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Auditory spatial attention capture, disengagement, and response selection in normal aging

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Abstract

Attention control is a core element of cognitive aging, but the specific mechanisms that differ with age are unclear. Here we used a novel auditory spatial attention task to evaluate stimulus processing at the level of early attention capture, later response selection, and lingering effects of attention capture across trials in young and older adults. We found that the shapes of spatial attention capture gradients were remarkably similar in young and older adults, but only the older group had lingering effects of attention capture on the next trial. Response selection for stimulus-response incompatibilities took longer in older subjects, but primarily when attending to the midline location. The results suggest that the likelihood and spatial tuning of attention capture is comparable among groups, but once attention is captured, older subjects take longer to disengage. Age differences in response selection were supported, but may not be a general feature of cognitive aging.

Keywords

inhibition; Simon effect; sustained attention

Healthy cognitive aging is associated with selective declines in some aspects of attention (Kramer & Madden, 2008), such as the ability to inhibit distracting information (Darowski, Helder, Zacks, Hasher, & Hambrick, 2008), perform dual tasks (Verhaeghen & Cerella, 2002), and some types of task switching (Basak & Verhaeghen, 2011). This has broad importance because attentional factors are vital for higher-level cognitive functions such as working memory (Baddeley, 2012; Yurgil & Golob, 2013) and executive functions (Diamond, 2013), which also exhibit marked declines in healthy cognitive aging.

A common approach to studying selective aspects of attention is to mix task-relevant information with unnecessary, and potentially distracting, information. Researchers then determine if manipulation of the task-irrelevant information has a differential effect on

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Footnotes

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performance in young vs. older adults. There are many ways to implement this strategy. Our study focused on two mechanisms of distraction: attention capture and response selection, which are related aspects of inhibition (Friedman & Miyake, 2004). By "attention capture", we mean that attention is drawn to a salient feature, such as an infrequent change in stimulus location (Simons, 2000). Attention capture is inferred from behavior, such as having slower responses relative to a comparison condition without the salient stimulus feature (Awh, Belopolsky, & Theeuwes, 2012). The term "response selection" refers to the process of mapping stimulus information onto a response code (Pashler, 1998). The stimulus-response mapping is defined by instructions given to the subject, such as which button to press for a given stimulus. In the next section we will present some background on attention capture and aging, which then will be followed by consideration of age differences in response selection with distracting information.

Inhibiting attention capture can be studied by comparing reading with vs. without distracting text that is presented in a different font. Studies reliably find that distracting text impairs performance more in older vs. young adults (Connelly, Hasher, & Zacks, 1991; Darowski et al., 2008). Another tactic is to examine attention capture by including a nonverbal stimulus that competes with a target for attention. Age-related reductions in attention control are sometimes evident by heightened visual attention capture (Pratt & Bellomo, 1999), but results have been mixed (Kramer, Hahn, Irwin, & Theeuwes, 1999) and depend on perceptual load (Maylor & Lavie, 1998).

Recent work using a visual search task distinguished the impact of attention capture on performance from the time needed to disengage attention once it was captured (Cashdollar et al., 2013). The time course of attention capture by a distractor stimulus was examined as a function of the time between onset of the distractor and the onset of a search array. At the shortest delay (50 ms) there were comparable attention capture effects in both young and older subjects. However, at longer delays (250 and 350 ms) disengagement from distractors sharing the target color was evident in the young but not older subjects. One possibility is that the delay in disengagement may be long enough to influence processing of the next stimulus. This is important because distinguishing initial capture from disengagement may bear on mixed results in the literature. The current experiment tested the possibility of prolonged disengagement in normal aging. In addition, targets and distractors are usually two different perceptual objects (Cashdollar et al., 2013). Here we assessed attention capture by presenting only one stimulus at a time. Within one stimulus both the distracting feature (infrequent changes in spatial location) and target feature (non-spatial discrimination feature) coexist, and therefore produce strong interference.

Age differences in the degree that distracting information affects attention control can also be explored by manipulating variables that index later cognitive stages such as response selection. We, and others, use the term "response selection" to label the process of mapping stimulus information onto a response code (Pashler, 1998). Response selection is usually more efficient (i.e. faster and/or more accurate) when the locations of a stimulus and response correspond, such as when both stimulus and response are on the left side, or right side, of the subject (Fitts & Seeger, 1953).

Later work showed that even when spatial location is not relevant to the task the correspondence between stimulus and response locations still matters, as shown by faster reaction times for corresponding locations (Simon & Small, 1969). The influence of stimulus location on performance even when location is not relevant has since been termed the "Simon effect". Additional studies revealed that the Simon effect indexes abstract spatial reference frames for action (Buhlmann, Umilta, & Wascher, 2007; Hommel, 1993; Wallace, 1971), and does not simply reflect the locations of the hands. Depending on task conditions, there can be multiple spatial codes for both stimuli and actions (Hommel, 2011). Some studies show a larger Simon effect in older vs. young adults (Castel, Balota, Hutchison, Logan, & Yap, 2007; van der Lubbe & Verleger, 2002; Vu & Proctor, 2008). However, due to mixed results on whether there are age differences in the Simon task after correcting for general slowing, a recent meta-analysis concluded that more work is needed to resolve the question (Rey-Mermet & Gade, 2017). We next turn to attention capture and response selection in the auditory modality, and how the current study can expand knowledge of potential age differences in these processes.

