Spatial Updating of Haptic Arrays Across the Lifespan

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RUNNING HEAD: Haptic Updating Across the Lifespan

Abstract

Background. Aging research addressing spatial learning, representation, and action is almost exclusively based on vision as the input source. Much less is known about how spatial abilities from non-visual inputs, particularly from haptic information, may change during lifespan spatial development. This research studied whether learning and updating of haptic target configurations differs as a function of age.

Method. Three groups of participants, ranging from 20 to 80 years, felt four-target table-top circular arrays and then performed several tasks to assess lifespan haptic spatial cognition. Measures evaluated included egocentric pointing, allocentric pointing, and array reconstruction after physical or imagined spatial updating.

Results. All measures revealed reliable differences between the oldest and youngest participant groups. Our age effect for egocentric pointing contrasts with previous findings showing preserved egocentric spatial abilities. Error performance on allocentric pointing and map reconstruction tasks showing a clear age effect, with the oldest participants exhibiting the greatest error, are in line with other studies in the visual domain. Post-updating performance sharply declined with age but did not reliably differ between physical and imagined updating.

Conclusion. Results suggest that there is a general trend for age-related degradation of spatial abilities after haptic learning, with the greatest declines manifesting in all measures in people over 60 years of age. Results are interpreted in terms of a spatial aging effect on mental transformations of 3D representations of space in working memory.

Keywords: life span development, haptics, spatial aging, spatial cognition, spatial updating

Introduction

One of the many aspects of cognitive competency that change across the adult years is the ability to think about and act within the spatial environment. Research on this topic, much of it over the past two decades, has amassed a range of spatial behaviors for which performance tends to become slower and more error prone with age (for reviews, see Moffat, 2009; Klencklen et al., 2012). This is especially relevant, as the next two decades will lead to a major demographic change in the U.S. population, with a projected 71 million people being 65 years or older by 2030, an increase of more than 100% since 2000 (U.S. Census, 2008).

Much of the human spatial aging literature has addressed small-scale tasks not requiring physical movement, with age-related deficits observed in rotational accuracy of static objects (Iachini et al., 2009), memory for building locations on a map (Kirasic, 2000), or correct target placement during map reconstruction (Moffat & Resnick, 2002). Speed/accuracy deficits for older adults compared to their younger counterparts are also known for navigation of large-scale spaces, including learning routes through physical environments (Barrash, 1994) and retracing of virtual routes (Wiener et al., 2012). Allocentric spatial memories seem to be most affected by age, with studies consistently showing poorer cognitive map development as a function of age on wayfinding and orientation tasks in unfamiliar environments, including supermarkets (Kirasic, 1991) and hospitals (Wilkniss et al., 1997). Corroborating evidence with unfamiliar computer-generated environments has shown learning and navigation performance by elders to be slower and less accurate than younger participants in virtual mazes (Head and Isom, 2010), museums (Lövdén et al., 2005), groups of buildings (Iaria et al., 2009) and on environmental transfer tasks requiring learning floors in virtual buildings and then transferring this knowledge to navigation between targets in the corresponding physical space (Kalia et al., 2008; Foreman et al., 2005).

Neuroimaging data supports this assertion, with the hippocampus and surrounding medial temporal regions involved in allocentric processing found to have decreased functional activity and volumetric reduction in elders compared to their younger counterparts (Antonova et al., 2009; Moffat et al., 2006; Head and Isom, 2010).

Like most research on human spatial cognition, the specialized literature on aging is almost exclusively based on vision as the input source supporting spatial learning, representation, and action. Much less is known about how spatial abilities from non-visual inputs may change during lifespan spatial development. The haptic (or active touch) modality, in particular, has been substantially neglected as a spatial-cognitive input channel.

The present research focuses on a basic spatial-cognitive capability, namely, to update one's relation to objects perceived in the world during the course of movement when they are no longer perceptually available. In this research the objects are perceived haptically. We are interested in whether learning and updating the locations of target configurations accessed through touch declines with age.

The research on whether haptic spatial abilities decrease with age has not led to a conclusive body of results. As with all sensory modalities, tactile acuity declines across the lifespan (Stevens, 1992; Tremblay et al., 2003; but see Legge et al., 2008). Considering higher-level spatial abilities, studies have found no reliable differences in healthy participants as a function of age on tasks requiring 3D haptic shape perception (Norman et al., 2011), haptic object recognition and naming (Ballesteros and Reales, 2004), or object discrimination (Norman et al., 2006). In contrast to these null effects of age, Kalisch and colleagues (2012) observed reduced recognition of unfamiliar haptic objects by healthy older adults compared to their younger counterparts. Notably, these declines in age-related performance were not correlated with reduced tactile acuity, suggesting a general cognitive aging effect (Kalisch et al., 2012). It is worth noting that the object stimuli and perceptual tasks employed in these haptic studies were very different from the visual environments and spatial behaviors previously mentioned from the spatial cognition research on aging. We are not aware of any research comparing haptic performance across the life span on these traditional spatial cognition tasks.

In an effort to fill this gap, this paper investigates learning and updating of haptically explored object arrays among three groups of participants, ages 20-39, 40-59, and 60-79. We evaluate several measures of spatial abilities between these participant groups, including learning egocentric target positions, reporting the allocentric direction between target pairs, and particularly of interest here, reconstructing previously learned target arrays after physical or imagined spatial updating.

Although there is no prior evidence as to whether spatial updating of haptically explored space changes as a function of age, or whether imagined versus physical updating after haptic learning will lead to differential age-specific performance, the literature provides some useful insights as to what we expect to find in the current study.

