4. Design

Each participant completed one practice block and eight experimental blocks. Each block consisted of 16 trials in which each target size occurred equally often (4 sizes × 4 repetitions). The tool condition was manipulated between blocks with the order of tool conditions counterbalanced across participants. Half of the participants used the tool in the first 4 blocks, and then switched to no-tool for the last 4 blocks. The other participants completed the conditions in the opposite order. In addition, we conducted an informal post-experiment interview in order to explore the relation between participants' subjective beliefs and their behavior. During the interview, the experimenter posed two questions to the participant: (1) *Can you guess what was tested during the experiment?*, and (2) *Did you feel any difference in the [*dimension named in the first question*] of the circles between when you were using the stylus and not using it?* Participants were asked to give a verbal response to each of the questions, and the experimenter noted their answers.

1.2. Results

Results are shown in Table 1. The perceived size was indexed by the diameter of the response circle when the participant submitted their response. As seen in the table, the perceived size of the target circle increased as the actual size of the target circle increased, $F(3, 69) = 1569, p < 0.001, \eta_p^2 = 0.99$. Importantly, the perceived size of the target circle was smaller in the tool condition (with a reach-extending tool) compared to the no-tool condition (where participants pointed only by hand), $F(1, 23) = 6.193$, $p = 0.021$, $\eta_p^2 = 0.21$. This is illustrated in Fig. 4, which shows the difference in perceived size between the tool and no-tool conditions, as a function of target size. The positive differences for each target size indicate that the tool caused the target to look smaller. There was no interaction between the effects of target size and tool condition, $F(3, 69) = 1.630$, $p = 0.190$, $\eta_p^2 = 0.07$, showing that the effect of tool use was numerically equivalent across the different target sizes.

Since participants overestimated the size of the target (i.e., the

Table 1
Mean perceived size (diameter of response circle; mm) as a function of tool condition and target diameter in Experiment 1.

	Target diameter (mm)			
	31.0	38.7	46.4	54.2
Tool	33.09	41.06	47.64	54.67
No tool	34.21	41.64	48.20	55.12

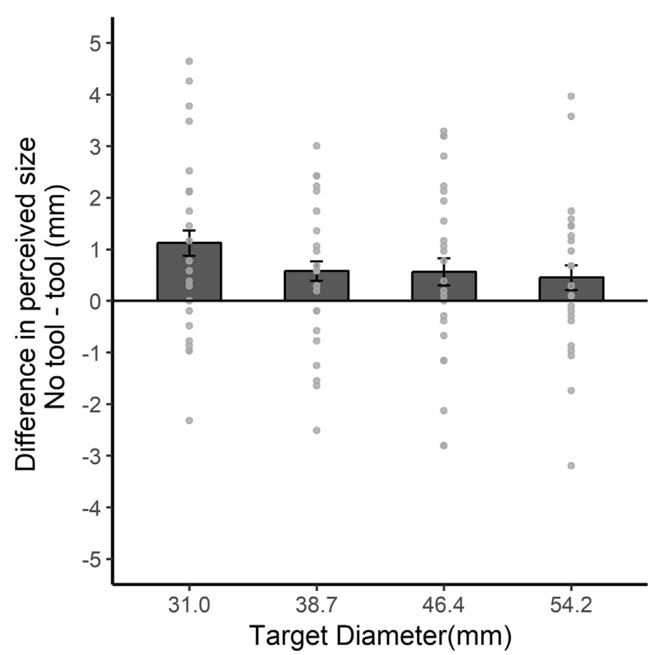

Fig. 4. Difference in perceived size (no-tool − tool) of the target in Experiment 1. Positive values indicate that perceived size was smaller with a tool than without a tool. Points show individual subjects; bars show the mean; error bars depict within-subject standard errors.

Table 2
Participants' answers from the post-experiment interview in Experiment 1.

Question 1 response (What was experiment testing?)	Question 2 response (What effect did tool have on the tested dimension?)	N (total = 24)
Size perception	More accurate with the tool	6
	Less accurate with the tool	2
	Smaller with the tool	1
	Faster judgments with the tool	1
	No answer	3
Distance perception	More accurate with the tool	4
	Less accurate with the tool	1
	Closer with the tool	1
	No answer	3
No answer		2

estimated sizes were always bigger than the actual sizes), it is possible that the smaller perceived size with the tool represents enhanced accuracy in the size estimation task. In order to examine the effect of tool-use on accuracy, the absolute error for each subject (|mean actual size − mean estimated size|) was analyzed as a function of tool condition and target size. The main effect of the tool condition was not significant, $F(1, 23) = 1.351, p = 0.257, \eta_p^2 = 0.06$, suggesting that using a tool did not simply improve the overall size estimation performance. Also, both the effect of target size, $F(3, 69) < 1$ and the interaction between tool and target size, $F(3, 69) = 2.009, p = 0.12, \eta_p^2 = 0.08$ were not significant.

