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Spatial Representations in Older Adults Are Not Modified by Action: Evidence From Tool Use

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Theories of embodied perception hold that the visual system is calibrated by both the body schema and the action system, allowing for adaptive action–perception responses. One example of embodied perception involves the effects of tool use on distance perception, in which wielding a tool with the intention to act upon a target appears to bring that object closer. This tool-based spatial compression (i.e., tool-use effect) has been studied exclusively with younger adults, but it is unknown whether the phenomenon exists with older adults. In this study, we examined the effects of tool use on distance perception in younger and older adults in 2 experiments. In Experiment 1, younger and older adults estimated the distances of targets just beyond peripersonal space while either wielding a tool or pointing with the hand. Younger adults, but not older adults, estimated targets to be closer after reaching with a tool. In Experiment 2, younger and older adults estimated the distance to remote targets while using either a baton or a laser pointer. Younger adults displayed spatial compression with the laser pointer compared to the baton, although older adults did not. Taken together, these findings indicate a generalized absence of the tool-use effect in older adults during distance estimation, suggesting that the visuomotor system of older adults does not remap from peripersonal to extrapersonal spatial representations during tool use.

Keywords: aging, perception, embodiment, tool use, distance perception

Although the visual appraisal of the environment is often considered a merely perceptual judgment, it has been shown to be surprisingly influenced by bodily and action-based factors. For instance, broad-shouldered participants report doorway widths to be narrower than do narrow-shouldered participants (Stefanucci & Geuss, 2009), weight encumbrance can increase slope estimates (Proffitt, 2006), and size and distance estimates can vary based on sports experience (Witt & Dorsch, 2009; Witt, Linkenauger, Bakdash, & Proffitt, 2008; Witt & Proffitt, 2005). These results suggest that bodily parameters and action experience can serve to calibrate perceptual judgments, a central tenet of both embodied cognition (Barsalou, 2008) and Gibsonian ecological theory (Gibson, 1979). Such theories have argued that sensorimotor function is central to cognitive function insofar as bodily action intrinsically regulates cognitive skills (Brockmole, Davoli, Abrams, & Witt, 2013).

Embodied effects in distance perception reflect the fact that spatial representations of distant targets appear to be calibrated differently based upon their proximity to the body. Studies with patients suffering from unilateral visuospatial neglect, in which brain lesions to the parietal cortex result in inattention toward the contralateral visual field (Heilman, Watson, & Valenstein, 2003; Vallar, 1998), have found that space is coded at either near distance (within arm's reach) or far distance (Halligan, Fink, Marshall, & Vallar, 2003; Weiss, Marshall, Zilles, & Fink, 2003). This peripersonal and extrapersonal coding distinction may be flexible, however (Berti & Rizzolatti, 2002; Ladavas & Serino, 2008). For instance, when perceivers interact with a distant object through tool use, the spatial representations of the distant object can be remapped according to peripersonal body space (Berti & Frassinetti, 2000; Longo & Lourenco, 2006).

Tool use has been shown to remap spatial representations in both patient populations (Berti & Frassinetti, 2000) and in healthy young adults. For instance, Witt, Proffitt, and Epstein (2005) found

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that distance estimates of targets located just beyond peripersonal space were reduced when healthy young adult participants used a reach-extending tool to touch targets that would otherwise be out of reach. This suggests a compression of spatial dimensions that is based upon bodily action and mediated through the tool (although cf. de Grave, Brenner, & Smeets, 2011). Throughout this paper, this tool-based spatial compression will be referred to as the *tool-use effect*. More recently, Davoli, Brockmole, and Witt (2012) found that distance estimates were reduced when participants pointed at targets with a laser pointer. In this case, the spatial compression occurred without an actual physical connection between the perceiver and the perceived target and operated over distances of up to at least 30 m. This remote tool-use effect suggests that the intention to act upon the object may be more important than physical touch itself.

Taken together, these results indicate that tool use, physical abilities, and intentional action can influence perceptual judgments. These phenomena can be explained through at least two theoretical positions. First, the action-specific account of perception (Witt, 2011) argues that intentional action upon an object changes one's perception of it, a position that is broadly compatible with grounded cognition (Barsalou, 2008) and enactivist theories (Noë, 2009). Second, the extended mind position argues that the mind is not limited to the head–brain but is extended when actively engaged with tools or artifacts (Wilson, 2010), words (Borghi & Cimatti, 2010; Borghi, Scorolli, Caligiore, Baldassarre, & Tummolini, 2013), and through bodily activity itself (Clark & Chalmers, 1998). Given that both describe the mind–brain as flexibly adaptive through actions and tool use, the action-specific and extended mind approaches have been considered compatible theories (Rowlands, 2009) that are broadly consistent with embodied cognition theory (Thompson & Stapleton, 2009).

Effects of Aging on Embodied Perception

Because embodied perception research has generally relied on young adult samples, relatively little is known about its developmental trajectory. In particular, there have been few studies examining whether or how embodied effects appear in older adults. This question is important for at least two reasons. First, older adults in particular exhibit a range of physical declines, including vision limitations (Owsley, McGwin, Sloane, Stalvey, & Wells, 2001; Weale, 1986); increased likelihood for chronic illnesses (Kramarow, Lubitz, Lentzner, & Gorina, 2007); mobility problems (Lindenberger, Marsiske, & Baltes, 2000); and deficits in working memory, divided attention, and processing speed (Craik & Bialystok, 2006; Salthouse, 2012; Verhaeghen, 2011). Age-related differences in embodied perception tasks might indicate specific changes in how the body influences perceptual representations. Second, embodied perception theory is well suited to address the growing awareness within the gerontological literature that cognitive changes during aging can be linked to physical changes. For instance, older adult grip strength and gait speed are significant predictors of mental state and fluid cognition, respectively (Clouston et al., 2013), and age-related cognitive declines can be offset through aerobic exercise (Colcombe & Kramer, 2003; Voss, Nagamatsu, Liu-Ambrose, & Kramer, 2011). However, such studies have been pragmatically directed toward applied outcomes rather than toward the theoretical investigation of embodied perception.