First, we know that accurate spatial updating of haptically perceived locations is possible, as several studies with participants in the 18-50 age range have demonstrated learning and updating of individual haptic targets (Barber and Lederman, 1988; Hollins and Kelley, 1988) or a haptic configuration of targets, as is used here (Pasqualotto et al., 2005; Giudice et al., 2009; Giudice et al., 2011). Accurate haptic updating has also been shown for objects beyond arm's reach, as when perceived from the end of a 2 m probe (Giudice et al., 2013A). Updating based on touch appears to be essentially the same as occurs after visual exposure, as is indicated by studies with younger participants demonstrating near identical spatial updating performance after learning maps or object layouts from touch and vision (Giudice et al., 2011; Giudice et al., 2009). These results add to a growing body of evidence showing that multiple spatial inputs give rise to working memory representations of surrounding space that function equivalently in the service of action (for review, see Loomis et al., 2013).

Although age-related differences in updating haptically acquired layouts have not to our knowledge been previously investigated, the evidence for functional equivalence across modalities leads us to predict similar declines across the lifespan as have been shown for updating with vision. Vision-based performance during triangle completion tasks, which require updating, is known to decrease with age (Adamo et al., 2012; Mahmood et al., 2009; Harris and Wolbers, 2012A). According to the hypothesis that updating is based on functionally equivalent spatial representations, assuming no differential age-related loss of sensory function, haptic and visual updating performance would exhibit similar changes over the lifespan, as the associated mental transformations of the underlying spatial representation are governed by sensory-invariant computations.

While a general decline in updating performance is expected as a function of age, we are particularly interested in whether tasks requiring imagined updating will be differentially impaired in older adults, as compared to those incorporating physical movement. A related question is whether aging affects imagined spatial transformations, such as mental rotation of objects. Relative to their younger counterparts, older individuals show increased errors and greater difficulty on mental rotation of visually perceived objects (Dror and Kosslyn, 1994) with the greatest impairment related to mental rotation of the body (Devlin and Wilson, 2010). In a study requiring transforming viewing perspective between learning and test, pointing performance was reliably worse for elders after an imagined shift of the learning perspective compared to real rotation (Joanisse et al., 2008). Similar results were observed for imagined translation tasks requiring visual scanning, with significantly more time and errors made by older adults for scanning imagined versus perceptual displays (Brown et al., 1998). More directly relevant to the question of age effects on spatial updating are studies that compare the effects of physical versus imagined movement. Although mental rotation of complex haptic displays has not been studied with older adults, several studies have used variants of a mental rotation paradigm with haptic displays in younger participant groups, demonstrating that updating performance was reliably more accurate after real versus imagined movement for scene recognition (Pasqualotto et al., 2005) and map orientation (Giudice et al., 2011). Age effects were assessed in two studies investigating path integration across the lifespan, which suggest that the role of physical body movement is particularly important for updating by older adults. Both studies found that there were no reliable differences between younger and older participant groups on a triangle completion task when outbound travel of the two legs was done by physical walking, but the older group performed significantly worse when only visual or vestibular information without real movement was allowed (Allen et al., 2004; Adamo et al., 2012).

In sum, the extant literature suggests that updating spatial locations after imagined transformation is reliably more difficult than after physical transformation in young participants, and that difficulties in imagined transformation are magnified with age, but that these deficits may be mitigated when updating is coupled with physical movement. Based on these results, in the current study we predict that all groups will perform worse on imagined versus physical updating trials, but that there will be an interaction between age and updating type, with imagined haptic updating being reliably less accurate for our oldest group compared to the other groups.

Clear boundaries between “young” and “old” have not emerged from the human spatial aging literature. The older group included in the majority of studies described in this paper is based on healthy adults ranging in age from 55 to 85 years, and the younger group composed of people between 18 and 40 years of age. When a middle group between these extremes is included, it has been found to resemble the younger age (Barrash, 1994; Jansen et al., 2010), but the generality of a trend toward decline at older ages, rather than continuously across the lifespan, is unknown. Without a clear theoretical rationale to guide separation of groups, or previously established age-related differences in spatial updating, we included participants ranging in age from 20 to 79 in the current study, representing three age ranges of two decades each.

Method

*Participants***.** Thirty-six participants (19 female and 17 male) were recruited for this study, split equally between three age groups of 20-39 (M = 25.0, SD = 4.7), 40-59 (M = 50.8, SD = 5.8), and 60-79 (M= 70.3, SD = 4.6). We acknowledge that twelve participants per group is not a large sample but this N is common in spatial cognition research and has yielded strong and consistent results in other haptic updating studies (Giudice et al., 2011). Participants were all right-handed and matched between groups on mean years of education: younger group = 16, middle group = 15.8, and older group = 16 years. All participants were initially surveyed as to sensory, cognitive, or motor impairments that might adversely influence performance on the tasks, and none reported any evidence of or change in these factors over the past five years. The research was approved by the University of Maine's local ethics committee and written informed consent was obtained from all participants, who received monetary compensation for their time. The experiment took approximately one hour per participant.

