Journal of Experimental Psychology:
Human Perception and Performance
2012, Vol. 38, No. 1, 80–89

0096-1523/11/$12.00 DOI: 10.1037/a0024981

# Compressing Perceived Distance With Remote Tool-Use: Real, Imagined, and Remembered

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Reaching for an object with a tool has been shown to cause a compressed perception of space just beyond arm's reach. It is not known, however, whether tools that have distal, detached effects at far distances can cause this same perceptual distortion. We examined this issue in the current study with targets placed up to 30m away. Participants who illuminated targets with a laser pointer or imagined doing so consistently judged the targets to be closer than those who pointed at the targets with a baton. Furthermore, perceptual distortions that arose from tool-use persisted in memory beyond the moment of interaction. These findings indicate that remote interactions can have the same perceptual consequences as physical interactions, and have implications for an action-specific account of perception.

*Keywords:* distance perception, tool use, embodied cognition, affordances, intention

According to the action-specific account of perception, people perceive the surrounding environment in terms of their ability to perform an intended action (e.g., Witt, in press-a). Perceivers who intend to throw, view the world as throwers, and optical information is scaled to their ability to throw. Perceivers who intend to reach, view the world as reachers, and optical information is scaled to their ability to reach. Not surprisingly, then, factors that determine one's physical ability such as body type and physical strength also affect one's perception of the visual environment. For example, people with broader shoulders perceive doorways to be narrower (Stefanucci & Geuss, 2009) and those with stronger hand grip perceive their hand to be larger (Linkenauger, Witt, Bakdash, Stefanucci, & Proffitt, 2009). Even when body size and strength are constant, the ability to control one's body influences perception. For example, participants trained in Parkour (also known as urban climbing) perceive to-be-scaled walls as shorter than do novices (Taylor, Witt, & Sugovic, submitted).

Physical ability, however, is not constant across time and one's ability to perform an action can change. In these circumstances, it is the perceiver's current ability to perform an action that influences perception. For example, softball players hitting better in a given game perceive the ball to be bigger than those hitting poorly (Witt & Proffitt, 2008). Similarly, golfers who are playing better in a given round perceive the hole as bigger (Witt, Linkenauger, Bakdash, & Proffitt, 2008), athletes who make more successful field goal kicks perceive the goal to be wider (Witt & Dorsch, 2009), and tennis players who successfully return a shot perceive the ball to be moving more slowly (Witt & Sugovic, 2010). Similar effects are also apparent in children, and those that hit a target more successfully than others perceived the target to be bigger (Cañal-Bruland & van der Kamp, 2009).

In addition to transient variation in skilled performance, physical abilities can also be temporarily altered through the use of tools, and, consistent with the action-specific account of perception, there is some evidence that tool usage also affects perception. For example, targets presented just beyond reach looked closer when they could be reached with the aid of a tool than when the tool was not used (Witt, Proffitt, & Epstein, 2005; Witt & Proffitt, 2008; Witt, in press-b). This compression of space is consistent with other evidence indicating that the use of a reach-extending tool results in an expansion of peripersonal (i.e., reachable) space. At the neural level, the receptive fields of neurons that represent the space immediately surrounding the body expand to include the space circumscribed by tool-use (Iriki, Tanaka, & Iwamura, 1996). In addition, patients who neglect (Berti & Frassinetti, 2000) or extinguish (Farnè & Làdavas, 2000; Maravita, Husain, Clarke, & Driver, 2001) stimuli in peripersonal space exhibit a transfer of that deficit to extrapersonal stimuli that were rendered reachable by tool-use. At a more behavioral level, tool-driven expansion of peripersonal space has been demonstrated by observations of extended attentional processing normally observed for the space immediately around the hand (Kennett, Spence, & Driver, 2002; Reed, Grubb, & Steele, 2006) to more distal areas of space. These include attentional prioritization of (Reed, Betz, Garza, & Roberts, 2010), and rapid shifts in cross-modal attention to (Maravita, Spence, Kennett, & Driver, 2002), the functional (but not necessarily the physical) end of the tool (Farnè, Iriki, & Làdavas, 2005). Applying these benefits to an applied problem, Schendel and Robertson (2004) reported alleviation of a patient's hemianopsia both near a hand and near the end of a reach-extending tool in the lesion-affected field.

The results described above suggest a link between the behavioral consequences of tool-usage to a spatial extension of periper-

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We thank Natalie Baldasare, Deborah Cronin, Matthew Donley, Emily Ehrman, Bryan Golubski, and Sarah Wiesen for their help with data collection.

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sonal space. By shifting an object from extrapersonal space to peripersonal space, the object may appear closer while remaining in the same physical location, an effect that would have implications for how one chooses to perform visually controlled tasks. In this report, we examine whether similar distortions of perceived distance also occur when an observer remotely interacts with very distant objects. On the one hand, given the discussion above, spatial judgments may be unaffected by remote interactions because peripersonal space is inherently limited. Few neurons that are responsible for representing peripersonal space have receptive fields that extend farther than 1 m from the body, while most do not extend beyond 20–50 cm (Graziano & Gross, 1993; Graziano & Gross, 1995; Graziano, Hu, & Gross, 1997). Hence, while the neural mapping of peripersonal space is flexible, it is unlikely to be without spatial limit. On the other hand, it is possible that interaction-induced distortions of perception are not specific to peripersonal space, but rather reflect one's capacity to interact with an object regardless of its location. Because one's ability to physically and remotely interact with objects may be functionally equivalent (e.g., using the hand or a remote control can equally alter the volume of a stereo), the perceptual consequences of each type of action may also be functionally equivalent. Under this view, perception adapts to represent *all* feasible interactions and the spatial distortions observed for interactions near the body should persist when objects are located further away. To discriminate between these possibilities, we took advantage of the spatial compression effect to investigate some perceptual and cognitive consequences of using tools designed to facilitate remote interactions with distal objects.