Given the range of cognitive, perceptual, and physical changes associated with aging, it is reasonable to expect age-related performance differences in perceptual tasks that explicitly incorporate bodily factors, and there is evidence to this effect. For instance, older adults judge hill slopes to be steeper than younger adults, with estimates similar to those of younger adults who are either encumbered, fatigued, or out of shape (Bhalla & Proffitt, 1999). Similarly, Sugovic and Witt (2013) found that older adults estimated distances to be farther than younger adults and that older adult distance perception was heavily influenced by floor texture. Specifically, floors that were covered in plastic tarp (and therefore difficult to walk upon) elicited farther distance estimates compared to floors covered in carpet (and therefore easier to walk upon). Hackney and Cinelli (2013) also found age-related embodied effects when older and younger participants walked through doorways of varying aperture widths, with older adults producing larger and more variable shoulder rotations compared to younger adults, but age group equivalence in nonwalking aperture judgment conditions. Collectively, these studies have argued that age-related physical changes can affect the perceptual judgments of older adults. In particular, older adults may be compensating for balance declines by adaptively adjusting their spatial judgments (Hackney & Cinelli, 2013; Sugovic & Witt, 2013), especially when action responses are required.

Age-related differences in the action–perception relationship are also evident in attentional tasks directed toward bodily action. Bloesch, Davoli, and Abrams (2013) examined the attentional reference frames that young and older adults used when performing goal-directed hand actions (i.e., reach-and-point movements). Consistent with prior research (e.g., Tipper, Lortie, & Baylis, 1992), Bloesch et al. (2013) found that young adults adopted an attentional reference frame that was action centered, such that the space along the hand's action path received prioritized visual attentional processing. In contrast to this, older adults exhibited an attentional reference frame that was consistently body centered, even in instances in which they reached away from their bodies.

Effects of Aging on Tool Use

To date, no study has examined whether adult age differences exist in the spatial compression characteristic of tool use (i.e., the tool-use effect). This question may offer theoretical insight into the interplay between aging and the recoding of action-specific spatial representations. The tool-use effect depends upon the flexibility of the action–perception system to adjust extrapersonal spatial representations in relation to peripersonal space (Berti & Frassinetti, 2000; Longo & Lourenco, 2006). Age group differences in this capacity may indicate that the effect of aging on the action–perception system runs deeper than mere fatigue and/or imbalance problems (cf. Hackney & Cinelli, 2013; Sugovic & Witt, 2013), pointing rather to aging altering the coding of peripersonal to extrapersonal spatial representations.

Research on age-related changes in pantomiming (i.e., imitated action) indicates that older adults may have specific deficits for tool use. Older adults struggle when performing pantomimed actions (Cavalcante & Caramelli, 2009) and, importantly, such deficits are especially evident when the pantomimed actions involve tools (Mozaz, Rothi, Anderson, Crucian, & Heilman, 2002). In such cases, older adult performance is affected by a characteristic body part as object (BPO) error, in which the subject's own body part is used to represent the intended tool (Peigneux & van der Linden, 1999; Ska & Nespoulous, 1987). For instance, when asked to pantomime the brushing of teeth, subjects committing a BPO error might shape their hand as the toothbrush rather than around an imaginary toothbrush. Age-related deficits in pantomiming appear even when merely recognizing tool-based gestures (Ska & Croisile, 1998). For instance, Mozaz, Crucian, and Heilman (2009) examined two cohorts of older adults (younger–old [66–77 years] vs. older–old [78–88 years]) in gesture recognition. The oldest–old group displayed increased errors for both tool-based and non-tool-based gestures when compared to the younger–old group, but both older adult groups demonstrated significantly greater problems in recognizing tool-based actions. Such errors in recognizing and performing actions with tools is characteristic of ideomotor apraxia (Wheaton & Hallett, 2007), a neurological condition in which patients make spatial and temporal errors to pantomimed actions involving tools (Goldenberg, 2013). While normal healthy aging does not produce apraxia, the evidence suggests that older adults struggle in identifying and executing the more complex movement requirements necessary for tool-based actions. In short, the normal aging process may yield apraxia-like deficits specific for tool use (Mizelle & Wheaton, 2010). Recent work measuring hand movements during tool use supports this possibility, with older adults demonstrating altered grip preparations when reaching for tools (Cacola, Martinez, & Ray, 2012; Rand & Heuer, 2013; Sutter, Ladwig, Oehl, & Musseler, 2012).

Age-related deficits in tool use may reflect changes in brain regions involved in tool-based distance perception. In particular, brain regions that are responsible for coding peripersonal space, such as the premotor cortex, the intraparietal sulcus, and the precuneous (e.g., Cavanna & Trimble, 2006; Makin, Holmes, & Zohary, 2007) are also thought to be integral in constructing and maintaining representations of action space when one wields a tool. The effect of aging on these key brain regions is profound, with volumetric declines in the parietal lobe (Kochunov et al., 2005; Lehmbeck, Brassen, Weber-Fahr, & Braus, 2006) and decreased functional connectivity along a frontoparietal pathway essential for visual attention (Bennett, Madden, Vaidya, Howard, & Howard, 2010). Tool-use activity itself has been localized along a dorsoventral processing stream (cf. Binkofski & Buxbaum, 2013; Gallivan, McLean, Valyear, & Culham, 2013) that includes the superior temporal and inferior parietal regions (Buxbaum & Kalenine, 2010), the anterior supramarginal gyrus (Orban & Caruana, 2014), and the ventral premotor cortex (Fridman et al., 2006), a broad network with regions vulnerable to age-related changes (Davis et al., 2009; Pardo et al., 2007).

In summary, the effect of aging on the action–perception system is complex and poses a potential paradox. On the one hand, older adults exhibit increased embodied perception effects when making spatial judgments under conditions of physiological strain (Bhalla & Proffitt, 1999), when actively walking on difficult floor textures (Sugovic & Witt, 2013), and when determining widths of door apertures (Hackney & Cinelli, 2013). These age-related increases of embodied effects may serve as a compensatory mechanism for physiological or sensory-level deficits. On the other hand, there is evidence indicating that older adults may have specific deficits for tool use (Mozaz et al., 2009) and exhibit body-centered (and not action-centered) attentional reference frames (Bloesch et al., 2013), suggesting an age-related decline in extending spatial representations when using tools. Older adults, therefore, may represent an important test case for two theoretical positions that are frequently viewed as complementary: the embodied (Barsalou, 2008) and action-specific positions (Witt, 2011), which argue that bodily action can alter perceptual judgments, and the extended mind position, which argues that mental agency can be extended through the body, tools, and other instruments (Borghi & Cimatti, 2010; Borghi et al., 2013; Wilson, 2010). These positions are often conjoined (Thompson & Stapleton, 2009), given their overlapping appreciation of bodily action on perception. However, this research is typically directed to younger adult samples, and older adults may represent a dissociation of the two positions, given their increased embodied effects (Bhalla & Proffitt, 1999; Hackney & Cinelli, 2013; Sugovic & Witt, 2013) yet diminished sensitivity during tool use (Cavalcante & Caramelli, 2009; Mozaz, Crucian, & Heilman, 2009; Ska & Croisile, 1998).