*Apparatus***.** Stimuli used for creating the learning target arrays for this study included four 24-inch diameter Masonite circles and sixteen 1-inch diameter textured targets composed of round magnets covered in velvet, sandpaper, glass, and rubber material (four targets for each type). Each of the Masonite circles contained four targets, one of each texture, which were arranged in different layouts (see Figure 1). To form the layouts, one target was placed at different locations in each quadrant of the circle at 3, 5, 8, or 11 inches from the center. The four experimental arrays included two unique arrays and their mirror images. A fifth four-target circular array was used for practice and a sixth 24-inch circle layered with sheet metal and four additional magnetic targets that could be affixed anywhere on this board was used for the reconstruction task. An adjustable height round pedestal table was used to support the circular boards. Pointing responses were performed using a custom-built digital pointing device consisting of a 360 degree rotatable arrow mounted on a 4-inch plastic box. The pointing device was calibrated for detecting angular differences to 0.1 degrees and connected to the computer coordinating the data logging via USB. A blindfold (Mindfold Inc., Tucson, AZ) was used throughout the experiment.

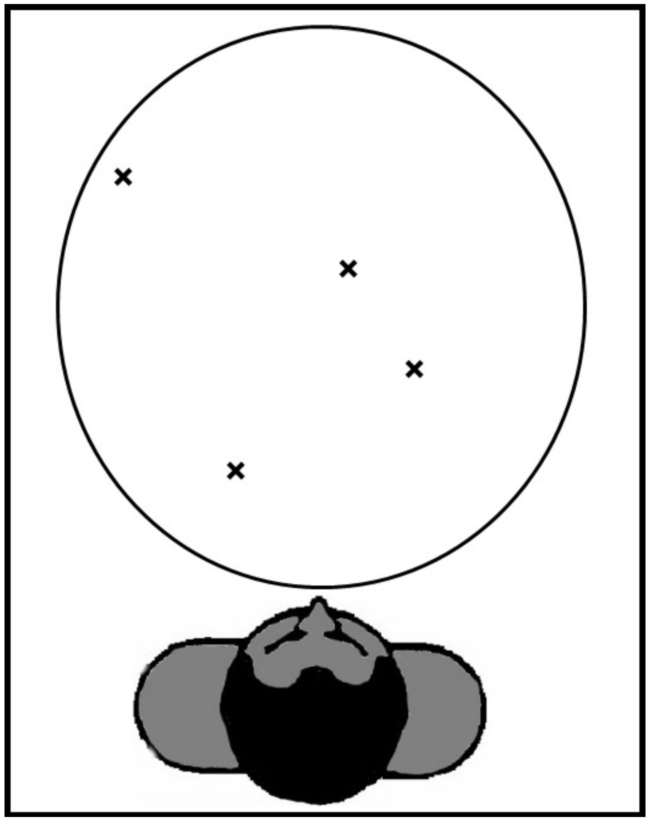

Figure 1. Depiction of a sample array used for the experiment with a "participant" seated at the base of the circular table.

*Procedure***.** The study employed a within-participants design, where every participant in each of the three age categories completed four experimental trials using four different target arrays (the trial by stimulus pairings were counterbalanced between participants). Age was a between-participants factor, but the same trial by stimulus ordering was used for each of the three age group conditions to ensure consistency. The study was run in six phases, which proceeded as follows. All participants wore a blindfold throughout the entire experiment.

Phase 1: Practice. Participants were introduced to the experimental procedure through a practice run that allowed them to experience the learning, pointing, and reconstruction phases of the experiment using a sample layout.

Phase 2: Exploration. During the exploration period, participants wore a blindfold and were requested to use their right (dominant) hand to explore the target array, which consisted of four differently textured targets distributed across a circular 24-inch round board. Participants were given one minute to learn the four target locations using a scanning strategy demonstrated by the experimenter during the practice session that facilitated localization of the four targets. The one-minute exposure time and scanning strategy, which involved lateral sweeping of the board progressing from near to far, were both established as sufficient from pilot studies in the lab. After the exploration phase, the experimenter instructed the participant to remove his/her hand from the board, and the pointing device was placed directly in front of him or her (contact was only made with the pointer device, and participants were not allowed to touch the board or targets).

Phase 3: Egocentric pointing. During this task, the experimenter verbally called out the material of each of the four target names (e.g., velvet, sandpaper, glass, and rubber) in a randomized sequence, and the participant was asked to point to each target upon hearing its name. Pointing was done by rotating the pointer such that it was oriented in the direction of the target as from their current position (the base of the arrow was aligned with the sagittal midline of their body). This task served as a learning criterion. To proceed, pointing accuracy had to be within 15 degrees of each target's physical location and the correct rank order of the four targets, based on its distance from their body, was given by verbal report. If the participant did not meet criterion, he or she was given another one-minute exploration phase and then re-tested. This sequence proceeded until either the criterion was met or a maximum of three iterations was reached, at which point the participant moved on to the next phase (no participant required more than two attempts).

Phase 4: Allocentric pointing. During these trials, the experimenter verbally called out the names of two targets, and the participant was asked to align the pointer to represent the direction between the target pair. Participants were instructed to consider the base of the arrow as positioned on the centerpoint of the first target and the tip of the arrow as pointing toward the second target. Each participant completed six pointing trials, representing all unidirectional combinations between the four start-end target pairs. The start-end pairings alternated between participants (i.e., if one participant pointed from sandpaper to rubber, the next participant would point from rubber to sandpaper). Thus, the complete set of 12 possible allocentric pointing judgments was balanced across the 36 participants.

Phase 5: Re-exposure. Upon completing the allocentric pointing judgments, the pointing device was removed and participants were re-exposed to the array for another one-minute exploration phase in order to re-instantiate the targets in memory. Upon completion, the array was removed and replaced with a blank magnetic board of the same dimensions.