Across three experiments, observers used a tool to interact with objects 2–30m away. Our first question was whether these remote interactions carry with them similar perceptual consequences as interactions occurring much closer to the body where tools permit direct physical contact with an object. We investigated this in Experiment 1 by asking observers to judge their distance from a target. Some participants were asked to do this while using a laser pointer to illuminate the target while others made their judgments without such interaction. Anticipating our results, we will show that pointing to an object with a laser pointer results in a nearly 30% reduction in perceived distance, confirming that remote tool use leads to similar perceptual consequences as direct contact with an object. With this result in hand, subsequent experiments then investigated some potential cognitive manifestations and/or limitations of this effect.

We next asked whether the perceptual distortions induced by tool usage can be observed through imagined interactions with an object. In this case, observers were given a nonfunctional laser pointer but told to use it as if it was working properly and to imagine illuminating the target with it. Mentally simulated actions have been shown to activate regions of the brain that are recruited during actual performance (Creem-Regehr & Lee, 2005; Higuchi, Imamizu, & Kawato, 2007), and alterations in visual processing that arise during the performance of an action have also been observed when an action is merely prepared (Vishton et al., 2007) or imagined (Davoli & Abrams, 2009; Witt & Proffitt, 2008). Given this evidence, along with the substantial neural overlap between perception and imagery (see Ganis, Thompson, & Kosslyn, 2009 for a review) and the weight that the action-specific account of perception places on intention to perform an action (Witt, Proffitt, & Epstein, 2004, 2010; Witt et al., 2005), imagined interaction with an object may be sufficient to lead to perceptual compression.

We then examined whether perceived distance depends on the nature of the intended interaction with the object. While tools enable interaction with objects, different tools enable different kinds of interactions. In studies of reaching, the observer's goal is to touch the object, which, when possible, makes the object look closer (e.g., Witt et al., 2005) or to bring the object closer, which, when possible, causes neurons that code for objects that are within reach to fire (Iriki et al., 1996). Thus, the observer's actions (to touch and/or bring closer) and the corresponding perceptual effects (to look closer) have been confounded. As a result, it is unclear whether perceptual compression reflects a general ability to act upon an object or if it depends on the goals or anticipated outcomes of the action. To resolve this ambiguity, we instructed participants to estimate the distance of a target while using an industrial vacuum that was off (a device that could have no effect on the target), running as a vacuum (a device that could pull the target closer), or running as a blower (a device that could push the target away). If anticipation of the consequences of the action influences perception, then the vacuum should lead to spatial compression while the blower should lead to spatial expansion (i.e., the target should look farther away). If, on the other hand, perception processes space in terms of what can be acted upon, regardless of the potential outcome of that action, both the vacuum and the blower should lead to spatial compression. Such an effect may help encourage action by indicating that something is "within reach" regardless of the end-goal of the action.

Finally, we considered the consequences of tool use on memory for perceived distance. It is unknown whether the distortions we have been describing persist in memory after the interaction is terminated. The formation of an action plan can cause changes in perception that persist several minutes beyond the final completion of the planned action (Vishton et al., 2007), and receptive fields of peripersonal-related neurons can stay expanded from tool-use after the tool has been discarded (Iriki et al., 1996). Those findings suggest the persistence of perceptual distortions, but leave open the question of whether those distortions are encoded into long-term memory. A further question remains as to whether tool use affects perception when implicit measures of distance are employed. To address both of these issues simultaneously, observers were given a cover task in which they generated stories about scenes that were presented at varying distances away from them. Observers were never asked to report the distance of the scenes. Some observers pointed at each scene with a laser pointer. Following the cover task, participants were taken to another room and completed a surprise memory test in which they were asked to indicate the location of each scene on a scale model of the hallway. If tool use leads to perceptual compression in an incidental manner, and if this compression persists in memory, then observers who illuminated each scene with a laser pointer would place the scenes closer together compared to those who did not.

## Experiment 1

In Experiment 1, we examined whether perceptual compression would be observed when participants performed a remote interaction with a distant object. For expository reasons, we divided this investigation into thirds. In Experiment 1A, we asked whether distance estimates vary as a function of remote tool use. In Experiment 1B, we ascertained whether tool use compresses space or if the absence of tools expands space. In Experiment 1C, we examined alternative explanations based on visual feedback and explored possible parallels between successful and imagined interactions with objects.

## Experiment 1A: Remote Tool Use

Here, we examined whether perceptual compression would be observed when participants performed a remote interaction with a distant object. Indeed, compression of perceived space has been observed in participants who use a tool to extend their reach (Witt et al., 2005), but it is unclear whether that same compression applies to remote interactions where physical contact with an object is not possible. Participants estimated the distance between themselves and a target. While doing this, some participants illuminated the target with a laser pointer, and others simply pointed at it with a baton (analogous in size, shape, and weight to the laser pointer) which did not afford an interaction with the target. If intended interactions with the environment influence perception, regardless of their spatial placement in the environment, then participants who interact with the target by shining a laser pointer at it should perceive it to be closer than those who pointed with the baton. If action-based perceptual distortions are limited to peripersonal space, however, equivalent performance should be observed in each condition.[1]

### Method

**Participants.** Forty experimentally naïve University of Notre Dame undergraduates participated in exchange for course credit.