Most studies investigate how visual attention shifts within circumscribed regions of space, such as the screen of a computer monitor. A key feature that distinguishes the auditory and visual systems is that the auditory system can function as an omnidirectional early warning device (Blauert, 1997; Schafer, 1977; Scharf, 1998). Spatial hearing, in turn, can be used to direct eye and body movements toward a sound's location (Arnott & Alain, 2011). Attention can be captured by sounds whose sources are distant, around corners, obscured, or occur in the dark. Salient sounds are a potent source for attention capture and highly conserved across species (Jerison, 1973; Sokolov, 1963), and audition is generally more resistant to vigilance decrements relative to vision (Arrabito, Ho, Aghaei, Burns, & Hou, 2015). Attention may also be more focused on visual inputs relative to other modalities, possibly to make-up for poor visual alerting functions (Posner, Nissen, & Klein, 1976).

Another difference between modalities is that for vision there are large differences in the quality of stimulus processing as a function of distance from the fovea (Rovamo & Virsu, 1979). Vision can also only maintain ocular focus at a single depth at a time. Auditory processing of stimuli at different locations is much more uniform and unaffected by depth (Blauert, 1997), which likely has implications for attention control by not having to take into account potentially large differences among 3-D locations in perceptual coding. Because high-resolution vision is limited to the fovea, specialized motor systems for moving the eyes around to sample visual space exist. The auditory modality does not have a similarly specialized motor system. Functional neuroanatomical studies indicate that visual attention functions have a substantial overlap with eye movement circuitry (Corbetta et al., 1998). Indeed a major theory of attention posits that attention biases stem from prepared, but not yet executed, eye movements (Rizzolatti, Riggio, Dascola, & Umiltá, 1987).

Lastly, a visual scene is akin to a canvas, with something to be perceived at all locations. In contrast, an auditory scene can be very sparse (Bregman, 1990), such as when a single stimulus is presented from a speaker in an otherwise quiet room. Taken together, the above paragraphs show that auditory attention operates on a sensory system that has substantial

differences relative to vision. Examining age effects in the auditory modality will provide a broader understanding of how attention operates in normal aging.

Age differences in attention capture are evident in the auditory modality when distractors are presented shortly (300 ms) before a visual target (Andres, Parmentier, & Escera, 2006). The sound has a larger impact on reaction time to the target in older subjects (~2x vs. the younger group), which is probably not due to general slowing as alerting effects did not differ with age. There are also age differences in the effect of distracting information when presented concurrently with target sounds, particularly for distractors that convey lexical information (Tun, O'Kane, & Wingfield, 2002). Studies that use dichotic listening methods, where two different sounds are presented through headphones at the same time but to different ears (Kimura, 1967), have found that older adults have greater difficulty shifting attention away from the dominant right ear (Andersson, Reinvang, Wehling, Hugdahl, & Lundervold, 2008).

In the above studies auditory attention capture in aging was studied using a crossmodal task or by presenting more than one sound at a time. Here we will examine auditory attention capture in aging by using a new paradigm based on work by Schröger and colleagues (Roeber, Widmann, & Schröger, 2003). As will be described below, we will test attention capture by changing the spatial features of individual sounds, rather than crossmodal or mixtures of > 1 sound. The study will also be the first to explore whether auditory attention gradients over a wide range (180°) differ with age.

The use of acoustic stimuli may be particularly useful for studying the Simon effect because it is usually larger as compared to visual stimuli (Vu et al., 2003), and is present over a wider range of reaction times instead of for only fast responses (Ivanoff, 2003; Wascher, Schatz, Kuder, & Verleger, 2001). We are not aware of any Simon effect studies of aging in the auditory modality that used standard methods, but one report used a compound visual-auditory stimulus and did not observe age differences (Proctor, Pick, Vu, & Anderson, 2005).

The purpose of this study was to test for age differences in auditory perceptual processing associated with attention capture, disengagement once capture occurs, and response selection. A novel auditory spatial attention task was used to parametrically define the shapes of spatial attention and Simon effect gradients over a 180° range. This was done by having subjects attend to a "standard location" and occasionally shift the stimulus' location away from the standard, in one of four increments of 45°. The spatial shapes of these gradients were operationalized using normalized reaction time measures, and then related to attention capture, disengagement, and response selection. Normalized reaction time was used to correct for general age-related slowing. Analyses also tested for performance asymmetries when attending to the left vs. right sides as well as midline vs. lateral locations.

We hypothesized that if aging was associated with heightened attention capture then the shape of attention gradients that reflect attention capture would have larger peaks due to greater slowing of reaction time by attention capture. If attentional disengagement is weaker in older subjects then we predicted slower reaction times for standards that followed a

location shift. Lastly, we predicted an overall larger Simon effect in older vs. younger subjects, that may also depend on the degree of discrepancy between the locations of the stimulus and responding hand.