The Current Study

In the current study, we consider the specific hypothesis that the tool-use effect in distance perception may be diminished in older adults given the aforementioned behavioral and neuroimaging evidence suggesting age-related changes in the representation of tool-based action. We examined this hypothesis in the context of both direct and remote tool use in distance estimation. Specifically, in Experiment 1, we tested age-related differences in the perception of targets that could be reached with the aid of a reach-extending tool. In Experiment 2, we examined whether such age-related differences would also be observed when interaction was mediated through remote tool use, without any direct physical contact with the target.

Experiment 1

There is ample evidence showing that reach-extending tools can be incorporated into representations of peripersonal space. For instance, patients who neglect peripersonal, but not extrapersonal, visual space confer this neglect to extrapersonal space during tool use (Berti & Frassinetti, 2000). In healthy humans, tool use can also change perception. When a person is given a tool to extend reachable space, the objects are perceived to be closer than without the tool (Witt & Proffitt, 2005; Witt & Proffitt, 2008). This finding is thought to reflect an action-specific bias in perception, such that the environment is represented in terms of feasible interactions (e.g., Witt, 2011).

Although little work has been done to examine the effects of tool use on perception in older adult samples, there is reason to suspect that older adults may not show the pattern of tool-induced spatial compression (i.e., tool-use effect) that has been repeatedly observed in young adults. Given the aforementioned behavioral evidence of older adult changes in visuomotor attentional reference frames (Bloesch et al., 2013), decreased sensitivity for tool-based pantomimes (Mozaz et al., 2002; Mozaz et al., 2009; Peigneux & van der Linden, 1999; Ska & Nespoulous, 1987), and age-related changes to brain regions critical for action–perception capacity (Davis et al., 2009; Pardo et al., 2007), it is expected that the tool-use effect will be reduced in older adult participants. We directly tested this notion here by comparing young and older adults on the extent to which tool use affected their subsequent judgments of distance.

Method

Participants. Forty-five older adults (mean age: 70.88 years; range = 65–85 years) and 32 young adults (mean age: 19.18 years; range = 18–21 years) participated in the study. Older adults were recruited from the Washington University in St. Louis Psychology Department's older adult volunteer pool, and younger adults were recruited from Washington University's undergraduate population. Participant details are summarized in Table 1. All research procedures were approved by Washington University's Institutional Review Board. Participants were screened for handedness, physical ability, and health. Participants were excluded if they had any self-reported neurological disorders; were left-handed; did not have full use of their right hand, arm, and shoulder; had a diagnosed movement disorder; or had a diagnosed eye disease. From the original recruitment of 48 older adults and 33 younger adults, three older adults and one young adult were excluded for failing to follow instructions. Older adults completed this experiment as part of a larger protocol, which lasted approximately 2.5 hr. In the session, older adults completed a nonstrenuous perceptual task (viz., the rubber hand illusion) prior to testing in the current distance estimation task. Young adult participants completed the experiment in a single session, and both age groups completed the distance estimation task within 30 min. Older adults were compensated $10 per hour of participation, and young adults received course credit.

Stimuli, apparatus, and procedure. Participants provided distance estimates to a target circle presented at varying locations on a table by adjusting the distance between two reference circles until both distances perceptually matched. The experimental setup is shown in Figure 1. Participants sat at a 152.4 × 152.4 cm table that was covered with white fabric. A yellow circle (2.54 × 2.54 cm) was affixed to the table centered at the midline of the participant's body, 20 cm from the edge of the table. A projector that was mounted from the ceiling projected the yellow target and white reference circles, all 2.54 cm in diameter. The yellow target circle could appear at one of 10 different locations 44, 49, 54, 59, 64, 69, 74, 79, 84, or 89 cm away from the fixed yellow circle. The two reference circles had an initial separation of 6.35 cm and were always 35.88 cm away in the participant's proximodistal axis.

Participants were told that at the beginning of each trial they would see a yellow circle projected onto the table that would be a variable distance away but always centered at their midline. When

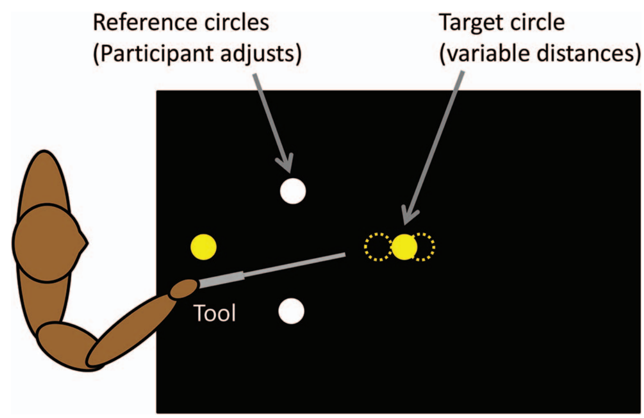

Figure 1. Experiment 1 setup. A yellow circle was affixed to the table near the participant's body, and a second yellow target circle was projected onto the table at a variable distance. Participants were to reach out with either their hand and point to the yellow target circle or reach out with a tool and touch the yellow target circle (simulated in this figure for clarity). Two white reference circles were then projected onto the table, and participants used response buttons to adjust the distance between the two white dots until it perceptually matched the distance between the two yellow dots. See the online article for the color version of this figure.

they saw this circle, they were to reach out and point to its location on the table, maintaining the gesture until the white reference circles appeared on the table 5 s later. When the reference circles appeared, participants brought their hands back to their bodies and then adjusted the distance between the reference circles until it matched the distance between the yellow circles. The reference circles could be moved by pressing one of two large buttons that were fixed to a board that was held on the participants' laps. The left button increased the distance between the reference circles, and the right button decreased the distance. Participants were instructed to be as accurate as possible and were given an unlimited amount of time to make each estimate. After the estimate was made, any key on the computer keyboard was pressed, which recorded the response and began the next trial.