1.2.1. Post-experiment interview

The responses to the post-experiment questioning are shown in Table 2. Only thirteen of the 24 participants believed that the experiment was about testing the effect of tool use on size perception. Of those participants, only one believed that the target looked smaller with the tool. Nine participants thought that the purpose of the experiment was about the effect of tool use on distance perception. Among those participants, only one believed that the target circle looked closer with the tool.

1.3. Discussion

Participants perceived the target to be smaller when they were able to reach it with a tool, compared to without a tool (in which case it was beyond reach). The results suggest that tool use either directly affects the perceived target size, or it alters the perceived distance to the target, causing it to appear closer, and because of size-distance invariance, to also appear smaller. Because the relation between size and distance is not an intuitively obvious one, the results seem unlikely to have been driven by demand characteristics. Moreover, accuracy, as indexed by the absolute error, was not influenced by tool use suggesting that the result was not due to an overall improvement in task performance with the tool.

The post-experiment interview also shows that participants were not able to discern the genuine purpose of the experiment. Thus, the results confirm earlier findings that have shown that tool use causes objects that can be reached with the tool to appear closer (e.g., Bloesch et al., 2012; Davoli et al., 2012; Witt et al., 2005). In Experiment 2, we attempted to replicate the tool use effect and extend it to a broader range of target sizes.

2. Experiment 2a

The purpose of Experiment 2a was to replicate the unique findings from Experiment 1 and to examine whether the tool use effect is limited to a narrow range of object sizes. In order to do that, we included four additional sizes of target circles.

Table 3
Mean perceived size (diameter of response circle; mm) as a function of tool condition and target diameter in Experiment 2a.

	Target diameter (mm)							
	31.0	38.7	46.4	54.2	61.9	69.7	77.4	85.1
Tool	32.62	41.30	48.55	56.39	62.78	70.83	78.33	84.82
No tool	34.03	42.12	49.59	56.79	63.84	71.06	78.04	85.42

2.1. Method

2.1.1. Participants

Twenty-four participants (13 females) from Washington University in St. Louis participated to fulfill a partial requirement for course credit. All of them had normal or corrected-to-normal vision.

2.1.2. Apparatus, stimuli, procedure, and design

The same apparatus as in Experiment 1 was used. Stimuli and procedure were identical to those of Experiment 1 except that here the target circle was shown in one of eight sizes (31.0 mm, 38.7 mm, 46.4 mm, 54.2 mm, 61.9 mm, 69.7 mm, 77.4 mm, and 85.1 mm). The four smaller sizes were the same as those used in Experiment 1. The initial diameter of the response circle varied randomly between 15.48 mm and 100.61 mm.

2.2. Results

Results are shown in Table 3 where it can be seen that the perceived size of the target increased as the actual size increased, $F(7, 161) = 3477, p < 0.001, \eta_p^2 = 0.99$. However, neither main effect of tool, $F(1, 23) = 2.052, p = 0.165, \eta_p^2 = 0.08$, or interaction of tool and target size, $F(7, 161) = 1.561, p = 0.151, \eta_p^2 = 0.06$, were significant.

Although the main effect of the tool did not reach statistical significance, the results showed the same trend as in Experiment 1. Fig. 5 illustrates the difference in perceived size between the tool and no-tool conditions, as a function of target size. Inspection of the figure suggests that the smaller targets, the ones used in Experiment 1, appear to reveal an effect of tool use as in Experiment 1. To test that possibility we conducted another ANOVA that included only the four smaller target sizes. In that analysis, the effect of tool was indeed marginal, $F(1, 23) = 3.87, p = 0.06, \eta_p^2 = 0.144$. The effect of size was reliable, $F(3, 69) = 2373, p < 0.001, \eta_p^2 = 0.99$, and there was no interaction, $F(3, 69) = 1.73$, n.s., $\eta_p^2 = 0.07$. In order to test whether tool use only affected the perceived size of smaller targets, paired t-tests were conducted on the differences in size caused by the tool, shown in Fig. 5 (31.0 mm: $t(23) = 2.553, p = 0.009$, 38.7 mm: $t(23) = 1.423, p = 0.084$, 46.4 mm: $t(23) = 2.061, p = 0.025$, 54.2 mm: $t(23) = 0.752, p = 0.230$, 61.9 mm: $t(23) = 1.813, p = 0.041$, 69.7 mm: $t(23) = 0.421, p = 0.339$, 77.4 mm: $t(23) = 0.414, p = 0.659$, 85.1 mm: $t(23) = 0.722, p = 0.239$).