Phase 6: Spatial updating and array reconstruction. This phase investigated participants' ability to reconstruct the targets on the array after physically or mentally updating to a novel perspective which was either 90 degrees left or right of the learning orientation. In the physical update conditions, participants walked 90 degrees left or right around the table, using the circular edge as a guide. Participants stood and moved to the new location while the experimenter placed the chair directly behind them at the new location. They stopped and sat back down when they reached a tactile indicator placed at the new point of observation and then oriented themselves toward the array using this marker as the new origin. In the mental updating conditions, participants remained at the learning orientation but were instructed to imagine that they had walked 90 degrees left or right around the table and were now facing the board from this new perspective. Thus, there was no physical movement in this condition; updating was purely a mental transformation. A tactile marker at the origin served as an orienting cue. Once oriented at the new perspective in either updating condition, they were handed the four textured targets (now affixed to a magnet) that were used during learning. Their task was to reconstruct the array, while still blindfolded, by placing the four targets on the blank board to reflect the global target configuration based on their post-updating location and to inform the experimenter when they were finished. Target placement was self-paced and could be done in any order. The complete experimental process was performed four times with four different arrays, with two replications of physical updating and two replications of mental updating, one each for left and right rotation. Trials were blocked by rotation type, and block order was counterbalanced between participants.

Upon completion of the four experimental trials, participants removed their blindfold and performed a paper-and-pencil mental rotation test, MRT-A (Peters et al., 1995), based on the stimuli of Shepard and Metzler (Shepard and Metzler, 1971). The test consists of twenty-four questions, completed within two three minute sections, each giving a reference shape, followed by four alternatives that must be mentally rotated to match the reference.

Data Analysis. As the design used a range of ages within each two-decade span, the data were analyzed both by treating age as a continuous variable and using it to define three distinct groups. The error measures from the egocentric pointing, allocentric pointing, and reconstruction tasks were initially analyzed using a stepwise regression model that included age, MRT-A score, gender, and education as the four predictors. Each predictor was allowed free entry into the model. As described below, age was the only significant predictor of performance for all DVs. As no other variables were significant predictors for any measure, they were not retained in the model, (all p's > 0.15). Subsequent mixed factorial ANOVAS, with the three age groups as the between-participants factor and the two updating modes as the within-participants factor were performed for all DVs of interest.

During the reconstruction task, individual target errors were analyzed by calculating the Euclidean distance between the participant's response and the physical target location. Global target configuration was determined using a bi-dimensional regression analysis (Tobler, 1994), using the updated techniques described by Friedman (2003). The process uses a least squares method comparing translation, rotation, and linear scaling of each re-created array with the original array to produce a best-fit polygon. The regression coefficients of this transformed best-fit polygon are used to determine several variables, the most important of which is the distortion index (DI), which represents the overall accuracy of the re-created array, irrespective of translation, angle, or scale. The resultant DI value ranges from 0 to 100, with 0 reflecting the most accurate reconstruction of the array and 100 reflecting the least accurate reconstruction, e.g. all targets are placed at a single point.

Results

Outliers were removed based on a cutoff of 2.5 standard deviations above the grand mean for each measure. This resulted in 3.7% of the total trials being removed. Table 1 contains all means and standard deviations for each measure, separated by each age group.

Measure	1-Younger mean (SD)	2-Middle mean (SD)	3-Older mean (SD)	Significant Group Comparisons
Egocentric Pointing (deg)	8.99 (2.3)	10.94 (4.36)	14.28 (6.51)	1 vs. 3
Allocentric Pointing (deg)	17.97 (17.27)	20.54 (18.31)	33.13 (33.21)	1 vs. 3 and 2 vs. 3
Reconstruction Distance (cm)	5.79 (4.17)	7.29 (4.74)	11.34 (8.23)	1 vs. 2, 1 vs. 3, and 2 vs. 3
Reconstruction DI values	19.42 (10.12)	31.44 (21.95)	47.96 (27.18)	1 vs. 2, 1 vs. 3, and 2 vs. 3

Table 1. This table contains all means and standard deviations for each measure, separated by each age group. The final column contains the significant group comparisons for each measure.

Egocentric Pointing Task. Egocentric pointing was used as a learning criterion task, as reported above. There was no significant difference for the number of iterations to reach criterion between the three age groups (attempts per array = 1.13, 1.13, and 1.23 for young, middle, and older groups), $F(2,35) = 1.290$, $p = 0.279$, $\eta^2_p = 0.018$. As is evident from the descriptive statistics, all participants were able to learn the targets with little effort.

The average egocentric pointing error made on the first learning trial for each participant, after substituting the group mean for outliers (errors greater than 44.1^o for the younger, 54.4^o for the middle, and 60.8^o for the older group), is shown by age in Figure 2. The four-predictor regression model described above showed that only age was a significant predictor of error ($\beta = 0.466$, $p = 0.015$). A subsequent one-way, between-participants ANOVA using the three predetermined age groups revealed significance for age, $F(2,35) = 3.857$, $p = 0.031$, $\eta^2_p = 0.189$. Subsequent post hoc *t*-tests only found reliable differences in error between the younger versus older age groups (see Table 1).