Method

Participants

Young (n=25, age 18.8 ±1.0 yrs., M/F = 9/16, 22/25 right-handed) and older (n=25, age 72.5 ±2.5 yrs., M/F = 7/18, 24/25 right handed) adult subjects were recruited from a university and nearby community. Selection of 25 subjects per group matched the number used in a previous study (Golob, Winston, & Mock, 2017). The young adults were university students, and received course credit for their participation. The 25 young adults in this report were randomly selected from previously collected data in a conference report (n=42)(Golob, Venable, Scheuerman, & Anderson, 2017). The subjects were randomly assigned a number between 0 and 1. The selection rule for this study was an arbitrarily ranking from smallest to largest numbers, and the participants corresponding to the smallest 25 random numbers were included here. The effect sizes in Golob, Venable, et al. (2017) that are relevant to this study were > .90 (Cohen's d). The selection of sample sizes of 25 subjects in each group allowed for detection of d's > .54 (power = .80, alpha = .05). Before testing subjects gave written informed consent. All subjects were screened by self-report for major psychiatric and neurological disorders, as well as substantial hearing impairments. Hearing thresholds were tested between 500–4,000 Hz using an audiometer (Maico, Eden Prairie MN) to ensure that thresholds were < 25 dB and differences between ears were <10 dB, and the Montreal Cognitive Assessment Exam was given to older subjects (mean = 26 ± 3 out of 30 possible). No potential subjects were rejected. As with other studies of sensory systems, there is the limitation that sensory processing is unlikely to be precisely equivalent in young and older subjects. Here the main variable of interest was spatial location, and the virtual locations were widely spaced and easily distinguishable on pre-testing. As reported below, accuracy also did not differ between the young and older groups. Thus, for present purposes subtle differences in hearing do not appear to be a factor in accounting for the results below. Subjects also filled out a handedness survey (Oldfield, 1971) and a musical experience survey that was part of an unrelated project. The experiment was performed accordance with protocols approved by the Tulane University and the University of Texas San Antonio Institutional Review Boards.

Apparatus

During the experiment subjects were seated in a sound booth and held a keypad for responding to stimuli. Acoustic stimuli were presented using insert headphones. While performing the tasks participants were instructed to look forward and to not close their eyes.

Stimuli

White noise stimuli were presented using insert earphones at an intensity of ~60 dB nHL (200 ms duration). Sounds were then spatialized to elicit percepts of originating at distinct locations in the frontal hemifield (Left→Right: −90°, −45°, 0°, +45°, +90°) using S-LAB (NASA) software. The software modifies sound files based on the cues that are naturally

used to perceive sound locations (for details see (Mock, Seay, Charney, Holmes, & Golob, 2015). The white noise stimuli were then amplitude modulated at either 25 or 75 Hz (90% depth), which sounded like a playing card 'shuffle' or a 'buzz' sound, respectively.

Experimental procedures

Participants listened to each of the sounds and marked on a piece of paper the perceived location relative to the center of their head. This verified that all subjects heard the sounds at approximately the intended location. They were also familiarized with the two amplitude modulation rates, and had a short practice run before testing (10 trials per standard location). For the main experiment participants were asked to distinguish between the 25 and 75 Hz modulation rates by pressing with the left/right thumb on the keypad. Stimuli were presented at a fixed 2.4 sec stimulus onset asynchrony (SOA) in order to provide a comfortable pace for all subjects, and mapping of left/right response hand to 25/75 Hz stimuli was approximately counterbalanced across subjects. Each subject was instructed to respond fast while maintaining high levels of accuracy. During an experimental block the majority of stimuli were randomly presented at a single standard location (p=.84, 126/150 trials per block), but occasionally shifted to one of the other locations (p=.04, 6/150 trials for each shift location, per block). Having subjects focus attention at a standard location mirrors everyday life where auditory spatial attention is typically oriented to a given location for more than a few seconds at a time, such as when having a conversation or listening to music. The approach of using standard and shift trials is similar to the use spatial cues to define valid and invalid trials (Posner, 1980), and was directly inspired by observations that changing stimulus location induces attention capture (Roeber et al., 2003). Each shift trial was always followed by a standard trial with an average of 5 standard trials (range=1–9) separating each shift trial. Separate blocks had the standard location at −90°, 0°, or + 90°, given in pairs of two blocks (150 stimuli/block) for each standard location (6 blocks total). Block order was approximately counterbalanced across subjects in each group, resulting in each combination being presented a comparable number of times.

Statistical analysis

The behavioral measures were accuracy and median reaction time on correct trials, and were analyzed using analysis of variance (ANOVA). Left and right hand measures were averaged together for the analyses of location, including responses to standard and shift locations, as well as for "sequence effects". Sequence effects refer to performance on standard trials following a location shift trial (i.e. the 1st standard after a shift, 2nd standard, etc.). Analyses of the Simon effect used separate performance measures for each hand, which are described in detail below.