**Apparatus and stimuli.** The experiment was conducted in a basement hallway of the psychology building at the University of Notre Dame. This hallway was 42.5 m long and 2.6 m wide. Participants stood at a fixed location at one end of the hallway and were asked to estimate the distance to a target as accurately as possible. The target was a standard shooting target, mounted on a wooden stand. The center of the target was 127 cm above the floor. The target could be placed at eight possible locations: 1.8m, 5.2m, 8.8m, 13.4m, 19.2m, 22.6m, 26.2m, or 30.5m away from the observer. There were two observations per location for a total of 16 experimental trials. The order of locations was randomized with the exceptions that each of the eight unique locations had to be used before a location could be repeated, and a location could not be repeated within three trials of its first occurrence. Participants pointed at the target with a laser pointer or a baton. The baton was fashioned to be analogous to the laser pointer in size, shape, and weight.[2] The laser pointer and baton were both cylindrical in shape, and measured 15 cm in length and 1.4 cm in diameter. Both were constructed from metals to equate, as much as possible, their look and feel.

**Procedure and design.** An equal number of participants were assigned to the laser pointer or baton conditions. Before each trial, participants turned around so that they could not see the experimenter position the target. When participants turned to face the target, those in the laser pointer condition illuminated the target with a laser pointer, while the others pointed a metal baton at the center of the target. Once participants felt that they were aiming their implement at the center of the target to the best of their ability, they then (while continuing to hold their aim) estimated their distance to the target using whatever unit of measurement they believed to be their most accurate (feet, yards, etc.). For analysis, all measurements were converted to meters.

### Results

Mean distance estimations were submitted to a 2 (tool condition: laser pointer or baton) × 8 (physical distance to target: 1.8m, 5.2m, 8.8m, 13.4m, 19.2m, 22.6m, 26.2m, 30.5m) mixed factors analysis of variance (ANOVA). The results are illustrated in Figure 1.

As would be expected, verbal estimates increased as the distance to the target increased, $F(7, 266) = 135.21$, $p < .001$, $\eta_p^2 = .78$. Importantly, participants who pointed with the laser pointed estimated the targets to be closer than did participants who pointed with the baton, $F(1, 38) = 8.30$, $p < .01$, $\eta_p^2 = .18$. Tool condition also interacted with physical distance such that the differences in estimations between the two tool conditions increased as physical distance increased, $F(7, 266) = 5.87$, $p < .001$, $\eta_p^2 = .13$. Planned comparisons revealed significantly shorter distance estimates in the laser pointer condition relative to the baton condition at all target locations, all $t$s$(38) > 2.40$, all $p$s $< .025$. These results, therefore, suggest that participants who pointed to a distant target with a laser pointer perceived the targets to be closer than did participants who pointed with a baton.

## Experiment 1B: No Tool

The results from Experiment 1A demonstrated that targets illuminated with a laser pointer were judged to be closer than those that were pointed at with a baton. However, it is unclear whether the use of a laser pointer compressed the perception of space or if the use of the baton resulted in an expansion of space. To address this question, participants in Experiment 1B estimated their distance to the targets without using any tools. If pointing a baton at an object causes an expansion of perceived distance, then we would expect this no tool control to resemble the laser pointer condition in Experiment 1A. On the

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[1] Like research on spatial compression in peripersonal space (e.g. Witt et al., 2005), distance estimations in the present experiment were provided by verbal report. Although verbal reports of distance can be inaccurate (Pagano & Bingham, 1998), these subjective reports nevertheless correlate strongly with the physical dimensions of the environment as well as other measures of distance (Philbeck & Loomis, 1997). Verbal reports also adhere to established principles of perception such as Weber's Law. Thus, verbal reports provide a valid method of determining the extent to which perception changes as a result of cognitive and environmental manipulations.

[2] The laser pointer weighed 40 grams less than the baton. While, substantial weight differences (e.g. 9 kg–16 kg or 20% of body weight) between held objects can influence perceptual judgments (Bhalla & Proffitt, 1999), the weight differential between our laser pointer and baton amounted to less than one tenth of one percent body weight. While we consider it unlikely that such a small weight differential can lead to the observed effects, we will conclusively rule this possibility out in Experiment 2.

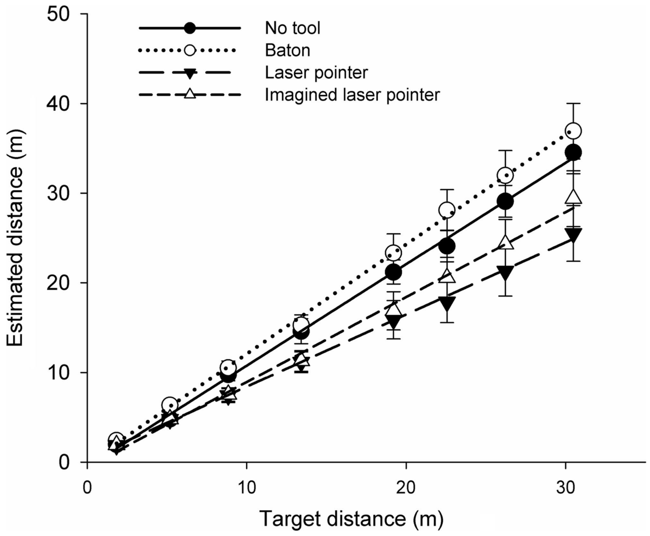

*Figure 1.* Mean estimated distance to the target as a function of the target's physical distance and the tool held by the observer in Experiment 1A (baton, laser pointer), Experiment 1B (no tool), and Experiment 1C (imagined laser pointer). Error bars represent 1 SEM. Lines represent linear regressions.

other hand, if interacting with the target compresses space, performance without a tool should resemble that obtained in the baton condition of Experiment 1A.