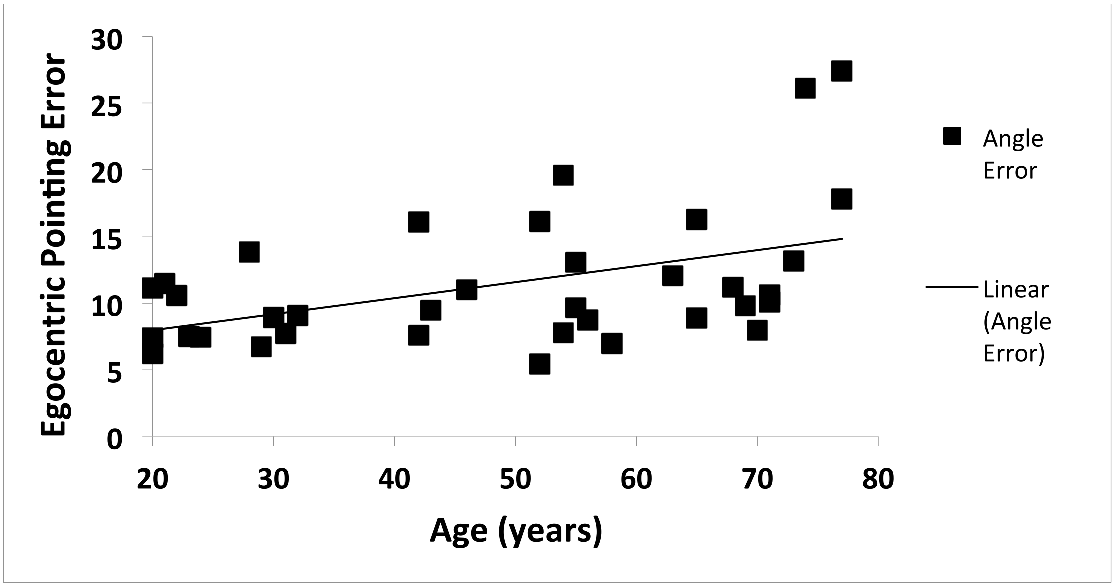

Figure 2. Average egocentric pointing error per participant plotted against their age. The solid line shows least-squares linear fit.

Allocentric Pointing Task. Data from this task, which took place prior to any spatial updating, were analyzed using the four-predictor regression model to explore the relation of each predictor against the absolute pointing error. Figure 3 plots mean allocentric pointing error against individual participant age; there is a clear trend for error to increase with age. Consistent with this trend, age was found to be the only significant predictor (β = 0.626, p < 0.001). A subsequent one-way, between-participants ANOVA using the three predetermined age groups revealed a significant effect of age, $F(2,35) = 31.468$, $p < 0.001$, $\eta^2_p = 0.071$. Post hoc *t*-tests showed reliable differences in error between the younger versus older and middle versus older age groups (see table 1).

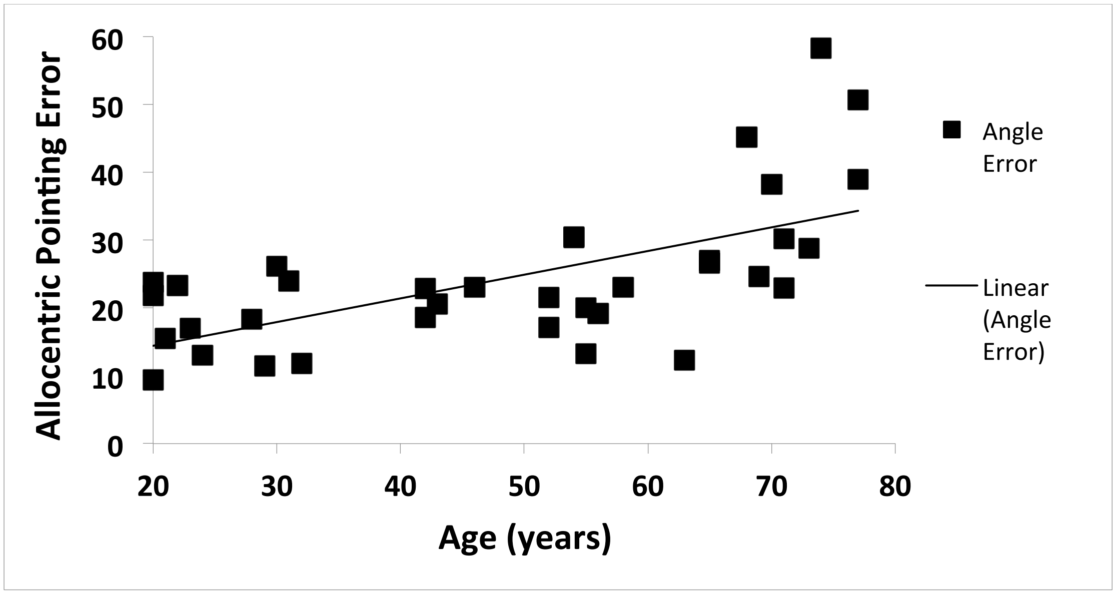

Figure 3. Average allocentric pointing error, plotted against age. The steepest increase in error occurs around age 65 and above. The solid line shows least-squares linear fit.

Distance Errors from the Reconstruction Task. Participants re-created the four target arrays after imagined or physical spatial updating. Target errors were calculated as the Euclidean distance between the response and physical target location on each trial. An increase in target distance errors as a function of participant age across updating modes is shown in Figure 4. When errors were analyzed with the four-predictor regression model, age was found to be the only significant predictor of error for both imagined updating (β = 0.551, p < 0.001) and physical updating (β = 0.658, p < 0.001). A mixed model ANOVA with factors of age and updating type found only significant differences for age, $F(2,35) = 45.163$, $p < 0.001$, $\eta^2_p = 0.142$. Post hoc *t*-tests revealed significant differences between all three age groups (see table 1).