Normalized reaction times were used to control for potential age-related overall slowing of reaction time (Birren & Fisher, 1995; Faust, Balota, Spieler, & Ferraro, 1999; Koga & Morant, 1923). Normalized data also help to better evaluate the shapes of reaction time profiles because individual differences in overall response speed do not inflate the standard error values. Normalized reaction times are expressed as values of 0.0–1.0, which are scaled over each subject's range of reaction times in all three standard conditions. For a given data point, j, the formula for normalization was: $norm_j$ = (reaction $time_j$ - minimum)/(maximum -

minimum). The “reaction $time_j$” variable is the median reaction time of a given location in a given condition. Each subject had 15 of these data points (5 stimulus locations x 3 standard conditions). The “maximum” and “minimum” refer to the slowest and fastest reaction times, respectively, among each subject’s 15 data points. For each subject the fastest reaction time has a normalized value of 0, the slowest normalized value is 1, and all other reaction times are in between 0 and 1.

When reaction time was analyzed using median and mean reaction time measures the results did not differ from what is reported below (see Supplemental Table). In this study age-related slowing was not substantial, and analysis of mean and median reaction times did not find any significant main effects of group, although there were some nonsignificant trends.

Factors in all analyses included stimulus location (5). To define spatial asymmetries between attending to the left and right sides, the left and right side standards were examined with a factor of standard location (2: −90°, +90°). To test whether measures varied as a function of how far away shifts were from the left/right standard location, the location of each stimulus was coded relative to the standard location rather than absolute space. Blocks with the standard at 0° were examined separately because unlike the lateral standard locations (−90°, +90°) shifts could occur in the left or right direction but had half the range (±90° vs. 180°). For analyses of the lateral and midline standards the omnibus ANOVA was followed by planned contrasts using quadratic functions to assess patterns across the 5 locations relative to the standard location. When sequence effects were examined the ANOVAs included a factor of sequence (5: 1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 5–9 standard stimulus after a shift trial).

The Simon effect is typically calculated by comparing reaction time and accuracy as a function of the relationship between the locations of the stimulus and response hand. When the stimulus and response hand are on the same side of midline they are considered to be “corresponding” trials (e.g. left side stimulus requiring a left hand response). Conversely, when the stimulus is on one side of midline and the responding hand is on the other, this is termed a “non-corresponding” trial. Corresponding and non-corresponding trials are equally likely (p=.50 each). Prior work on normal aging has shown that attention capture and stimulus-response compatibility can be studied within the same task (Lawo & Koch, 2014). The main analysis compared behavior on corresponding and non-corresponding trials for each of the four lateral locations. Location was further subdivided into factors of side (2: left, right) and eccentricity (2: ±45°, ±90°). The midline location does not fit either category (corresponding, non-corresponding). For this reason we also calculated performance across the five locations by subtracting left-right hand responses, and tested whether there were differences among hands at 0° using t tests.

Significance was defined as $p<.05$, and Greenhouse-Geisser correction was used to control for violations of sphericity. For clarity, the original degrees of freedom are reported below.

Results

Attention capture effects

Normalized reaction times as a function of standard location are shown in Figure 1A-C. Note that the locations shown in Figure 1 are in absolute coordinates, with negative values to subject's left and positive values are to subject's right. For all standard locations reaction times were fastest at the standard, slowed for shifts near the standard, and then sped up, to different degrees, for shifts that were far from the standard. These results suggest quadratic attentional gradients centered on the standard location in each condition. Analysis of lateral standards using a 2 (group) x 2 (standard) x 5 (stimulus location) ANOVA test showed a main effect of location ($F_{(4,192)}$=16.6, p<.001, η_p^2=.26) and a standard x stimulus location interaction ($F_{(4,192)}$=4.5, p<.01, η_p^2=.09). Planned contrasts showed a significant quadratic function for the −90° standard (p<.001, η_p^2=.60) and a smaller, but significant, effect for the +90° standard (p<.01, η_p^2=.16). When the standard was at 0° midline there was a significant effect of location ($F_{(4,192)}$=13.0, p<.001, η_p^2=.21), with increased reaction times for near shift locations (±45°) and then comparable (−90°) or somewhat faster responses (+90°) at the far shift locations. There were no significant effects or interactions involving age group.

Overall accuracy was nearly identical among groups for lateral standard (young = 96.2 ± 1.0%, older 96.6 ± 0.6%) and midline standard blocks (young = 97.1 ± 0.6%, older 96.7 ± 0.6%), and did not significantly differ among groups (Figure 2A-C). For lateral standards there was a main effect of location, indicating progressive reductions in accuracy from the standard, with a small increase at the farthest location ($F_{(4,192)}$=13.1, p<.001, η_p^2=.22). There were no significant effects in the midline standard condition. The accuracy data indicate that any potential age differences in hearing ability did not adversely affect performance on this task.