There were two conditions, hand pointing and tool touching, which were manipulated within subjects. In the hand-pointing condition, participants reached out with their right hands and pointed to the location of the projected yellow circle. In the tool-touching condition, participants reached out with a 64.77-cm-long rod-like tool held in their right hands and touched the location of the projected yellow circle. The distances of the projected yellow circles were such that the circles were beyond reach of the hand but within reach of the tool for all participants. Each distance was presented once per block. Participants completed eight blocks of 10 trials, with the order of distances independently randomized within each block. Participants used one condition for the first four blocks and the other condition for the final four blocks, with condition order counterbalanced across participants. Participants received four practice trials at the beginning of each half of the experiment. Distances of the projected yellow circle were randomly chosen for these trials, and the experimenter was present to ensure that participants understood the task. During the experiment, no feedback was given. Older adult participants were alone in the experimental room during the session following the practice

Table 1
Participant Characteristics by Age Group for Experiment 1

	M		*SD*	
	Younger	Older	Younger	Older
Age (years)	19.18_a	70.88_b	1.14	3.91
Vision	$20/21.7_a$	$20/24.6_b$	3.72	5.16
Education (years)	13.20_a	15.57_b	1.18	2.44

Note. n = 33 for younger adults and 45 for older adults. Means in the same row that do not share subscripts differ by t test at $p < .05$. Vision was assessed using a Snellen chart.

trials, and young adult participants completed the session with the experimenter in the room to record their responses.[1] The testing session required around 30 min to complete; to prevent fatigue, participants were allowed to take breaks during the experiment and were provided a formal break halfway through the testing session. Testing time was equivalent across the two age groups.

Results

Participants' perceived distances to the yellow projected circle were found by calculating the distance between the two reference circles at the end of each trial. These estimates were analyzed using a 2 (Group: young, old) × 2 (Reach: hand, tool) × 10 (Distance: 44–89 cm) mixed-factors analysis of variance (ANOVA). As expected, there was a main effect of distance, such that as the distance between the projected yellow circle and the fixed yellow circle increased, participants' distance estimates increased also, $F(9, 675) = 1{,}134.85$, $p < .001$, $\eta^2_p = .94$. Overall, young and older adults were not significantly different in distance estimation, $F(1, 75) = 1.05$, $p > .05$. Importantly, however, there was a significant Group × Reach × Distance interaction, $F(9, 675) = 2.59$, $p = .006$, $\eta^2_p = .03$. As has been found previously, young adults showed a compression of perceived distance when reaching with the tool: Distance estimates were smaller after a tool reach than after a hand reach, with the difference between the two reach types getting slightly larger as the distance increased (Figure 2A). Older adults did not show this pattern. Instead, older adults' distance estimates were not affected by the type of reach they performed (Figure 2B).

The two age groups were also analyzed separately. Young adults showed a significant reach main effect, $F(1, 31) = 15.07$, $p = .001$, $\eta^2_p = .33$, and a significant Reach × Distance interaction, $F(9, 279) = 2.52$, $p < .01$, $\eta^2_p = .08$, with distance estimates being smaller after reaching with the tool than with the hand and this difference getting larger as the distance increased. Older adults, however, showed neither a main effect of reach, $F(1, 44) = 1.01$, $p > .10$, $\eta^2_p = .02$, nor a Reach × Distance interaction, $F(9, 396) = 1.16$, $p > .10$, $\eta^2_p = .03$.[2]

Discussion

It has been repeatedly found that using a tool to reach out and interact with a distant object causes the object to be judged as closer than when that same object cannot be interacted with (Bloesch et al., 2013; Bloesch, Davoli, Roth, Brockmole, & Abrams, 2012). In the present experiment, young adults showed this typical pattern of spatial compression after reaching to a projected object with a reach-extending tool. Older adults, however, did not show this pattern. Older adults had similar distance estimates for objects regardless of whether they reached for the object with their hands or with a tool—the ability to interact did not affect distance perception. In fact, the distance judgments for older adults were numerically smaller after reaching with their hands. This pattern is inconsistent with what would be expected if older adults were using the tool to functionally extend their peripersonal space.

Young adults are able to incorporate a tool into their peripersonal space representations, allowing those representations to extend outward to include the length of the tool (Holmes, Calvert, & Spence, 2004; Witt & Proffitt, 2005; Witt & Proffitt, 2008). It is presumed that this ability relies on an accurate and flexible representation of the body and near-body, or peripersonal, space. Given that the neural regions that code and update peripersonal space decline with age (Kochunov et al., 2005; Lehmbeck et al., 2006), older adults may not have a representation that is as flexible as that of young adults. Because of this, older adults may not have the ability to flexibly accommodate a tool in their peripersonal space representations, and thus they demonstrate a diminished tool-use effect.

Experiment 2

The central finding in Experiment 1 was the disappearance of the tool-use effect in older adults, with older adults not displaying the spatial compression that is characteristic of younger adults' perception of distance during tool use (Witt & Proffitt, 2005). In Experiment 2, we examined whether this pattern may also be evident during far-distance estimation with remote tool interaction, with "far" defined as extrapersonal space beyond immediate reaching distance. It is reasonable to predict an equivalent age-related absence of the tool-use effect at farther distances, given that the spatial compression characteristic of tool use is broadly equivalent during both peripersonal and extrapersonal distance estimates (Brockmole et al., 2013; Davoli et al., 2012). However, the brain regions coding for peripersonal and extrapersonal space are anatomically distinct (Berti & Frassinetti, 2000; Ladavas & Serino, 2008) and change unevenly in aging (Kochunov et al., 2005; Lehmbeck et al., 2006) and, as such, the results from Experiment 1 may not generalize to farther distances.

To explore this possibility, we examined age group differences of the tool-use effect during far-distance perception. Older and younger adult participants were asked to estimate distances of targets placed along a long hallway by verbally reporting target distances under one of two conditions. In the first condition, participants pointed a laser pointer beam toward the center of a target prior to and during distance estimation (the "laser" condition). In the second condition, participants pointed a metal baton (approximately 14 cm in length) toward the center of a target prior to and during distance estimation (the "baton" condition). We expected that for younger adults, the laser pointer condition would elicit decreased distance estimates indicative of spatial compression, following Davoli et al. (2012). If the results of Experiment 1 are indicative of a generalized age-related absence of tool-use effect, then older adults should show no differences in distance estimates between conditions.

[1] The age group differences in testing conditions reflect pilot testing with younger adults, who responded more carefully when the experimenter sat nearby. Older adults did not need this additional motivation.

[2] Secondary analyses were conducted to explore individual differences among the older adults. We computed for each older adult subject the difference at each distance between the hand-point and tool-point conditions (hand–tool) and then correlated that difference score with participant age for the older adults only. There was a significant correlation between the difference score and age, $r(45) = -.313$, $p = .036$, indicating that increasing age was associated with diminished difference scores. However, this effect was driven by the three older adults who were over 75 years old, and their removal negates the association, $r(42) = -.049$, $p = .757$.