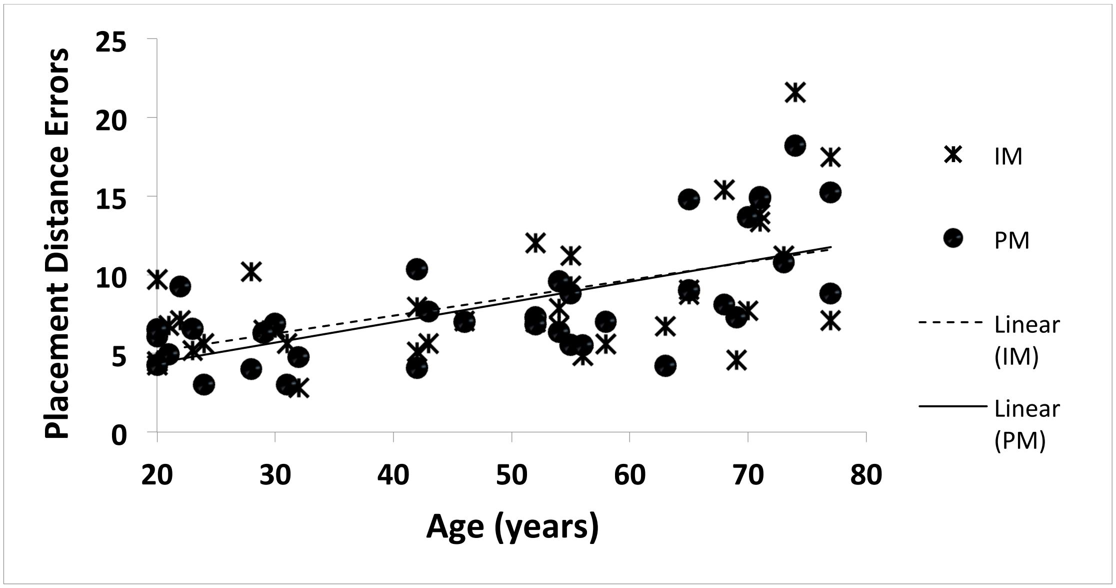

Figure 4. Depicts average Euclidean distance errors for target placement during the reconstruction task. Data for physical and imagined updating is shown separately and plotted against participant age. IM is imagined movement and PM is physical movement. The solid and dashed lines show least-squares linear fit to the two variables, as indicated in the legend.

Reconstruction Task with Bi-Dimensional Regression. From the bi-dimensional regression conducted for each re-created array, the resulting distortion index (DI) values were entered into the regression model separately for the imagined and physical updating modes. Figure 5 shows the average DI values by age across updating modes; a trend toward increases in DI with age is evident. Age was found to be the only significant predictor for both updating modes, imagined ($\beta = 0.618$, $p < 0.001$) and physical ($\beta = 0.649$, $p < 0.001$). A subsequent mixed model ANOVA on age and updating mode revealed reliable differences only for age, $F(2,35) = 23.067$, $p < 0.001$, $\eta^2_p = 0.256$. Post hoc *t*-tests showed significant differences between all three age groups (see table 1). By comparison, our DI values, ~19 for younger participants and ~47 for elder participants, were within a range similar to those reported in previous research. Results from reconstruction of object arrays with young participants revealed mean DI values around 20 (Shelton & McNamara, 2005) and between 35 and 65 for map reconstruction by older participants (Yamamoto & DeGirolamo, 2012).

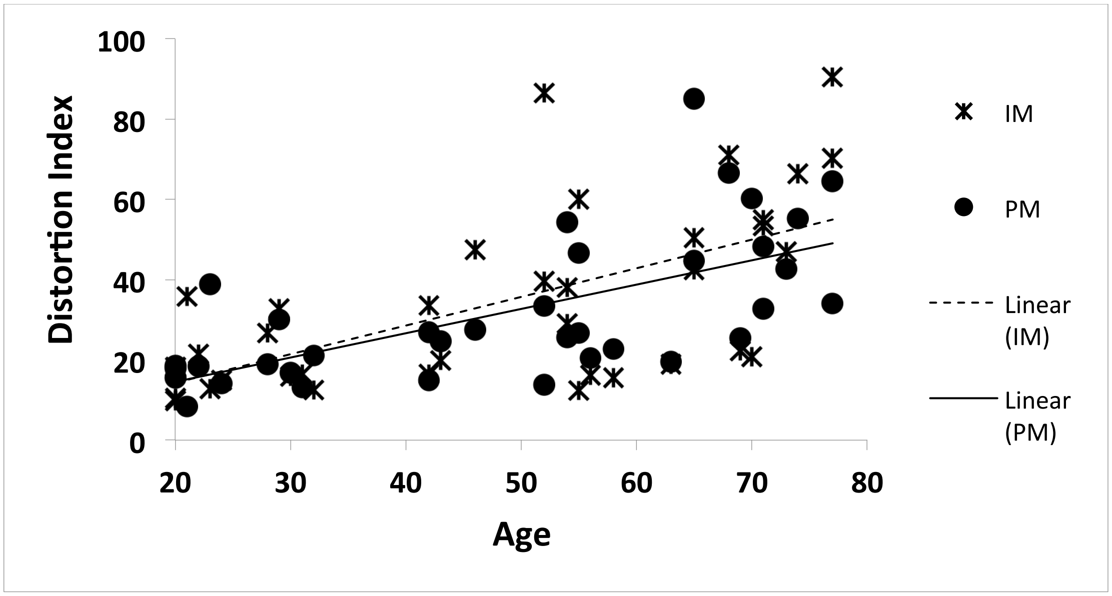

Figure 5. Depicts the average distortion index value for placements made during reconstruction task. Data for physical and imagined updating is shown separately and plotted against participant age. IM is imagined movement and PM is physical movement. The solid and dashed lines show least-squares linear fit to the two variables, as indicated in the legend.