Sequence effects

The impact of a shift trial on processing subsequent stimuli at the standard location was tested using a 2 (group) x 3 (standard location) x 5 (sequence) ANOVA test. The standard locations were all tested together because the question was whether there were age differences in how shifts affected performance to subsequent standards, which is a separate issue from the detailed spatial patterns analyzed in the "attention capture" section above. Analysis of normalized reaction time revealed an effect of sequence ($F_{(4,192)}$=9.6, p<.001, η_p^2=.17) that was qualified by a group x sequence interaction ($F_{(4,192)}$=5.6, p<.001, η_p^2=.10)(Figure 1D). Follow-up ANOVA tests in each group showed a main effect of sequence in older subjects ($F_{(4,96)}$=14.9, p<.001, η_p^2=.38) but not for the young (p<.70, η_p^2=.02). There were no significant effects involving the standard location, but there were some non-significant trends[1]. The same ANOVA testing on accuracy showed no significant effects or interactions. These results show that shift trials had a lingering effect that slowed responding to the next stimulus in the older but not young group, and suggests prolonged attentional disengagement from shifts in older participants.

[1]Nonsignificant effects involving the standard factor: standard ($F_{(2,96)}$=3.0, p=.054, η_p^2=.06); group x standard ($F_{(2,96)}$=2.7, p=.071, η_p^2=.05); standard x sequence ($F_{(8,384)}$=2.0, p=.062, η_p^2=.039).

Simon effects

To help visualize the Simon effect across the five locations, the group means of normalized left minus right reaction times are illustrated in each of the three standard conditions. As shown in Figure 3A-C, negative values indicate faster left vs. right hand responses, and positive values indicate the converse. Thus, Simon effects are present when the difference measure (left-right hand) is negative for sounds on the left and a positive value for sounds on the right. Quantitative analyses of left-right hands are given in a footnote[2].

The main analysis quantified the Simon effect by using the traditional metric of subtracting corresponding (ipsilateral) from non-corresponding (contralateral) locations of the stimulus and responding hand (Figure 3 D-F). This analysis excluded midline locations because they cannot be classified as corresponding/non-corresponding since the midline location is not lateralized. However, t tests comparing left-right differences in younger and older subjects at the midline location for each standard condition did not show significant group differences.

Analysis of lateral standards using a 2 (group) x 2 (standard) x 2 (side) x 2 (eccentricity) ANOVA test showed a standard x side interaction ($F_{(1,48)}$=51.7, p<.001, η_p^2=.52), due to larger Simon effects in the hemispace contralateral to the standard location (Figure 3 D,F). There was a small effect of eccentricity (±°90 > ±°45), which suggests a small gradient within each hemispace. There was also a complex 4-way interaction ($F_{(1,48)}$=7.5, p<.001, η_p^2=.13). This appeared to reflect larger group differences at the ±45° locations when the standard was at +90°, relative to the −90° standard condition (Figure 3A,C). For standards at midline there was a main effect of group ($F_{(1,48)}$=10.4, p<.01, η_p^2=.18), with larger Simon effects in older partcipants (see Figure 3E). There was a small effect of eccentricity ($F_{(1,48)}$=4.4, p<.05, η_p^2=.08), that was qualified by a group x eccentricity interaction ($F_{(1,48)}$=4.2, p<.05, η_p^2=.08) because age differences in the Simon effect were larger at the ±45° locations.

For accuracy the Simon effect was calculated the same as with reaction time, by subtracting accuracy for the right hand from the left hand. Analysis of the lateral standards used a 2 (group) x 2 (standard) x 5 (stimulus location) ANOVA. There were no effects involving age group (Figure 2D, F). There was a main effect of standard ($F_{(1,48)}$=19.7, p<.001, η_p^2=.29), due to the subtraction order, and location ($F_{(4,192)}$=13.3, p<.001, η_p^2=.22). The location effect indicated that Simon effects were only present in the hemispace contralateral to the standard location. In the 0° standard condition there was a main effect of location ($F_{(4,192)}$=16.8, p<.001, η_p^2=.26). As with lateral standards, there was better accuracy for the left hand to left side sounds and the right hand to right side sounds (corresponding > non-corresponding), with comparable accuracies to midline sounds.

[2]Analysis of the lateral standards using a 2 (group) x 2 (standard) x 5 (stimulus location) ANOVA test, where location was coded at the absolute location relative to the head, had a main effect of stimulus location ($F_{(4,192)}$=43.5, p<.001, η_p^2=.48). There were no significant effects involving group. For the 0° standard a 2 (group) x 5 (location) ANOVA had a significant effect of location ($F_{(4,192)}$=38.5, p<.001, η=.45), and a group x location interaction ($F_{(4,192)}$=5.2, p<.01, η_p^2=.10)(Figure 3B). The group x location interaction was due to larger Simon effects in the older group at lateral locations.

Discussion

This study used a novel auditory spatial attention task to distinguish age differences in attention capture, reorienting after attention capture, and response selection. Attention capture was shown by quadratic-shaped reaction times curves relative to the attended location. Young and older subjects had comparable gradient shapes, including asymmetries when attending to the left vs. right side. Disengagement of attention was tested by examining reaction times to stimuli following location shifts, and only the older group had slower responses to the next stimulus. In both groups Simon effects had spatial gradients that were modulated by the standard location, which had the smallest Simon effect. Age differences were indicated by larger Simon effects in older subjects at the midline standard, which were not clearly evident for the lateral standards. Taken together, these results support the idea that a specific mechanism for age differences in distractibility is a delay in recovering from distraction, rather than being unable to inhibit distraction from occurring. The Simon effect findings support prolonged resolution of stimulus-response interference in aging, with the important qualification that here it was most evident when attending to the midline. We speculate that these age differences in attention control and response selection likely have downstream consequences, such as older adults having better memory for distracting information relative to young adults (Connelly et al., 1991).