The accuracy, as indexed by absolute error, was analyzed to test whether tool-use enhanced the overall task performance. There was no effect of tool, $F(1, 23) = 3.058, p = 0.094, \eta_p^2 = 0.18$, suggesting that the accuracy did not change across the different tool conditions. In addition, the main effect of size, $F(7, 161) = 1.326, p = 0.24, \eta_p^2 = 0.05$, and the interaction, $F(7, 161) < 1$, were not significant.

2.2.1. Post-experiment interview

Responses to the post-experiment interview are shown in Table 4. Fourteen of the 24 participants believed that the experiment tested how tool use influences size perception, with only one of the fourteen thinking that the tool made the target appear to be smaller. Seven participants believed that the purpose of the experiment involved distance perception. Only one among those people thought that the target circle appeared closer with the tool.

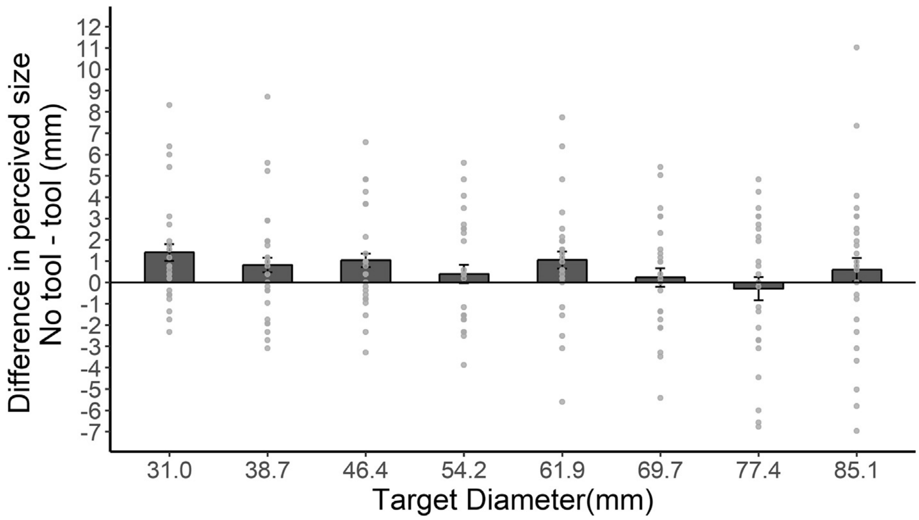

Fig. 5. Difference in perceived size (no tool − tool) of the target in Experiment 2a. Positive values indicate that perceived size was smaller with a tool than without a tool. Points show individual subjects; bars show the mean; error bars depict within-subject standard errors.

Table 4
Participants' answers from the post-experiment interview in Experiment 2.

Question 1 response (What was experiment testing?)	Question 2 response (What effect did tool have on the tested dimension?)	N (total = 24)
Size perception	More accurate with the tool	5
	Less accurate with the tool	3
	Smaller	1
	No effect or no answer	5
Distance perception	More accurate with the tool	3
	The circle looks closer with the tool	1
	No effect or no answer	3
No answer		3

2.3. Discussion

As in Experiment 1, the perceived size of a target tended to be smaller when participants were able to reach the target with a tool, primarily for the smaller targets (that matched the sizes used in Experiment 1). However, the findings here were weaker than in Experiment 1, perhaps because the doubled number of target sizes necessitated a 50% reduction in the number of trials per target. Nevertheless, the findings suggest that tool use affected either the perceived size or the perceived distance to the target. The analysis on the accuracy also highlights that tool use biased the perceived size of the object not simply by helping people to estimate the size better. Importantly, the post-experiment interview shows that the size judgments are unlikely to have been driven by demand characteristics. The reported pattern was stronger for smaller targets—an effect that we discuss further in the General discussion.

3. Experiment 2b

In Experiment 2a, we found that the estimated size of the target object was smaller with the tool but the effect was marginal presumably due to the absence of the effect in the bigger targets. Given this weak evidence, here we replicated Experiment 2a to confirm our conclusions. In addition, we conducted a more detailed post-experiment interview in order to more thoroughly explore the relation between participants' subjective beliefs and their behavior.

3.1. Method

3.1.1. Participants

Twenty-four participants (18 females) from Washington University in St. Louis participated to fulfill a partial requirement for course credit. All of them had normal or corrected-to-normal vision.