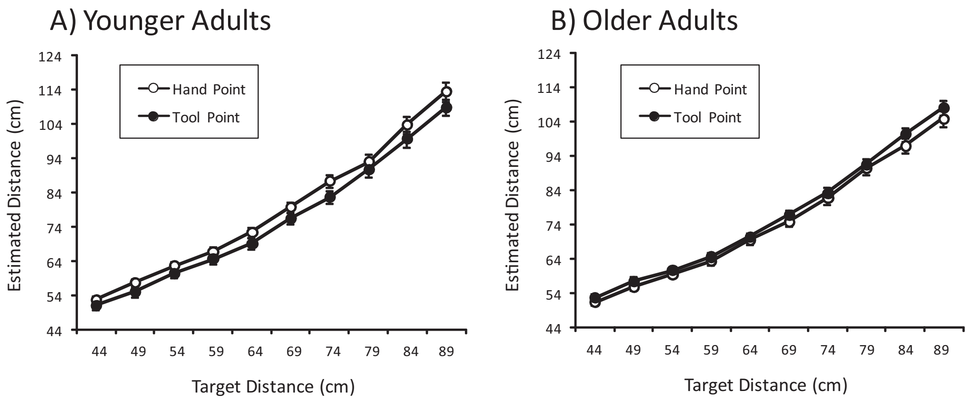

Figure 2. Perceived distance of the projected object as a function of distance and reach type for Experiment 1 for younger adults (A) and older adults (B). Error bars represent standard errors.

Method

Participants. Fifty-two older adults (mean age: 68.04 years; range = 60–80 years) and 52 younger adults (mean age: 22.40 years; range = 18–33 years) participated in the study. Younger adults were drawn from the undergraduate student population of Indiana University South Bend (IUSB), and older adults were drawn from local newspaper ads. All research procedures were approved by the IUSB Institutional Review Board, and all participants provided written, informed consent. From the original recruitment of 58 older adults and 56 younger adults, eight participants (four older) were removed from the data set because they had more than three distance estimates that were deemed extreme outliers, and two older participants were removed from the data set because of Mini-Mental State Exam (MMSE) failures (scored <27). Testing took place in one session of approximately 1.5 hr. Participant characteristics in a range of cognitive and perceptual capacities were assessed prior to the distance estimation tasks and are presented in Table 2. All participants possessed distance visual acuity (corrected) of at least 20/40 (Bach, 1996) and at least 27 out of 30 points on the MMSE (Folstein, Folstein, & McHugh, 1975).

Table 2
Participant Characteristics by Age Group for Experiment 2

	M		*SD*	
	Younger	Older	Younger	Older
Age (years)	22.40_a	68.04_b	3.78	5.59
Education	13.69_a	15.71_b	1.48	2.19
FRACT	-0.15_a	-0.04_b	0.12	0.13
MMSE	29.23_a	28.88_a	0.90	1.10
Gait speed	8.61_a	9.14_b	1.17	1.47
RAPID	1.67_a	3.42_b	2.55	3.95
ROS	7.63_a	5.54_a	6.76	5.07
Fatigue	1.72_a	1.54_a	2.20	2.21

Note. $n = 52$ per age group. FRACT = visual acuity in logMar, with 0.0 equivalent to Snellen 20/20 (Bach, 1996); MMSE = score (maximum of 30) on Mini-Mental Status Examination (Folstein, Folstein, & McHugh, 1975); gait speed = mean speed (in seconds) during comfortable walking across 12.2 m. interior distance; RAPID = rheumatology assessment patient index data subtest within the Multi-Dimensional Health Assessment Questionnaire (MDHAQ); ROS = review of symptoms subtest within the MDHAQ (maximum of 60); fatigue = fatigue subtest scale within MDHAQ (maximum of 10). Means in the same row that do not share subscripts differ by *t* test at $p < .05$.

Embodied perception effects in distance perception have been shown to be sensitive to bodily parameters, such as fatigue (Bhalla & Proffitt, 1999), physical effort (Witt, Proffitt, & Epstein, 2004), and physical pain (Witt et al., 2009). To clarify the relative health status of the two age groups, participants were administered the Multi-Dimensional Health Assessment Questionnaire (MDHAQ R808-NP2). The MDHAQ is divided into three subtests: (a) the rheumatology assessment patient index data (RAPID), a measure of physical function, pain levels, and global pain estimates; (b) the review of symptoms (ROC), a checklist of health problems, with scores greater than 30 indicating possible fibromyalgia; and (c) a fatigue index that is scaled from 0 (*fatigue is not a problem*) to 10 (*fatigue is a major problem*). Finally, participants were timed while walking comfortably across a 12.2 m. distance. Gait speed has been shown to be a reliable predictor of survival rates in older adults (Cesari et al., 2005) and as a general measure of well-being among older adults (Hall, 2006).

Stimuli, apparatus, and procedure. The target was a standard black and white hunting bull's-eye (25.4 cm in diameter) affixed to a wooden frame. The wooden frame was composed of a base (30.48 × 35.56 × 2.54 cm), a supporting pole (5.08 × 10.16 × 121.92 cm), and a face board (30.48 × 30.48 × 2.54 cm). The hallway used was an infrequently trafficked hallway at IUSB. It was brightly lit by overhead lights and measured 2.36 m high × 1.29 m wide × 27.13 m long. Participants estimated targets while using either the laser pointer or the baton. The laser pointer was an Apollo MP 1350 Slim Line Executive laser pointer that measured 13.97 × 1.91 cm. The baton was a metal rod that closely matched the laser pointer in color (silver), shape, size, and weight. The target was placed along the hallway at five possible distance points 3.4, 7.9, 13.4, 20.4, and 25.3 m away from the participant. Each distance point was assessed twice to derive a mean value, therefore resulting in 10 estimates per participant overall. The order of target locations was pseudorandomized, with five different location orders that were evenly distributed across participants.

The participant stood at the end of a long hallway, and the experimenter placed the target at various points along the hallway.

Figure 3 shows the experimental setup. Participants reported the distances of the targets under one of two conditions. In the laser condition, participants were instructed to direct the laser beam toward the center of the target before and during target estimation. In the baton condition, participants were instructed to direct the baton to the center of the target before and during target estimation. After every target estimate, the experimenter moved the target to the next location. To reduce the possible influence of the experimenter's walking as a visual cue of distance, participants were instructed to turn their backs to the experimenter between distance assessments. During the initial instruction phase, participants were given two sample distance points (at 4.6 and 10.1 m) in a hallway adjacent to the testing hallway. The distance estimation session took approximately 20 min, and the testing format was identical for the two age groups. Note that unlike Experiment 1, where the tool condition was a within-subjects factor, in the current experiment, the tool condition was between subjects. Previous research on remote tool effects on distance estimation has found that imagined tool use results in equivalent spatial compression as actual tool use (Davoli et al., 2012, Experiment 1C). Accordingly, the tool condition was applied between subjects to decrease any potential transfer across the two condition levels.