In the auditory modality, previous work has shown that occasional shifts between two locations substantially increases reaction time (Roeber et al., 2003). Here we used this same basic approach, but used more locations to map-out attention capture effects as a function of angular distance from a standard location. The results showed quadratic gradients (inverted u-shapes), that were more pronounced when attending to the left vs. right side, and compressed when attending to the midline. The midline pattern is likely due to having a smaller range for shifts (±90°) relative to lateral standards (180° range).

Earlier work identified linear, rather than quadratic, auditory attention capture profiles (Mondor & Zatorre, 1995; Rorden & Driver, 2001). A major difference among studies is that the earlier ones used attentional cueing tasks, where the attended location varied within a block of trials, rather than sustaining attention to one location for the duration of a block. Other variables such as the spacing of stimulus locations (Bahcall & Kowler, 1999) and noise in discriminating stimuli (Allen, Kaufman, Smith, & Propper, 1998) may also be relevant. Besides factors in sustaining attention and vigilance (Warm & Parasuraman, 2008), cued attention also requires frequent reorienting, and has similarities to task switching (Monsell, 2003). Cueing tasks also have more explicit proactive control (Braver, 2012), and cues that precede the targets have alerting effects (Posner, 1978). Future work is needed to understand the variables that account for these different spatial attention capture patterns. In addition, spatial hearing is panoramic but most laboratory spatial attention studies do not test a full 360° range of stimulus locations. The spatial range may be a vital factor in determining the shape of attention gradients, and would boost ecological validity.

The comparison of young and older subjects in the present study found no significant differences in the pattern of spatial attention gradients, which is not consistent with a reduced ability to inhibit distracting information in aging (cf. Hasher & Zacks, 1988; Rey-

Mermet & Gade, 2017). Even quantitative details in the attention capture spatial profiles, such as left-right asymmetries, were maintained in the older subjects. Such observations agree with a study that found comparable spatial attention switching between two concurrent stimuli in young and older adults (Oberem, Koch, & Fels, 2017). We note, however, recent evidence that the spatial spread of visual inhibition of return may be smaller in older vs. younger adults (Lawrence et al., 2018). Taken together, these findings provide further support for the idea that reduced inhibition in normal aging is not a general phenomenon (Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Rey-Mermet & Gade, 2017), although some particular expressions of inhibition may show age differences.

A previous visual study found age differences in reorientation if the distracting feature was also relevant to the main task (Cashdollar et al., 2013). In this experiment the common feature was spatial information, as shifts were defined only by a change in location from the standard location. We did not compare common vs. dissimilar features here, but it is worth doing in the future. Amplitude modulation rate was the criterion for discrimination, but subjects also focused attention on the standard location. This was given in the instructions, comported with experience as most stimuli came from the standard, and was verified by data showing that the standard location had both the fastest reaction time and highest accuracy. In the older group, the strong carryover effect on the trial following a shift suggests that the upper bound of age differences in reorientation in Cashdollar et al. (350 ms) may last much longer (2.4 sec here). Note that the next stimulus after a shift was always a standard location (i.e. there were never two shift trials in succession). The lack of age differences in accuracy show that the slower reaction times in older subjects for the first standard were not due to a speed-accuracy tradeoff.

More basic research is needed to better understand whether slower attentional disengagement is a consistent feature of normal cognitive aging. Nonetheless, it is worth briefly considering practical applications. Slower disengagement would be particularly undesirable in common risky situations such as driving (Anstey, Wood, Lord, & Walker, 2005), or where there is a risk of falling (Holtzer et al., 2007), and may be a feature of anxiety disorders in aging (Van Bockstaele et al., 2014). There is currently a great deal of interest in finding ways to use cognitive training to lessen the impact of cognitive aging, particularly in the domains of attention and executive functions (Anguera & Gazzaley, 2015). On the other hand, prolonged attentional processing may have benefits in some respects. For example, we speculate that longer processing of distractors may be one mechanism for why older people are better at remembering task-irrelevant information relative to young adults (Amer, Campbell, & Hasher, 2016; but cf. Tun et al., 2002). Unlike most laboratory experiments, in everyday life the utilities of remembrances are not fixed. Information that is extraneous in one context may be highly useful in a different situation.

Simon effects also had a spatial gradient, and the results were broadly consistent with the only study that examined Simon effect gradients, in that case using visual stimuli (Klein, Dove, Ivanoff, & Eskes, 2006). Among lateral standards, the smallest Simon effect was at the locations in the hemispace of the standard location (see Figure 3D&F). The Simon effect was much larger at the two locations in the hemispace opposite to the standard. When the standard location was at midline, attention was focused on a neutral location (being in

neither the left nor right hemispace), and Simon effects were comparable in the left and right hemispace locations. Taken together, attending to a lateral standard location may have conferred an advantage to resolving stimulus-response incompatibility, that was offset by greater interference at far locations. Although linear fits were significant, in our view the results were reasonably consistent with linearity being driven by differences between left hemispace, midline (neutral), and right hemispace locations. Fine-grained mapping, with more than two locations in each hemispace, would be needed to fully test for any differences within each hemispace.