3.1.2. Apparatus, stimuli, procedure, and design

The apparatus, stimuli and procedure were identical to those of Experiment 2a except for the post-experiment interview. We revised the post-experiment interview in order to more precisely gauge participants' beliefs about the purpose of the experiment and the expected outcome. In addition, we asked an additional question in order to confirm participants' beliefs about size-distance invariance. The interview included three questions: (1) *Can you guess what the purpose of the experiment is?*; (2) *Did you feel any difference in estimating sizes of the circles between when you were using a tool and not using it?; and (3) It is known that an object looks closer with a tool. If you believe this, would you expect its perceived size to change too? If so, can you guess the direction (bigger or smaller)?* Participants were asked to give a written response to each of the questions.

3.2. Results

Results are shown in Table 5 where it can be seen that the perceived size of the target increased as the actual size increased, $F(7, 161) = 3536.44$, $p < 0.001$, $\eta_p^2 = 0.99$. Again, the main effect of tool was not significant, $F(1, 23) = 1.493$, $p = 0.234$, $\eta_p^2 = 0.06$. The difference in perceived size between tool conditions is shown in Fig. 6 where positive values indicate that the perceived size of the target was smaller with tool use. Importantly, the interaction of tool and target size was marginally significant, $F(7, 161) = 1.97$, $p = 0.06$, $\eta_p^2 = 0.08$ confirming the apparent decrease in the tool effect as target size increased. The paired *t*-tests were conducted on the differences in size caused by the tool, shown in Fig. 5 (31.0 mm: $t(23) = 2.553$, $p = 0.009$, 38.7 mm: $t(23) = 1.423$, $p = 0.084$, 46.4 mm: $t(23) = 2.061$, $p = 0.025$, 54.2 mm: $t(23) = 0.752$, $p = 0.230$, 61.9 mm: $t(23) = 1.813$, $p = 0.041$, 69.7 mm: $t(23) = 0.421$, $p = 0.339$, 77.4 mm: $t(23) = 0.414$, $p = 0.659$, 85.1 mm: $t(23) = 0.722$, $p = 0.239$).

Table 5
Mean perceived size (diameter of response circle; mm) as a function of tool condition and target diameter in Experiment 2b.

	Target diameter (mm)							
	31.0	38.7	46.4	54.2	61.9	69.7	77.4	85.1
Tool	31.85	40.47	47.31	55.41	62.50	69.96	76.51	83.45
No tool	32.98	41.01	48.02	55.79	62.82	70.18	76.14	82.91

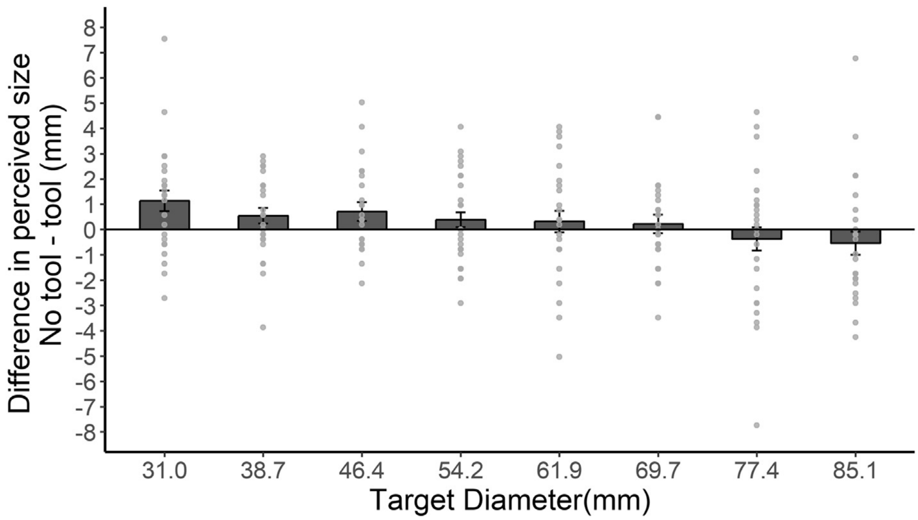

Fig. 6. Difference in perceived size (no tool − tool) of the target in Experiment 2b. Positive values indicate that perceived size was smaller with a tool than without a tool. Points show individual subjects; bars show the mean; error bars depict within-subject standard errors.