## Method

**Participants.** Twenty new and experimentally naïve University of Notre Dame undergraduates participated in exchange for course credit.

**Apparatus, procedure, and design.** The methodological details of Experiment 1B were identical to those of Experiment 1A with the only exception being participants did not hold a tool during the task. Instead, participants held their arms at their sides.

## Results

We first compared mean distance estimations from the no-tool condition to estimations from the baton condition of Experiment 1A in a 2 (tool condition: no-tool, baton) × 8 (physical distance to target: 1.8m, 5.2m, 8.8m, 13.4m, 19.2m, 22.6m, 26.2m, 30.5m) mixed factors ANOVA; the results are illustrated in Figure 1. Distance estimations increased as physical distance to the target increased, $F(7, 266) = 170.65$, $p < .001$, $\eta_p^2 = .82$. However, there was no difference in the magnitude of the estimations between the no-tool and baton conditions, $F(1, 38) < 1$, nor did tool condition interact with physical distance to the target, $F(7, 266) < 1$. This indicates that estimations made without a tool were not different from those made with a baton.

We next compared estimations from the no-tool condition to the laser pointer condition of Experiment 1A in a 2 (tool condition: no-tool, baton) × 8 (physical distance to target: 1.8m, 5.2m, 8.8m, 13.4m, 19.2m, 22.6m, 26.2m, 30.5m) mixed factors ANOVA; the results are also illustrated in Figure 1. Distance estimations again increased as physical distance to the target increased, $F(7, 266) = 207.36$, $p < .001$, $\eta_p^2 = .85$. The magnitude of estimations was larger in the no-tool compared to the laser pointer condition, $F(1, 38) = 10.39$, $p < .005$, $\eta_p^2 = .22$. Furthermore, tool condition and physical distance to the target interacted, as the difference between estimations made in each condition increased as physical distance increased, $F(7, 266) = 5.92$, $p < .001$, $\eta_p^2 = .14$. Collectively, then, the results from Experiment 1B support the notion that illuminating a target with a laser pointer caused a truncation of perceived space, while ruling out the alternative explanation that pointing with a baton caused a spatial expansion.

# Experiment 1C: Imagined Tool Use

When one remotely interacts with an object by illuminating it with a laser pointer, one also receives visual feedback from the light reflecting off of the surface of that object. Thus, it is possible that this additional visual cue—and not the interaction per se—drove the compression of perceived space. To address this issue, participants were given a nonfunctional laser pointer but were told to use it as if it was working properly and to imagine illuminating the target with it. In doing so, any visual feedback that would be associated with typical laser pointer usage was removed, but the intention to interact was preserved. Thus, if spatial compression is evident in this imagined tool use condition (i.e., estimates are shorter than those from the baton condition in Experiment 1A), then it cannot be the case that the visual feedback available in previous experiments drove the compression of perceived space.

In addition to ruling out visual feedback as the source of the compression effect, observing spatial compression in Experiment 1C would be of substantial theoretical interest because it would reveal some degree of equivalence between perceptual and imagined interactions. It is known that imagining an action can cause the same patterns of neural activation (Creem-Regehr & Lee, 2005; Higuchi et al., 2007) and perceptual alteration (Davoli & Abrams, 2009; Vishton et al., 2007) as actual performance. Furthermore, according to the action-specific account of perception, all intended interactions, as long as they are feasible, should affect perception; indeed, targets just beyond reach looked closer when perceivers imagined holding a tool while reaching to them (Witt & Proffitt, 2008). Most relevant for our purposes, the imagined illumination of a distant target meets the criteria of an intended interaction. Thus, we would predict that a compression of perceived space should be observed in this situation. Moreover, the magnitude of the compression effect should be similar to that observed in Experiment 1A where observers engaged in real interactions with the target.

## Method

**Participants.** Twenty new and experimentally naïve University of Notre Dame undergraduates participated in exchange for course credit.

**Apparatus, procedure, and design.** The methodological details of Experiment 1C were identical to those of Experiment 1A with the following exceptions. All participants were given a laser pointer, removed of its batteries, to point at the target.[3] Participants were told that the laser pointer was broken, but that they should nevertheless use it as if it was working properly and to imagine illuminating the target with it. The baton condition from Experiment 1A also served as the control condition in Experiment 1C.

## Results

Mean distance estimations from the imagined laser pointer condition were compared to estimations from the baton condition of Experiment 1A in a 2 (tool condition: imagined laser pointer, baton) × 8 (physical distance to target: 1.8m, 5.2m, 8.8m, 13.4m, 19.2m, 22.6m, 26.2m, 30.5m) mixed factors ANOVA; the results are illustrated in Figure 1.

Distance estimations increased as the physical distance to the target increased, $F(7, 266) = 160.43$, $p < .001$, $\eta_p^2 = .81$. Importantly, distance estimations were overall greater in the baton condition compared to the imagined laser pointer condition, $F(1, 38) = 4.95$, $p < .05$, $\eta_p^2 = .12$. These factors interacted as the differences between the two tool conditions were magnified as physical distance increased, $F(7, 266) = 2.70$, $p < .015$, $\eta_p^2 = .07$. Planned comparisons revealed significant differences between tool conditions at the six nearest target locations, all $t$s(38) > 2.23, all $p$s < .035. Numerically, these trends continued through the two farthest locations, although increased variability in responses resulted in statistically marginal effects, all $t$s(38) > 1.72, all $p$s < .09.