Prior work shows that healthy aging is associated with larger Simon effects (Castel et al., 2007; van der Lubbe & Verleger, 2002), even after correcting for overall slower response speed in older subjects. The present findings are compatible with these results when subjects attended to the midline standard, which has similarities to typical paradigms where voluntary attention is likely directed forward. However, the data also argue against a general age-related decline in resolving stimulus and response code interactions (Hommel, Musseler, Aschersleben, & Prinz, 2001; Proctor & Cho, 2006). Such a general mechanism would presumably be evident for all standard locations. Instead, lateral standards had no clear age differences in the Simon effect. The reason for the dissociation is unclear, but may involve interplay between auditory and visual attentional systems (Arnott & Alain, 2011), eye position information, which can influence spatial hearing (Lewald, 1997; Lewald & Getzmann, 2006), and possibly front vs. back or central vs. eccentric asymmetries in auditory attention (Golob, Lewald, Jungilligens, & Getzmann, 2016; Golob, Venable, et al., 2017).

Conclusion

The main results were that a quantitative analysis of the shape of spatial attention capture gradients showed that they were comparable in young and older adults. However, the older group showed a lingering effect of attention capture that affected performance on the next trial. The Simon effect was larger in older vs. younger participants when they focused attention towards the midline, but not lateral, locations. These findings suggest comparable auditory spatial attention capture among groups, but once attention is captured, older subjects take longer to disengage. Age differences in response selection were found, but the lack of age differences in the same subjects when attending to lateral locations dovetails with prior findings that inhibition deficits may not be a general feature of cognitive aging.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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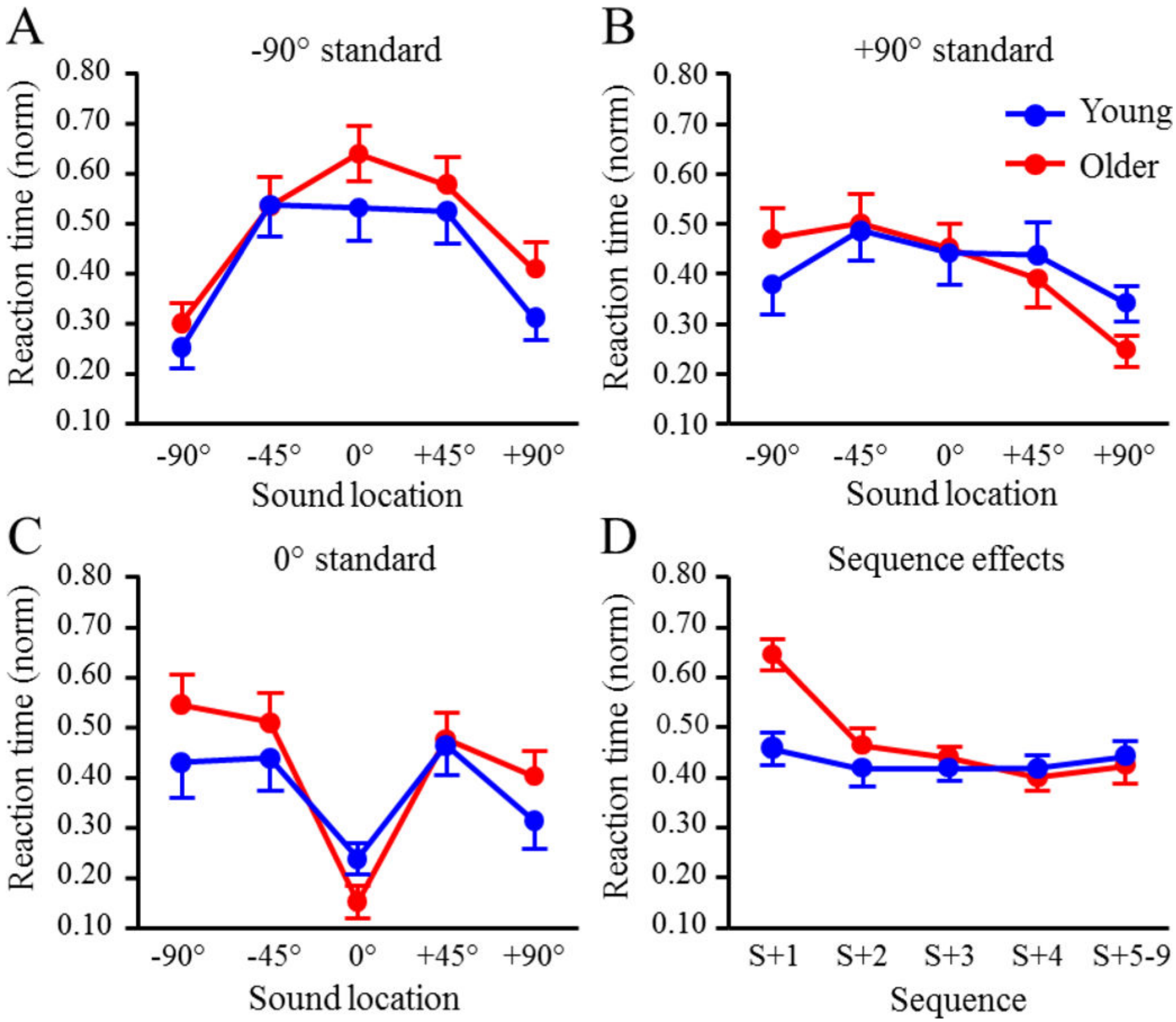

Figure 1.