In order to confirm the nature of the marginal interaction and compare the result of Experiment 2b to that of Experiment 1, we conducted separate ANOVA analyses on the four smaller and four bigger target sizes. For smaller targets (diameter: 31.0 mm, 38.7 mm, 46.4 mm, and 54.2 mm), the main effect of tool was significant, $F(1, 23) = 6.531$, $p = 0.018$, $\eta_p^2 = 0.22$, showing that the perceived size of the target was smaller with the tool compared to without the tool which is consistent with the results of Experiment 1 (using the same target sizes as Experiment 1). In addition, the main effect of target size, $F(3, 69) = 1830.58$, $p < 0.001$, $\eta_p^2 = 0.99$, was significant indicating that perceived size increased as target size increased. However, the interaction of tool and size, considering just the four smaller targets, was not significant, $F(3, 69) = 1.045$, $p = 0.38$, $\eta_p^2 = 0.04$. For bigger targets (diameter: 61.9 mm, 69.7 mm, 77.4 mm, and 85.1 mm), however, the main effect of the tool was not significant, $F(1, 23) < 1$, nor was the interaction, $F(3, 69) = 1.052$, $p = 0.375$, $\eta_p^2 = 0.04$. Only the main effect of target size was meaningful, $F(1, 23) = 1703.145$, $p < 0.001$ $\eta_p^2 = 0.99$, showing increases in estimated size the target size increased. We also compared the tool effect between the smaller and bigger targets by performing a 2 target size (smaller vs. bigger) × 2 tool condition (tool vs. no tool) repeated measures ANOVA and. The interaction between target size and tool was significant, $F(1, 23) = 5.046$, $p = 0.035$, $\eta_p^2 = 0.18$, confirming that perceived size was smaller with the tool only for the smaller objects.

The accuracy, as indexed by absolute error, was analyzed to test whether tool-use enhanced the overall task performance. Unlike in the previous experiments, there was an effect of tool, $F(1, 23) = 15.899$, $p < 0.001$, $\eta_p^2 = 0.41$, showing that participants were making smaller size-estimation errors with the tool than without it. On average, the absolute error was 3.4 mm ($SD = 0.33$) without the tool and 2.71 mm ($SD = 0.32$) with the tool. The main effect of target size, $F(7, 161) = 1.002$, $p = 0.432$, $\eta_p^2 = 0.04$, and the interaction, $F(7, 161) < 1$, were not significant.

3.2.1. Post-experiment interview

Responses to the post-experiment interview are shown in Table 6. Nineteen of the 24 participants believed that the experiment tested how tool use influences size perception. Among those nineteen participants, ten of them (53%) expected that the tool would make size perception more accurate or easier. Three of them thought that the size perception would be less accurate with the tool (12.5%). Only two participants believed that the purpose of the experiment involved distance perception and they both thought that tool use would be detrimental in estimating the distance.

For the last post-experiment question, we provided participants with some background for the present study (previous findings regarding the effect of tool use on distance perception), and requested their best guess as to whether tool use would cause objects to appear either bigger or smaller. Sixteen of the 24 participants responded that using a tool would cause an object to appear bigger, and three participants thought that the tool would produce no difference in perceived size. Surprisingly, only five participants (21% of the total) thought that using the tool would make the target appear smaller. In order to check whether the tool's influence on perceived size was modulated by individual's belief in the size-distance relationship, we plotted each participant's effect of the tool (no tool − tool, in mm) based on their choices (bigger, smaller, or no difference) for the four smallest target sizes. The results are shown in Fig. 7. The figure shows that participant's belief does not change the direction of the tool use effect, $F(2, 21) < 1$. This finding highlights the fact that it is unlikely that size estimation was influenced by demand characteristics such as expected results of the experiment.

Table 6
Participants' answers from the post-experiment interview in Experiment 2b.

Question 1 response (What was experiment testing?)	Question 2 response (What effect did tool have on size estimation?)	N (total = 24)
Size perception	More accurate with the tool	7
	Less accurate with the tool	3
	Easier with the tool	3
	No effect or no answer	5
	Different (unspecified)	1
Distance perception	Less accurate with the tool	1
	More difficult with the tool	1
Location	More accurate	1
Shape	More accurate	1
No answer	Less accurate	1

3.3. Discussion

In Experiment 2b, we replicated the results of Experiment 2a. Consistent with Experiment 2a, the perceived size of the target was smaller when using a tool, with the effect significant only for the smaller targets. We discuss possible reasons for this size dependency in the General discussion.

Additionally, the absolute error analysis showed that participants here made smaller errors with the tool, an effect that was not observed in the earlier experiments. We discuss this further in the General discussion.