To compare the effects of imagined tool use and real tool use on perception, we contrasted the distance estimations derived from the laser pointer condition of Experiment 1A and the imagined laser pointer condition of Experiment 1C in a 2 (tool condition: laser pointer, imagined laser pointer) × 8 (physical distance to target: 1.8m, 5.2m, 8.8m, 13.4m, 19.2m, 22.6m, 26.2m, 30.5m) mixed factors ANOVA. Not surprisingly, distance estimations increased as the distance to the target increased, $F(7, 266) = 204.66$, $p < .001$, $\eta_p^2 = .84$. However, there was no main effect of tool condition, [$F(1, 38) = 1.20$, $p = .28$, $\eta_p^2 = .03$] nor did tool condition interact with distance to the target [$F(7, 266) = 1.57$, $p = .15$, $\eta_p^2 = .04$], thus indicating that there were no reliable differences in distance estimations whether use of a laser pointer was real or imagined.

## Discussion

In Experiment 1A, we presented evidence that objects are perceived to be closer when they are acted upon by remote tools than when they are not. When participants illuminated a target with a laser pointer, we observed a roughly 30% reduction in distance estimations compared to a noninteractive condition in which participants pointed at the target with a baton. The results from Experiment 1B then showed that this effect is not reflective of an expansion of perceived space caused by the use of the baton, but rather by a compression of space resulting from use of the laser pointer. The results from Experiment 1C demonstrated that the compression of space resulting from the use of a laser pointer did not arise from visual feedback but rather from the intended action, even when that action was simply imagined. From this evidence, it is clear that remote tool use affects the perception in a manner similar to that previously observed with physical interaction with objects near the body (Witt et al., 2005; Witt & Proffitt, 2008).

Experiment 1 has additionally shown that imagined remote interaction produced a perceptual compression analogous to that of an actual remote interaction. This finding is in agreement with others that show how motor simulations have neurological (Creem-Regehr & Lee, 2005; Higuchi et al., 2007), attentional (Davoli & Abrams, 2009), and perceptual (Vishton et al., 2007; Witt & Proffitt, 2008) consequences that are akin to those of actual performance. Furthermore, this finding aligns with a host of demonstrations suggesting functional equivalence between imagery and perception (see Finke, 1980, 1985; Ganis et al., 2009; Kosslyn, 1994). With respect to the action-specific account of perception, our results suggest that the environment may be perceived in terms of remote interactions even if they are only intended and not actually performed. Notably, though, imagined interactions may only influence perception if the imagined action can be physically performed. For instance, Witt and Proffitt (2008) showed that when participants imagined that their arm could stretch and reach targets presented beyond arm's reach, the targets did not look any closer than when they did not imagine this impossible action. Thus, it does seem that there are limits to what the imagination can do for perception.

In summary, the spatial compression observed for remote interactions in Experiment 1 mirrors situations where a tool is used to extend reachable space (Witt et al., 2005). Witt and colleagues (2005) speculated that the truncation of perceived space was a support for an action-specific account of perception, in which the environment is perceived in terms of the actions it affords the observer. It may be inferred from the present findings, then, that the environment is also perceived in terms of remote interactions. In Experiments 2 and 3, we further investigate this perceptual effect by considering the degree to which it is affected by the intended purpose of the tool and persist in long-term memory, respectively.

# Experiment 2

In studies that look at the effect of tool use on perceptual processing, the tool was typically used to manipulate whether the target could be acted upon or not (e.g., Witt et al., 2005). In the current study, we examined if perception is also sensitive to the nature of the intended interaction. In particular, we looked at whether the perceived distance to the target varied as a function of whether participants intended to bring the object closer (by using a vacuum) or move it farther away (by using a blower).

## Method

**Participants.** Thirty new and experimentally naïve University of Notre Dame undergraduates participated in exchange for course credit.

**Apparatus, procedure, and design.** The methodological details of Experiment 2 were identical to those of Experiment 1 with the

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[3] Removing batteries resulted in a 20 gram reduction in weight relative to the functional laser pointer in Experiment 1A. A separate sample of eight observers performed at chance when attempting to determine the heavier of the functional and battery-less laser pointers.

following exceptions. Experimentation was conducted in a shorter basement hallway (14.1 m long and 1.6 m wide) of the psychology building at the University of Notre Dame. The target could be placed at four possible locations: 1.8m, 5.2m, 8.8m, or 13.4m away from the observer. There were two observations per location for a total of eight experimental trials. The order of locations was randomized with the exception that a location could not be repeated on the trial immediately following its first occurrence.

All participants held the nozzle of an industrial vacuum cleaner throughout the experiment. In the two interactive conditions, the industrial vacuum cleaner was powered "on" and functioned either as a vacuum (taking in air) or as a blower (expelling air). Prior to beginning the experiment, participants in these conditions were informed of the mode in which the industrial vacuum was operating (vacuum or blower) and were asked to momentarily hold their unoccupied hand up to the mouth of the nozzle so as to physically experience the direction of airflow. These participants were instructed to point the nozzle at the center of the target as if to use the tool to act upon the target in its current mode (vacuum or blower). Importantly, the target was not physically affected in the vacuum and blower conditions (i.e., it did not actually move closer or farther away as a result of the tool use). Additionally, there was a control condition in which the nozzle of the vacuum was detached from the rest of the device. To limit potential influences of imagined interaction (Experiment 1C), the remaining components of the machine were out of sight and switched "off". Participants in this control condition were told nothing about the nozzle except that they would be using it to point. An equal number of participants were assigned to the vacuum, blower, and control conditions. All participants were instructed to point the nozzle at the center of the target and, when they felt they had successfully done so, estimate their distance from the target.

## Results

Mean distance estimations were submitted to a 3 (tool condition: vacuum, blower, control) $\times$ 4 (physical distance from target: 1.8m, 5.2m, 8.8m, 13.4m) mixed factors ANOVA. Results are illustrated in Figure 2.