Results

For each participant, we derived the mean distance estimate for each of the five tested locations based upon two estimation attempts per location. The two distance estimates were highly correlated for both younger adults (mean $r = .765$; range = .699–.851) and older adults (mean $r = .684$; range = .593–.812). Data were analyzed using a 5 (Distance: 3.4, 7.9, 13.4, 20.4, and 25.3 m) × 2 (Age Group: young, older adults) × 2 (Condition: laser, baton) repeated-measures ANOVA. The main effect of distance was significant, $F(4, 400) = 1{,}073.22$, $p < .001$, $\eta^2_p = .92$, indicating increasing verbal estimates with increasing target distances. Main effects of condition, $F(1, 100) = 2.30$, $p = .133$, and Age Group, $F(1, 100) = .33$, $p = .565$, were not significant, nor was the three-way Distance × Condition × Age Group interaction, $F(4, 400) = 1.50$, $p = .203$. There was a significant Distance × Condition interaction, $F(4, 400) = 3.72$, $p < .01$, $\eta^2_p = .04$, indicating that the tool-use effect increased with greater distances. Importantly, the two-way Distance × Age Group interaction was not significant, $F(4, 400) = .436$, $p = .782$, indicating that (regardless of condition differences) the two age groups estimated equivalently across the five target distances. This finding is particularly relevant while interpreting the Age Group × Condition interaction, for it indicates that tool-use differences between the two age groups cannot be attributed to distance estimation accuracy.

Most critically, there was a Condition × Age Group interaction, $F(1, 100) = 4.23$, $p < .05$, $\eta^2_p = .04$, indicating that the effect of tool use varied by age groups. These values are depicted in Figures 4A (younger adults) and 4B (older adults). To explore the Condition × Age Group interaction, we ran separate repeated-measures ANOVAs within each age group. Distance was significant for both younger adults, $F(4, 200) = 618.78$, $p < .001$, $\eta^2_p = .93$, and older adults, $F(4, 200) = 475.74$, $p < .001$, $\eta^2_p = .91$, indicating increasing estimates across the five target location points. For younger adults, there was a main effect of condition, $F(1, 50) = 6.67$, $p < .05$, $\eta^2_p = .12$, with the laser-pointing condition resulting in shorter distance estimates compared to the baton condition. Younger adults also showed a significant Distance × Condition interaction, $F(4, 200) = 4.73$, $p = .001$, $\eta^2_p = .09$, indicative of increasing tool-use effect at farther distances, a result that validates the similar finding in Davoli et al. (2012). Older adults, however, showed neither a condition effect, $F(1, 50) = .14$, *ns*, nor a Distance × Condition interaction, $F(4, 200) = 1.01$, *ns*. However, the three-way interaction of Age Group × Distance × Condition was not significant, so the results must be interpreted cautiously. Age group means of within-subject variability of the distance estimates for the two between-subjects variables (younger laser $M_{SD} = 26.23$; younger baton $M_{SD} = 31.19$; older laser $M_{SD} = 28.45$; older baton $M_{SD} = 29.97$) were statistically equivalent across age group but differed by condition ($p = .043$).

Figure 3. Experiment 2 setup. Target was placed at five points along a hallway. Participants stood at center line and reported the distances under either the laser or baton condition. See the online article for the color version of this figure.

Discussion

Experiment 2 examined age-related differences in a task that assessed far-distance perception under tool-use conditions. As expected, younger adults estimated distances to be shorter when using the laser pointer compared to the baton. This finding replicates previous evidence of perceptual compression during remote tool use (Davoli et al., 2012) and thus lends further support to the notion that tool effects reflect action intention and not simply physical contact (Witt, 2011). Replication of this effect is also noteworthy given the differences in testing environments and samples across the two studies. However, the central finding for Experiment 2 is the lack of the tool-use effect for the older adults.

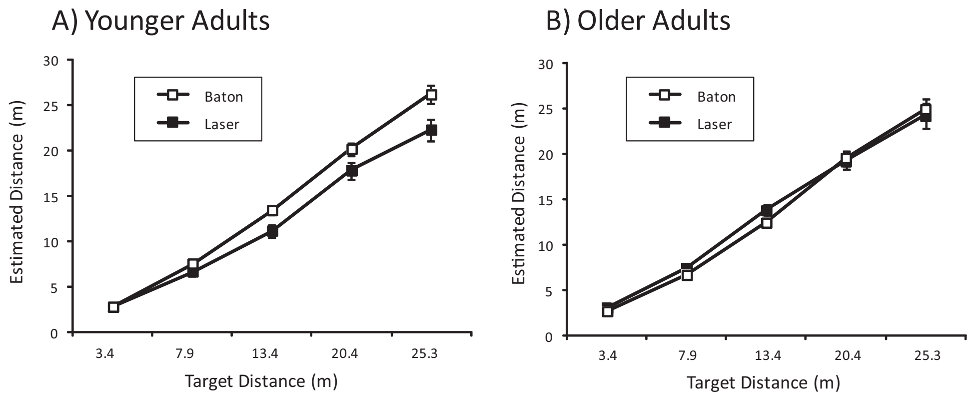

Figure 4. Mean distance estimates by condition in Experiment 2 for younger adults (A) and older adults (B). Error bars represent standard errors.

Distance estimates for the older adults were equivalent under the laser pointer and baton conditions, a result similar to that of Experiment 1.

This age-related absence of the tool-use effect cannot be considered an artifact of overall distance estimation problems in the older adults, because the two age groups were equivalent in their overall distance estimates. Note that this equivalence is itself surprising, given previous research indicating an age-related overestimation of target distances (Sugovic & Witt, 2013) and the slant of steep hills (Bhalla & Proffitt, 1999). However, we do not view our contrary finding as necessarily incompatible with these prior findings. Our older adult participants were younger ($M = 68.04$ years) than those in both the Sugovic and Witt (2013; $M = 81.38$ years) and Bhalla and Proffitt (1999; $M = 73.0$ years) studies and were largely healthy relative to our younger adults. For instance, the two age groups of Experiment 2 were equivalent in both the ROC and fatigue subtests within the MDHAQ (see Table 2), indicating comparable levels of physical ailments and fatigue. Considering that Witt and Dorsch (2009) found that patients in a chronic pain condition overestimated distances compared to healthy controls, it is likely that the age group effects in these earlier studies reflect increased pain and physical mobility limitations to their older adult sample, a position consonant with the action-specific theory of perception (Witt, 2011).