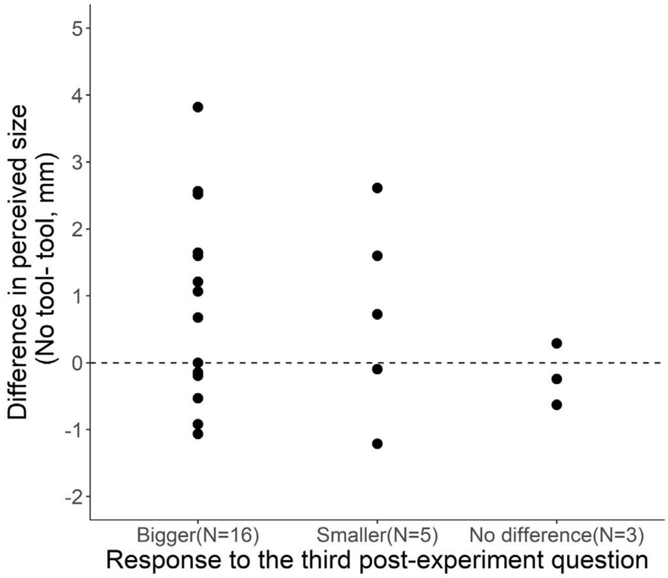

Fig. 7. Individual tool use effect (no tool − tool) as a function of response to the third post-experiment question for the four smallest target sizes in Experiment 2b. Values above zero (dashed line) correspond to the tool reducing the perceived size of the target.

4. Experiment 3

In Experiment 3, we attempted to replicate the tool use effect on perceived size by using a tool that permits only an indirect interaction—specifically, a laser pointer. Previous studies have shown that illuminating a target with a laser pointer also changes its perceived distance (causing it to appear closer; Bloesch et al., 2012; Davoli et al., 2012). Following the same logic presented earlier, changes in perceived distance caused by use of a laser pointer should also produce changes in perceived size.

4.1. Method

4.1.1. Participants

Twenty-four participants (17 females) from Washington University in St. Louis participated to fulfill a partial requirement for course credit. All of them had normal or corrected-to-normal vision.

4.1.2. Apparatus, stimuli, procedure and design

The setup of the present experiment was identical to that of Experiment 1 except that a laser pointer was used instead of a stylus. Also, the target circle was presented 161.58 cm away from participants (99 cm was used in the earlier experiments). In the tool condition, participants were asked to shine the laser pointer onto the target. In the *dummy* condition, participants held a dummy laser pointer (a non-functioning laser pointer that was similar in shape and weight to the other laser pointer) and pointed it to the target without illuminating it.

4.1.3. Post-experiment interview

The interview questions were identical to that of Experiment 2b except, in Experiment 3, participants were asked to give a verbal response to each of the questions, and the experimenter noted their answers.

4.2. Results

The results are shown in Table 7. There was a significant main effect of target size, $F(3, 69) = 717.964$, $p < 0.001$, $\eta_p^2 = 0.97$, showing that perceived size increased as the actual target size increased. Importantly, the main effect of tool was significant, $F(1, 23) = 14.118$, $p = 0.001$, $\eta_p^2 = 0.38$ (see Fig. 8): The perceived size was smaller with a working laser pointer compared to a dummy laser pointer. The tool and target size interaction was not significant, $F(3, 69) < 1$.

The analysis of absolute error showed that tool use did not influence the overall accuracy in the size estimation task, $F(1, 23) = 1.765$, $p = 0.197$, $\eta_p^2 = 0.07$. The main effect of target size, $F(3, 69) < 1$, and interaction, $F(3, 69) = 2.426$, $p = 0.073$, $\eta_p^2 = 0.10$, were also not significant.

Table 7
Mean perceived size (diameter of response circle; mm) as a function of tool use and target diameter in Experiment 3.

	Target diameter (mm)			
	31.0	38.7	46.4	54.2
Tool	32.68	40.59	46.29	52.94
No tool	34.36	42.20	47.51	54.06

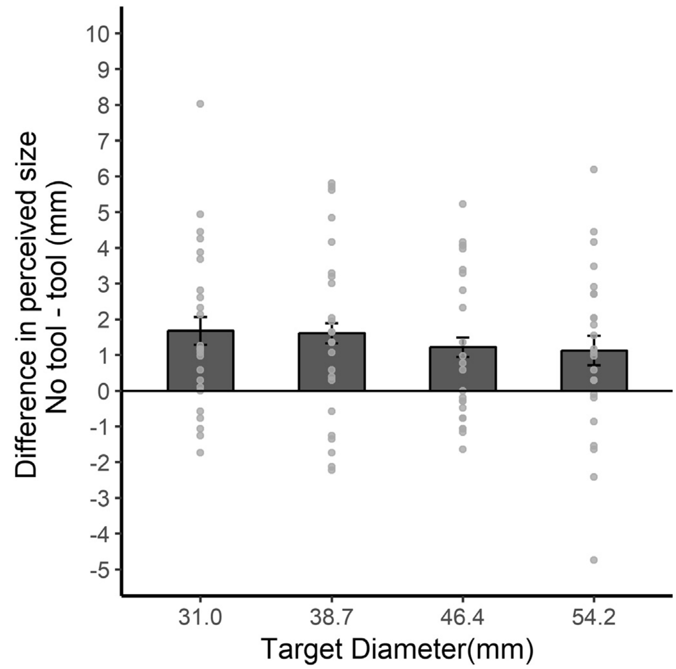

Fig. 8. Difference in perceived size (no tool − tool) of the target in Experiment 3. Positive values indicate that perceived size was smaller with the laser pointer. Points show individual subjects; bars show the mean; error bars depict within-subject standard errors.