Distance estimations increased as the physical distance to the target increased, $F(3, 81) = 184.80$, $p < .001$, $\eta_p^2 = .87$. Importantly, estimations were overall greater in the control condition compared to the vacuum and blower conditions, $F(2, 27) = 4.92$, $p < .02$, $\eta_p^2 = .27$. Furthermore, tool condition interacted with physical distance such that the differences in estimations between the control condition and both experimental conditions increased as physical distance increased, $F(6, 81) = 4.36$, $p < .005$, $\eta_p^2 = .24$. Planned comparisons revealed significant differences between blower and control conditions at target locations 2, 3, and 4 [$ts(18) > 2.78$, $ps < .015$], and significant differences between vacuum and control conditions at target locations 2 [$t(18) = 2.63$, $p < .02$] and 4 [$t(18) = 2.18$, $p < .05$].

## Discussion

A compression of perceived distance was observed when participants used an industrial vacuum as if to interact with the target, regardless of whether the industrial vacuum was operating as a vacuum or as a blower. If the potential consequences of tool-use dictated the direction of the perceptual distortion, then an expansion of space should have been observed when using it as a blower (as a blower has the intended outcome of pushing an object away), which was not the case. Rather, it appears that perception was sensitive to the potential for and intention of interaction in general, as a truncation of space was found for both functional modes of the industrial vacuum but not when participants held a detached nozzle and there was no explicit intention to interact with the target. Indeed, those findings are in line with analogous compressions of space that were observed when intended remote interactions were actualized (Exp. 1A) or merely imagined (Exp. 1C)[4].

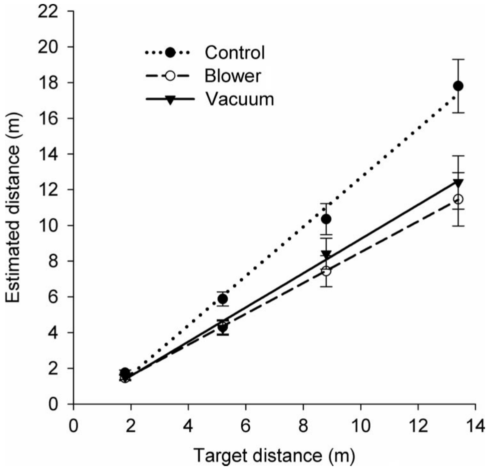

*Figure 2.* Mean estimated distance to the target as a function of the target's location and type of tool used to act on the target for Experiment 2. Error bars represent 1 SEM. Lines represent linear regressions.

## Experiment 3

The intention to use a tool seems to clearly produce a compression of perceived space, whether that usage is direct (e.g., Witt et al., 2005) or remote (Exp. 1A), completed (e.g., Witt et al., 2005; Exp. 1A of the present study) or mentally simulated (Exp. 1C), designed to attract or repel (Exp. 2). It is uncertain, however, whether spatial compression is a transient perceptual distortion or if it is a feature of the environment that persists in memory after the interaction has terminated. There is reason to suspect the latter. The formation of an action plan can cause changes in perception that persist several minutes beyond the final completion of the planned action (Vishton et al., 2007), and receptive fields of peripersonal-related neurons can stay expanded from tool-use after the tool has been discarded (Iriki et al., 1996). These findings suggest the persistence of perceptual distortions, but leave open the question of whether those distortions persist in long-term memory.

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[4] The detached nozzle in the control condition weighed less (475 grams) than the nozzle in the experimental conditions due to the additional weight of the hose (700 grams). However, distance estimations were larger in the control condition. We are thus able to rule out the alternative explanation that spatial compression observed in Experiment 1 was attributable to the lesser weight of the laser pointer. Taken together, these findings demonstrate that there was no correlation between the weight of the implements used in this study and perceived distance.

In Experiment 3, then, we examined whether participants would remember an environment with which they interacted as being spatially compressed.

We employed a cover task in which participants generated stories about scenes that were presented at varying locations in a hallway. The goal of the cover task was to provide participants a reason to deeply engage with the visual features of spatially staggered objects without explicitly making judgments about their distances. Following the cover task, participants completed a surprise memory test in which they were asked to recreate the location of each scene on a scale model of the hallway. Hence, in addition to revealing the impact of perceptual distortions on memory, the methods in Experiment 3 will also indicate whether these distortions can arise incidentally and if they can be revealed with a different dependent measure.

## Method

**Participants.** Thirty-nine new and experimentally naïve University of Notre Dame undergraduates participated in the following experiment in exchange for course credit.

**Apparatus, procedure, and design.** The experiment was conducted in the same hallway as Experiment 1. Participants were instructed to generate a story about a depicted scene that was mounted on the faceplate of the target apparatus used in the previous experiments. Three scenes were obtained from a children's coloring book centered on the theme of pond-life: a turtle (scene A), a frog (scene B), and a salamander (scene C). Each scene measured 38.5 cm wide and 47 cm tall. Scenes A, B, and C were positioned 5.2m, 13.4m, and 22.6m, respectively, from the observer, and the center of each scene was 127 cm above the floor. The order of scene presentation was randomized across participants. An equal number of participants described their story while illuminating the scene with a laser pointer, while pointing at the scene with a metal baton, or without any pointing aid (cf. Experiment 1B). Participants turned around between each trial so that they could not see the experimenter reposition the target. Following the final trial, participants were brought into the laboratory and given a surprise memory test in which they were asked to mark the location of each scene on a scale model (1 cm = 1.2 m) of the hallway.