General Discussion

The current study examined potential age-related changes in the ability to flexibly represent space in accordance with one's actions. We did this by examining age-related differences in the effects of tool use on distance estimation. Research on younger adults has found that tool use causes spatial compression at both near distances with the tool touching the target (Witt & Proffitt, 2005) and at far distances using a laser pointer (Davoli et al., 2012), although it was unknown whether this effect would be evident in older adults. We examined that possibility in two experiments. Experiment 1 examined age group differences in the effects of tool use on the perceived distance of near objects, with the hand-held tool allowing contact with the target through a physical extension of the arm and hand. Experiment 2 examined age effects at far distances, with the laser pointer allowing remote interaction with the target. We hypothesized an age-related absence of the spatial compression that is characteristic of tool use (i.e., the tool-use effect), given (a) the behavioral evidence of age-related differences in visuomotor attentional reference frames (Bloesch et al., 2013) and in recognizing and executing pantomimed actions involving tools (Mozaz et al., 2002; Mozaz et al., 2009; Ska & Croisile, 1998) and (b) the age-related deterioration of key brain regions that support tool-based actions (Davis et al., 2009; Pardo et al., 2007) and peripersonal spatial representations (Heuninckx, Wenderoth, & Swinnen, 2010; Kochunov et al., 2005; Lehmbeck et al., 2006).

Our results validated our initial hypothesis. In Experiment 1, younger adults showed the typical tool-use effect, with shorter distance estimates when touching the target with the tool compared to merely pointing at the target. Older adults, however, provided equivalent distance estimates across the two conditions. This major finding of Experiment 1 corroborates previous work showing an age-related difference in peripersonal space coordinates used to represent nearby objects (Bloesch et al., 2013). We tested for a similar age-related disappearance of the tool-use effect at farther distances by assessing distance estimates while participants either pointed to the target with a metal baton (offering no tool-based interaction) or a laser pointer (offering a remote tool-use interaction). Once again, we found that younger adults evidenced spatial compression by tool use, and older adults did not.

The similar result across the two experiments indicates a generalized age-related absence in the tool-use effect during distance estimation. We describe this as a "generalized" effect because it is robustly present despite the many differences between Experiments 1 and 2. First, its disappearance is evident regardless of whether targets are near (as in Experiment 1, 44–89 cm) or far (as in Experiment 2, 3.4–25.3 m). Second, the absence is evident regardless of tool type; the tool in Experiment 1 was a hand-held rod that allowed direct physical contact with the target, whereas the tool in Experiment 2 was a laser pointer that offered remote contact. Third, the lack of the tool-use effect in older adults was found regardless of how the participants provided their distance estimates; in Experiment 1, participants physically manipulated reference circles to provide nonverbal estimates, whereas in Experiment 2, the estimates were verbal responses. This final difference is of particular importance, given the criticism against verbal reports in distance estimation tasks (Woods, Philbeck, & Danoff, 2009).

The similarity of results across Experiments 1 and 2 suggests a broad consensus between our nonverbal and verbal reports in regard to the age group comparison with tool use and offers robust support for a generalized age-related absence of tool use in distance perception. Note that this age group difference appears independent of raw perceptual ability. Although there were statistically significant age group differences in visual acuity in both experiments (cf. Tables 1 and 2), they did not translate into group differences in distance estimates; the two age groups were equivalent in overall distance estimates in both Experiments 1 and 2. Thus, the age-related absence of the tool-use effect is specific to the activity of exploring the target with the tool during distance perception rather than an artifact of older adult difficulty in distance perception.

How can we best interpret the significance of the age group differences in the tool-use effect? There are at least two probable interpretations. First, older adults can approach cognitive and perceptual tasks with differing response strategies than those employed by younger adults (Neider & Kramer, 2011; Ratcliff, Thapar, & McKoon, 2007)—specifically, a more conservative response criterion (Maltz & Shinar, 1999), perhaps to compensate for lower-level perceptual deficits (Park & McDonough, 2013; Scialfa, Thomas, & Joffe, 1994; Veiel, Storandt, & Abrams, 2006). A more conservative criterion in distance perception would likely manifest itself with older adults focusing on accurate calculations of distance rather than relying on their immediate perceptual judgment, and such a strategy could negate the tool effect with an overreliance on calculation.

However, we find the phenomenon of increased cautiousness in older adults (Maltz & Shinar, 1999; Ratcliff et al., 2007) to be largely unsatisfactory to explain the present results for three primary reasons. First, if age-related differences in the response criterion were a factor, they would be more likely to manifest in the distance estimates themselves, yet Experiment 2 shows that our age groups were equivalent in overall distance estimation capacity. Second, the experimental design of Experiment 1, in particular, largely precludes strategy differences, for its viewing space offered an absence of environmental cues or contextual factors that might influence different response strategies. Finally, the phenomenon of increased cautiousness in older adults is typically evident within time-limited conditions, in which participants are purposefully rushed in making their decisions. Yet this was not a factor for either Experiments 1 or 2; participants were instructed to take their time and focus on accuracy. While we cannot rule out the possibility of cautiousness affecting the tool-use results for older adults, it does not appear to be central to our interpretation.

The more likely interpretation is that the age group difference in the tool-use effect represents an age-related change in flexibly extending representations of peripersonal space representations into extrapersonal space through the use of tools. It is reasonable to assume that this loss reflects changes to the aging brain. Older adults display atrophy in brain regions essential for peripersonal representations (Cavanna & Trimble, 2006; Makin et al., 2007), with volumetric reductions in parietal (Kochunov et al., 2005; Lehmbeck et al., 2006) and frontoparietal pathways (Bennett et al., 2010). Skillful tool use depends upon a dorsoventral processing stream (cf. Binkofski & Buxbaum, 2013) also subject to volumetric decline as we age (Davis et al., 2009; Pardo et al., 2007).