4.2.1. Post-experiment interview

A summary of the responses to the first two post-experiment questions is shown in Table 8. Twenty of the 24 participants believed that the purpose of the experiment was to examine the ability to judge sizes of objects. Of those, none thought that the laser would make the target look smaller. Only three participants thought that the experiment

Table 8
Participants' answers from the first two questions of the post-experiment interview in Experiment 3.

Question 1 response (What was experiment testing?)	Question 2 response (What effect did laser have on the tested dimension?)	N (total = 24)
Size perception	No effect	15
	More accurate	4
	Bigger	1
Distance perception	No effect	2
	More accurate	1
Response speed	More accurate	1

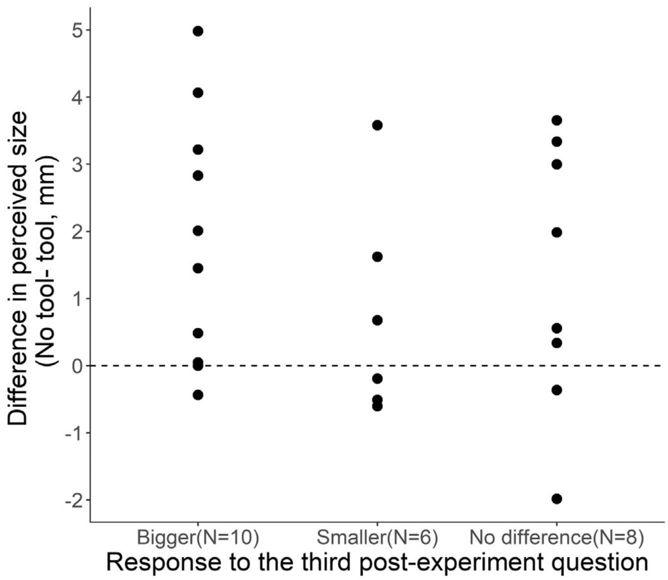

Fig. 9. Individual tool use effect (no tool − tool) as a function of response to the third post-experiment question in Experiment 3. Values above zero (dashed line) correspond to the laser reducing the perceived size of the target.

pertained to perceived distance.

Again, for the last post-experiment question, we provided participants with some background for the present study (previous findings regarding the effect of tool use on distance perception) and requested their best guess as to whether tool use would cause objects to appear either bigger or smaller. Ten of the 24 participants responded that using a tool would cause an object to appear bigger, and eight participants thought that the laser would produce no difference in perceived size. Surprisingly, only six participants (25% of the total) thought that using the laser would make the target appear smaller. We separately evaluated every participant's tool use effect as a function of their responses to this question. The results are shown in Fig. 9. The figure shows that the magnitude of the tool use effect did not depend upon a participant's beliefs about the consequences of tool use, $F(2, 21) < 1$. This suggests that the responses were not driven by demand characteristics or the participants' expectations.

4.3. Discussion

Target circles appeared to be smaller when they could be "reached" by a laser pointer. That finding is consistent with previous results showing that remote tool use causes people to perceive objects to be closer (Bloesch et al., 2012; Davoli et al., 2012). Thus, as in the earlier experiments, interaction with a tool altered either the perceived size of the target object, or the perceived distance to the object (and, in turn, the perceived size due to size-distance invariance). Moreover, the additional analysis on the absolute error revealed that tool use biased the perceived size but did not alter overall task performance.

In the post-experiment interview, the majority of participants did not guess the actual purpose of the experiment. More interestingly, when we asked about the expected direction of the effect on perceived size, more participants thought that objects should look bigger when illuminated by the laser pointer, in contrast to the size estimation results which showed the opposite effect. This mismatch between participants' common beliefs and the actual judgments suggests that the tool use effect is not due to demand characteristics. Rather, it confirms that tool use indeed changes perception.