*Comparisons of age effects across measures. R*esults from the post hoc *t*-tests from the above analyses, based on two-tailed tests with Bonferroni correction and *p* values less than 0.05, are shown in Table 1 below. Column 5 indicates the significant differences between age groups. All measures showed significant differences between the youngest and oldest groups, but an intermediate position of the middle age group was less reliably identified from the three-group analysis. Both allocentric and egocentric pointing error showed statistical equivalence between the two younger groups, whereas the measures of reconstruction reliably segregated the middle group from both extremes.

To further compare the age-related trends across the dependent measures, we correlated each variable with age, as shown in the first column of Table 2, and compared the correlation coefficients. Recall that in the four-predictor regressions described above, age was consistently the only significant predictor. Any correlation with a magnitude of .34 and above is significant by two-tailed test. All correlations were significant, and no differences between correlations were significant. Although the study lacks ample power to detect such differences, the correlations of the dependent measures with age are all within the range from .46 to .66, which does not indicate strikingly different age effects.

Measure	Correlation with age	Correlation with MRT-A	Residual correlation with age
Egocentric pointing	0.46	-0.14	0.40
Allocentric pointing	0.62	-0.21	0.68
IM Distortion Index	0.62	-0.10	0.65
PM Distortion Index	0.65	-0.42	0.68
IM distance	0.55	-0.26	0.45
PM distance	0.66	-0.40	0.52

Table 2. The correlations with age and MRT-A scores for each measure are presented in this table. IM is imagined movement and PM is physical movement.

A further analysis asked whether the ability to do imagined spatial transformations, as measured by the mental rotation test, might account for the similar age trend across measures. Previous research has shown lower mental rotation ability as a function of increasing age (Dror and Kosslyn, 1994; Devlin and Wilson, 2010). Similarly, in the present data, correlating age directly with the MRT-A scores revealed a strong negative relation (r = -0.45, p = 0.003). The MRT scores are shown by age group in Figure 6. To assess whether the age effects on the dependent measures might be mediated by rotation ability, we first conducted a principal-components analysis on the six dependent variables along with MRT-A. Adopting a cutoff of .5 for the factor loadings, the solution showed the dependent variables, but not MRT-A, all loading on a single factor, which accounted for 58% of the variance. The MRT-A measure, but none of the dependent variables, loaded on a second factor, which accounted for 15% of the variance. Next we determined the residual correlation with age after accounting for MRT. The last two columns of Table 2 show the correlation of each variable with MRT and the residual correlation. After adjusting for MRT, correlations of the dependent measures with age are all reliably greater than zero and do not differ significantly from each other. Together the PCA and residual correlations with age suggest that the spatial ability indexed by MRT does not account for the common age trend underlying the dependent variables.

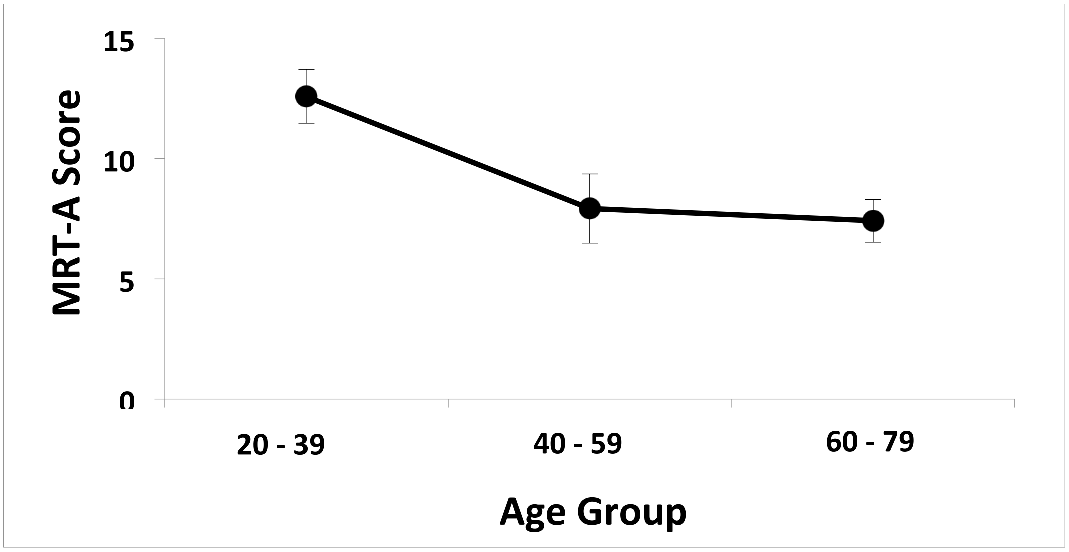

Figure 6. Average MRT-A scores for the three age groups, out of a possible 24 score.