## Results

Each participant's marks on the scale model were measured and converted to their equivalent in actual meters between observer and target. Those results were then submitted to a 3 (tool condition: laser pointer, baton, no tool) × 3 (physical distance to target: 5.2m, 13.4m, or 22.6m) mixed factors ANOVA. The results are illustrated in Figure 3.

Distance estimations increased as the physical distance to the target increased, $F(2, 72) = 534.61, p < .001, \eta_p^2 = .94$. Although distance estimations did not differ overall between the tool conditions [$F(2, 36) = 1.64, p = .21, \eta_p^2 = .08$], tool condition did interact with physical distance, $F(4, 72) = 2.70, p < .05, \eta_p^2 = .13$. Planned comparisons revealed that participants who used the laser pointer remembered Scene C as being closer than did those who used the baton [$t(24) = 2.16, p < .05$] and those that did not use a tool [$t(24) = 2.59, p < .05$]. Estimates made in the laser pointer condition were not different from the other conditions for the closer scene (scene A) [baton: $t(24) = .91, p = .37$; no tool: $t(24) = .14, p = .89$] or the middle scene (scene B) [baton: $t(24) = .21, p = .83$; no tool: $t(24) = 1.63, p = .12$].

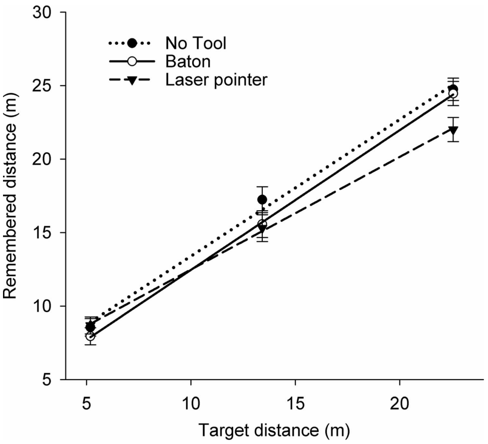

*Figure 3.* Mean estimate of the location of each scene for Experiment 3, converted to the dimensions of the hallway. Error bars represent 1 SEM. Lines represent linear regressions.

## Discussion

For very far interactions, spatial compression of the testing environment remained active in memory for several minutes beyond the termination of an interaction. This persistence in memory was only apparent for the furthest target, which may be due to the larger differences in initially perceived distance as suggested by Experiments 1 and 2 and/or our use of a task that involved incidental memory for a single viewing episode. Nevertheless, our results provide evidence that a perceptual distortion has the capacity to persist in memory. In terms of the action-specific account of perception, the present results indicate that environments can be encoded into long-term memory in terms of perceived interactions.

## General Discussion

Every day we use tools as functional extensions of our bodies to make contact with and physically influence objects that would otherwise be out of reach. However, in this "golden age of wireless" as singer/songwriter Thomas Dolby once dubbed it, more and more of our interactions with distant objects are being achieved remotely. While using a tool to extend reachable space has several known consequences on perception (e.g., Iriki et al., 1996; Reed et al., 2010; Witt et al., 2005), up until now it was unclear whether remote tool-use abided by those same rules. In the present study, we explored the consequences of remote interactions on perception and memory.

In Experiment 1A, a target that was illuminated with a laser pointer was judged to be closer than one that was simply pointed to with a baton. That finding replicates the compression of space that has been observed when a tool is used to extend reach, an effect that is thought to reflect how perception changes to express the interactions in the environment that are possible (Witt et al., 2005). Because we observed that same compression of perceived distance with a laser pointer, this implies that the intent to remotely interact with the environment meets the perceptual criteria for a feasible interaction. For the first time, then, our results provide evidence that analogous perceptual effects can be driven by direct and remote interactions and, as a consequence, that the environment is perceived in terms of both kinds of interaction.

Although a similarity between direct and remote interactions with objects was observed in the experiments reported here, there is evidence suggesting that the parallel may not be universal. Both Berti and Frassinetti (2000) and Longo and Lourenco (2006) had participants perform a line-bisection task in extrapersonal space. It is well-established that there is a slight leftward bias for bisecting lines presented in peripersonal space (see Jewell & McCourt, 2000, for a review), and indeed, in both studies that bias was observed for lines that could be reached with a stick. This suggests that the stick expanded peripersonal space to the line. However, when participants used a laser pointer to bisect a line that was beyond reach, no leftward bias was found. In this task, then, the act of shining a laser pointer is not sufficient to cause an extension of peripersonal space, thus calling into question the breadth of tasks that may be affected by remote devices.

Perhaps more curious is the discrepancy between our results and those of Witt (in press-b), who found no evidence for compression of perceived distance to targets just beyond arm's reach following use of a laser pointer. However, several potentially critical differences between her methodology and ours could explain the pattern of results. In the previous study (Witt, in press-b), participants were instructed to touch the target with the laser pointer if they could, but only to shine the light if the target was too far to touch. Thus, touching was the main action goal. In the current studies, the object was a shooting target, and thus well-suited to the type of effect that accompanies acting with a laser pointer. Furthermore, in the previous study (Witt, in press-b), the stimuli were projected onto a table such that the farthest possible target was approximately 1m away from participants. Given our finding that the magnitude of the compression effect increases over physical distance, the range of distances tested by Witt may have been too short to observe compression by remote tool use. In fact, a similar explanation could be made for a failure of laser pointers to extend peripersonal space in the line bisection task described above (Berti & Frassinetti, 2000; Longo & Lourenco, 2006). Indirect interactions with objects may require spatial separation beyond what one could reasonably expect to be within reach either by arm or by tool. In fact, laser pointers are used exactly for this purpose and observing perceptual compression at far distances is consistent with the normal use of laser pointers. Hence, the perceputal effects elicited by a tool may be related to the spatial scale within which the tool is designed to function.