5. General discussion

In four experiments, we found that objects were perceived to be smaller when participants were able to reach them with a hand-held tool. The effect reveals a new illusion caused by tool use. As noted earlier, the changes in perceived size are assumed to reflect changes in the perceived distance to the targets. Thus, the results are consistent with previous findings showing that tool use causes reached objects to appear closer (e.g., Witt et al., 2005). Those findings were interpreted as supportive of the action-specific account of perception. According to that account, perceptions are scaled by one's ability to act in or on objects in the environment. Thus, objects that are out of reach look further away than those that (with the aid of a tool) can be reached. Importantly, here we used size judgments as an indirect measure of perceived distance. The size judgments are less likely than explicit distance judgments to be influenced by demand characteristics. Indeed, the results of the post-experiment questionnaire administered after Experiments 2b and 3 revealed that a minority of our participants could correctly describe the relation between perceived distance and perceived size.

We also found that the tool use effect was not significant overall in Experiments 2a and 2b, where the target was one of eight different sizes, whereas in Experiments 1 and 3, a meaningful tool use effect was observed when the target was one of four smaller sizes. One possible explanation for this is that the smaller targets we used were of a size that would permit easy manipulation in the hand, whereas the larger ones might have been unwieldy. Thus, the ability to reach an object may affect the perceived distance to, and perceived size of, the object—but only for objects that would easily allow interaction or manipulation. (Of course all of our objects were images projected onto a screen, so none of them could have been manipulated anyway.)

We have so far characterized the effect of tool use on perceived size as an effect that is merely a consequence of the effect of tool use on perceived distance. But it is also worth mentioning that there may be a practical advantage conferred by the shrinking of perceived size with tool use. When a tool, such as a hammer for example, is wielded to interact with an object, the reduced apparent size of the object may encourage increased precision of the movements of the tool because more precision would be needed to contact a smaller target. Such increased precision might lead to more accurate interactions with the object.

It is also worth considering an alternate explanation of our results. It is logically possible that tool use directly alters perceived size, as we have reported here, and that the changes observed in perceived distance such as those reported in earlier studies (e.g., Witt et al., 2005) were caused by the size changes due to size-distance invariance. While it is not possible to definitively rule-out this alternative, two types of experimental findings argue against it. First, brain imaging studies have revealed that a larger area in primary visual cortex (V1) is activated by a stimulus when the stimulus is perceived to be further away (Murray, Boyaci, & Kersten, 2006; Sperandio, Chouinard, & Goodale, 2012). The results suggest that V1 receives feedback from later distance-perception mechanisms that can scale the size of the early representation of an object (Qian & Yazdanbakhsh, 2015). These results reveal a mechanism through which perceived distance can influence perceived size, and not the other way around. Second, Stefanucci and Storbeck (2009) had people judge the height of a balcony and also the size of an object on the ground, when standing on the balcony. They found that individuals who were fearful of heights exhibited greater overestimations of height and also of object size compared to those who were not fearful of heights. The close correspondence between the height and size judgments suggests strongly that perceived distance altered perceived size and not the other way around—it would be unlikely for height-fearful individuals to initially perceive distorted sizes and for that to then drive their overestimation of perceived height.

With these considerations in mind, it is possible to calculate the change in perceived distance that would lead to the changes we observed in perceived size. For the average target size used in Experiments 1 and 3, a reduction in perceived distance of 23.2 mm would produce a decrease of 1 mm in the diameter of the target (the approximate size of the changes that were observed).

Nevertheless, it is also worth noting that there are some special situations in which perceived size can alter perceived distance. That can theoretically occur anytime a stimulus provides cues to its size that are independent of distance information. For example, people are very familiar with the appearance and sizes of various coins and paper money. And when viewing objects with familiar size, the perceived size may drive perceptions of the viewing distance. Such effects are revealed by studies in which familiar objects such as coins are presented in atypical sizes (e.g., Epstein, 1963). In those studies, the size manipulation also affects perceived distance, revealing an effect of perceived size on perceived distance.

One could argue that using a tool might have caused people to attend more to the target objects compared to when no tool was used, and perhaps the enhanced attentional allocation is what led to the reduced perceived size. However, Anton-Erxleben, Henrich, and Treue (2007) showed that attention actually *increases* the perceived size of visual objects. Therefore, if tool use actually changes attentional allocation, the effect that we reported may have been partially offset by the effects of attention and thus our findings may underestimate the effect of tool use on perceived size.

In summary, the present study showed that using a reach-extending tool (a stylus or a laser pointer) reduced the perceived size of the reached-for object, presumably as a consequence of a reduction in the perceived distance to the object. The size judgments are unlikely to have stemmed from the demand characteristics of the experiment which could potentially have affected some earlier studies. Thus, our findings support the action-specific perception account of perception, revealing one of the ways in which our action capabilities influence how we perceive the world.

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