A related possibility is that the spatial recoding characteristic of skillful tool use depends upon multiple brain regions involved in multisensory integration (MSI) and that these brain regions alter with age. Tool use is a complex activity, requiring the smooth integration of multiple factors, such as hand movements with the tool, tactile feedback from the tool, visual perception of the target, and cognitive evaluation of distance. Neuroimaging studies have found an extensive network of brain regions centered around premotor and parietal regions that are critical for MSI (Bremmer et al., 2001; Culham & Kanwisher, 2001), and these regions are sensitive to peripersonal spatial representations (Ladavas & Serino, 2008; Makin et al., 2007).

Behavioral studies examining MSI in older adults have yielded complex results, with older adults exhibiting gains in performance with multisensory inputs compared to unisensory inputs (Diaconescu, Hasher, & McIntosh, 2013; Laurienti, Burdette, Maldjian, & Wallace, 2006; Peiffer, Mozolic, Hugenschmidt, & Laurienti, 2007) and impairments to multisensory processing (Poliakoff, Ashworth, Lowe, & Spence, 2006; Setti et al., 2011; Wu, Yang, Gao, & Kimura, 2012). Age-related differences for MSI-based illusions are also inconsistent. For instance, older adults show greater susceptibility for the audiovisual illusion of the McGurk effect (Sekiyama, Soshi, & Sakamoto, 2014; Setti, Burke, Kenny, & Newell, 2013) and the sound-induced flash illusion (DeLoss, Pierce, & Andersen, 2013) but equivalent susceptibility for the motion illusions of the Enigma and Pinna illusions (Billino, Hamburger, & Gegenfurtner, 2009). Similarly, older adults performed equivalently to younger and middle-aged adults in the haptic horizontal–vertical curvature illusion (Ballesteros, Mayas, Reales, & Heller, 2012).

Although brain regions supporting tool use represent an extensive network of frontoparietal regions coding for hand and tool movements (Gallivan et al., 2013), there is substantial overlap with the peripersonal spatial representations, and the two are functionally related. In the case of tool use in distance perception, MSI (in the form of the integration of the hand operating the tool and the visual input of the target) works in conjunction with peripersonal spatial representations (the tool extending peripersonal coordinates to extrapersonal space). The overlap may explain the host of action–perception changes that occur with aging, such as older adult dedifferentiation of cortical networks dedicated to the guidance of motor actions (Heuninckx et al., 2010), declines in motor imagery capacity (Gabbard, Cacola, & Cordova, 2011; Mulder, Hochstenbach, van Heuvelen, & den Otter, 2007; Personnier, Kubicki, Laroche, & Papaxanthis, 2010), evidence of greater disjunction between motor imagery and actual hand movements (Skoura, Personnier, Vinter, Pozzo, & Papaxanthis, 2008), and older adult performance declines and altered activation networks during motor–action prediction tasks (Diersch et al., 2013).

Our results differ from previous work on embodied perception with older adults, which found that older adults expressed exaggerated estimates in slant perception (Bhalla & Proffitt, 1999), distance estimation (Sugovic & Witt, 2013), and aperture estimation (Hackney & Cinelli, 2013) under action conditions, results the authors attributed to fatigue (Bhalla & Proffitt, 1999) and/or imbalance problems (Hackney & Cinelli, 2013; Sugovic & Witt, 2013) with the elderly. Such explanations seem unlikely to directly explain our results, given that our tasks were physically nondemanding and our older adult samples were relatively healthy and physically fit. Although in neither task was balance assessed, the distance judgments were static and relatively brief (the distance estimation task duration for Experiment 1 was 30 min; Experiment 2 was 20 min), and none of our older adult participants reported fatigue or imbalance. A probable explanation for the differing direction (exaggeration vs. absence) of the age group effect is that our tool-use tasks reflect the functional adaptability of the action–perception system and indicate that beyond any immediate fatigue or imbalance concerns, our older adults displayed a muted adaptive response for the tools. Tool use modifies spatial representations by quickly extending peripersonal to extrapersonal coordinates (Berti & Frassinetti, 2000; Longo & Lourenco, 2006). This visuomotor adaptation occurs rapidly and serves as the foundation for actions on objects outside of our reach. Our experiments provide strong evidence that this foundation is affected by aging, and older adults may have to compensate for its dysfunction. This interpretation does not preclude the role of physiological factors but suggests that gradual lifelong reductions in such capacities can alter the underlying visuomotor representations essential to the tool-use effect. Indeed, one potential explanation for exaggerated age effects in physically demanding tasks (i.e., Bhalla & Proffitt, 1999; Hackney & Cinelli, 2013; Sugovic & Witt, 2013) is that older adults must compensate for decrements to the action–perception system.

Our experiments are the first to document an age-related absence of the tool-use effect that is robustly evident in both physical and remote tool use. This finding speaks to the gerontological literature that has documented a strong link between the aging body and the aging mind. For instance, older adult physical capacities are linked with their relative cognitive capacity (Clouston et al., 2013), and older adults have shown gains in cognitive capacity after engaging in aerobic training (Colcombe & Kramer, 2003; Voss et al., 2011), indicating that physical exercise may serve as a neuroprotective factor (Hillman, Erickson, & Kramer, 2008). Our results speak to this literature insofar as the older adults in our studies evidenced a specific deficit in the modification of spatial representations during tool use. For younger adults, peripersonal spatial representations are flexible and can be elongated during tool use (Ladavas & Serino, 2008), although this flexibility appears to be lost with the older adults from the present study. It remains an open empirical question as to whether aerobic exercise and physical training for older adults could impact the older adult loss of the tool-use effect.

Our results also speak to the growing interest in embodied cognition and extended mind debate. Specifically, it points to a potential dissociation between these two theories that are generally considered complementary. Although there is ample evidence of heightened embodied effects for older adults (Bhalla & Proffitt, 1999; Hackney & Cinelli, 2013; Sugovic & Witt, 2013), our results indicate that older adults exhibit an absence of mental extension through tool use. Future studies could explore the breadth and causal factors to this potential embodied–extended dissociation in older adults. For instance, there is emerging evidence that words function as tools to extend the mind (Borghi et al., 2013). Given the current results of an age-related decline in the tool-use effect, could this also be true for motor–word extension? There is recent evidence toward this possibility. Obayashi and Hara (2013) found that decreased activity in supplementary motor area (SMA) interfered with verbal fluency for older adults but not younger adults. Furthermore, an open question is whether older adult reductions in visuomotor adaptation are truly caused by aging or merely reflect the decline in physical activity associated with aging. If the latter is true, then we would expect that older adults who exercise regularly to be more likely to evidence the tool-based alteration to distance estimates that is common to younger adults. Further research will be necessary in order to determine whether the processing associated with peripersonal space representations, and extendable through tool use, can be maintained or even regained through physical training programs.

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