In Experiment 1C, we found that the imagined use of a laser pointer caused the same perceptual distortion as actually using it. This result is consistent with prior work demonstrating that the intention to use a tool (e.g., Witt et al., 2005) or projectile (Witt et al., 2004) or to perform an action (Bekkering & Neggers, 2002; Vishton et al., 2007; Witt et al., 2010) is critical for inducing perceptual alterations. The use of imagery to generate these perceptual biases also supports claims of structural similarity between visual imagery and visual perception. Although many examples of this relationship have been observed (see Finke, 1985 and Kosslyn, 1994 for reviews), one poignant example to raise here concerns psychophysical scaling. Estimates of a perceived stimulus's properties such as length, area, or weight are related to the stimulus's physical magnitude by a power function known as Steven's Law (Stevens, 1957). Similar power functions have also been shown to describe the relationship between estimates pertaining to an imagined stimulus's properties and corresponding physical stimuli (Kerst & Howard, 1978; Moyer, Bradley, Sorensen, Whiting, & Mansfield, 1978). This suggests that actively maintained images are similar to perceptions, a notion the current research expands into action-specific interactions between observers and the environment.

In Experiment 2, we examined whether the nature of the intended interaction with the object differentially influenced perceived distance. Nearly all of the previous research used the tool to manipulate whether or not an object could be acted on. Yet, for most studies, the goal was simply to touch the object (e.g., Witt et al., 2005) or bring the object closer (e.g., Iriki et al., 1996). Being able to reach an object or being able to grasp it more easily makes the object look closer (Linkenauger et al., 2009; Witt et al., 2005) and smaller (Linkenauger, Witt & Proffitt, 2011). Desirable objects that one would want to reach and grasp also look closer (Balcetis & Dunning, 2010). In contrast, objects that should be avoided, such as the ground when viewed from a tall balcony, look farther away (Stefanucci & Proffitt, 2009). Thus, perception could reflect whether an object could be acted upon regardless of the nature of the interaction or perception could reflect the goal or anticipation of the action. To test between these possibilities, we instructed participants to use a vacuum-like device that could potentially pull the object closer or a leaf-blower-like device that could potentially push the object farther away. Although, in neither case did the target actually move in response to these actions, simply using the device as if to act upon the target was sufficient to influence perception (Experiment 2; Witt & Proffitt, 2008). We found that intending to act on the object, regardless of the type of action, made the targets look closer. Thus, perceivers see distances to objects in terms of their potential to act on the object, rather than the anticipated outcome of the action.

Finally, the results from Experiment 3 demonstrated that our interactions with objects not only affect here-and-now perceptual judgments, but they can also have consequences for remembered aspects of visual environments. Observers who illuminated distant stimuli with a laser pointer later judged them to have been closer than those who pointed with a baton. Importantly, the memory test was a surprise to participants, thus there was no reason to explicitly evaluate the distances of the scenes during the story-generation phase. As a result, interactions with objects are long-lasting and arise even when specific aspects of the environment are not explicitly encoded during a perceptual event. Memory for visual environments, then, is built not only from explicitly encoded spatial relationships, but also by incidental interactions with objects. The persistence of a distorted spatial environment in memory is in line with findings by Maravita, Clarke, Husain, and Driver (2002) of a patient with cross-modal extinction who showed prolonged (up to 60–90 min) alterations of peripersonal space representations following continuous (10–20 min) tool use.

What mechanism may account for the action-modulated perceptual effects we have described in this report? In our introduction, we described experiments that suggest tool usage can cause a remapping of neural receptive fields which in turn remap peripersonal and extrapersonal space. While this mechanism may provide an explanation for spatial distortions near the body, it is unlikely to account for spatial distortions that result from remote tool use because the extent to which receptive fields can be altered by action is limited (Graziano & Gross, 1993; Graziano & Gross, 1995; Graziano et al., 1997).

Other possibilities that may account for both proximal and distal interactions exist, however. One possibility is that the intention to interact with an object alters the spatial distribution of attention. For example, more attention may be devoted to objects when one intends to interact with them. Given the coupling between attention and perceptual awareness (e.g., Currie, McConkie, Carlson-Radvansky, & Irwin, 2000; Henderson & Hollingworth, 1999; Rensink, O'Regan, & Clark, 1997), any alteration in attention allocation may likewise alter perception. Another possibility is that both perceptual and action-based representations arise from a common code (Hommel, Musseler, Aschersleben & Prinz, 2001). Hence, the simultaneous activation of perceptual information related to visible objects, and action representations related to an observer's potential behavior, can alter an object's perceived spatial and temporal properties.

Together, the present results fit well into the emerging field of embodied cognition. There is mounting evidence that our capacity to interact with the world is a driving force in how the world is understood (e.g., Fischer & Zwaan, 2008; Glenberg, 1997), evaluated (e.g., Beilock & Holt, 2007), and perceived (e.g., Vishton et al., 2007; Witt, in press-a). Furthermore, recent research has revealed that objects in peripersonal space are processed and attended to in ways that benefit potential interaction (Abrams, Davoli, Du, Knapp, & Paull, 2008; Cosman & Vecera, 2010; Davoli, Du, Montana, Garverick, & Abrams, 2010; Reed et al., 2006). Thus, successful interaction with the environment, even if it occurs remotely, appears to not simply be one cognitive end-goal out of many, but rather may be a blueprint for how perception is structured.

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Received January 4, 2011
Revision received April 26, 2011
Accepted June 16, 2011 ■