Discussion

This experiment was designed to address whether spatial cognitive processing of multi-target arrays learned by touch changes over the lifespan. The absence of reliable differences in number of trials required to learn the arrays, based on the egocentric pointing criterion task, demonstrates that all participants easily learned the four-target arrays and that subsequent differences in performance observed between age groups were not due to failures to encode spatial relations. Although age did not affect trials to criterion, the egocentric pointing errors on the first learning trial did show reliable age effects (even when extreme outliers were eliminated). These results after haptic learning depart from previous research in the visual domain showing that age does not have a reliable impact on egocentric pointing tasks (for review, see Klencklen et al., 2012). When possible, older adults prefer to use egocentric versus allocentric spatial strategies (Rodgers et al., 2012), and as was discussed in the introduction, most behavioral deficits related to spatial aging involve allocentric knowledge, mental transformations, and cognitive map development. Here, however, we found that spatial representation even of egocentric relationships to objects encoded by touch is subject to impairment with age.

Performance on tasks subsequent to haptic learning also showed clear age-related degradation of spatial abilities, in this case mirroring the general trend found in the spatial aging literature after visual learning. This trend for decreasing performance with increasing age can be seen across all post-learning measures: allocentric pointing error (Figure 3), target distance error (Figure 4), and global distortion index values measuring array reconstruction (Figure 5). While the allocentric pointing data showed equivalence between the younger and middle groups, as has been found in spatial cognition studies reviewed above, both target placement errors and DI values reliably differed between all three groups.

The finding that allocentric pointing accuracy is reliably worse for older participants after haptic learning is congruent with previous findings from allocentric judgments by older adults after visual learning (see Moffat, 2009 for review). Likewise, the finding that the oldest group performed significantly worse than the younger groups on array reconstruction, both in terms of metric correctness and global configuration accuracy, is consistent with previous work showing that older adults make more errors and take more time on map reconstruction and target placement after visual learning (Head and Isom, 2010; Iaria et al., 2009; Moffat and Resnick, 2002). Note that age-related differences in map reconstruction were not found by Yamamoto and Degirolamo (2012), but their study did not require any mental transformations between encoding and map recreation and it is these transformations (e.g., updating) that we believe led to the reliable differences in lifespan spatial performance found in the current study.

The similarity of the age-related correlations observed across the lifespan for different performance measures (shown in Table 2), including egocentric as well as allocentric tasks, suggests that the data reflect general underlying spatial aging effects. It should be noted, however, that although the four-variable linear regression consistently found that age alone generally accounted for significant and substantial variance, all four figures exhibit some indication of positive acceleration, with the greatest degradation manifesting in those greater than 60 years of age. A quadratic fit to the same data accounted for an additional 3% to 13% of variance, depending on the dependent variable, at the cost of an extra parameter. When factor scores were computed for each participant (by summing the DVs, each weighted by its loading on the first factor of the PCA), sharply higher values were found for the three oldest participants, and a quadratic trend accounted for 66% of the variance (cf. 58% for linear).

On the other hand, the older group tends to be the most heterogeneous, including some very accurate participants who are over-predicted by the linear trend. Among the measures in Table 1, the egocentric pointing measure, in particular, shows a substantial increase in the coefficient of variation with age (s.d. scaled by mean, with values of .26, .40, and .46 across the three age groups). This trend suggests caution when treating age as a three-valued variable that can be summarized by the group means and associated ANOVA test. Assigning people within a two-decade range to a common group, particularly when they are older adults, misses both meaningful age-related variation within the 20-year span and differential capabilities of individuals who may be close in age. The regression approach is more sensitive to these effects.

Finally, we consider the implication of these results for the effects of age on spatial updating. We predicted that imagined updating would be reliably more difficult than physical updating after haptic learning for our oldest group, as previous studies have shown that elders exhibit increased errors on mental rotation tasks (Dror and Kosslyn, 1994; Devlin and Wilson, 2010; Iachini et al., 2009) and on pointing judgments after imagined versus physical shifts of the learning perspective (Joanisse et al., 2008). Although we found the expected negative correlation between age and mental rotation ability on the MRT-A task, post-updating performance, to our surprise, did not reliably differ as a function of imagined versus physical updating. Irrespective of updating type, the oldest participants made significantly more errors than the younger participants in terms of metric correctness on individual target placement and overall global configuration as assessed by the distortion index. These results suggest that imagined updating in this experiment imposed no additional cognitive load. The current results do not preclude an age by updating type (imagined vs. physical) interaction in other tasks. Indeed, even allocentric spatial performance, which is widely considered to be impaired with age, only yields age-related deficits on a subset of allocentric switching tasks (Harris et al., 2012B).

Taken together, the current results add to a growing body of literature demonstrating accurate haptic updating of multi-target arrays by young participants (Barber and Lederman, 1988; Hollins and Kelley, 1988; Pasqualotto et al., 2005; Giudice et al., 2011). Our findings showing that haptic updating performance is subject to significant degradation across the lifespan are also consistent with previous studies with visual updating (Adamo et al., 2012; Mahmood et al., 2009; Harris and Wolbers, 2012A). Although we did not directly compare updating performance between modalities in this study, the similar trends observed between studies and paradigms are consistent with our view that multiple inputs feed into a common spatial representation that supports equivalent behavior, irrespective of the modal source (Loomis et al., 2013). From this perspective, the differences we found relating to lifespan spatial aging are explained by degradation of transformations of the spatial representation (i.e., the updating process) rather than to degradation of sensory-specific spatial computations. To address this hypothesis, future studies are needed to investigate whether the functionally equivalent updating behavior exhibited in younger people between vision and touch (Giudice et al., 2009, 2011) persists across the lifespan.

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