Normalized reaction time as a function of absolute location in each standard condition (A-C) and sequence effects (D). Standard locations at −90° (A) +90° (B) and 0° (C) had significant effects of location and no effects involving age group. D) Sequence effects collapsed across the three standard locations after a shift trial. Older, but not younger, participants were significantly slower on the standard trial following a location shift. Error bars = SEM.

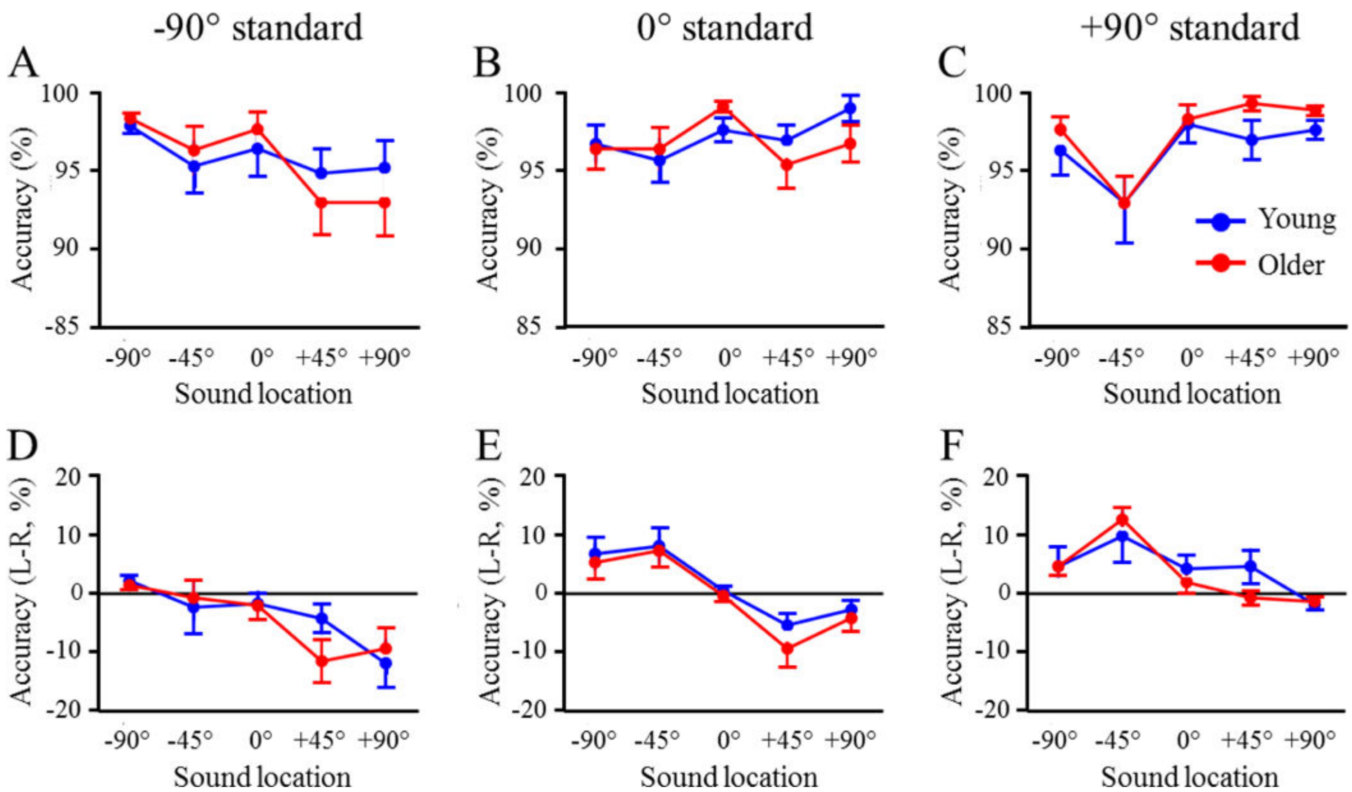

Figure 2.

Accuracy as a function of standard location and stimulus locations (A-C). Locations are in absolute coordinates relative to the subject. For the lateral standards accuracy was significantly lower for locations away from the standard location. There was no effect of location in the 0° standard condition. D-F) Plots of left – right hand accuracy to illustrate Simon effects as a function of standard and stimulus locations. For all three standard locations the Simon effect was evident at locations away from the standard. For lateral standards the Simon effect was present only in the hemispace contralateral to the standard location. Error bars = SEM.

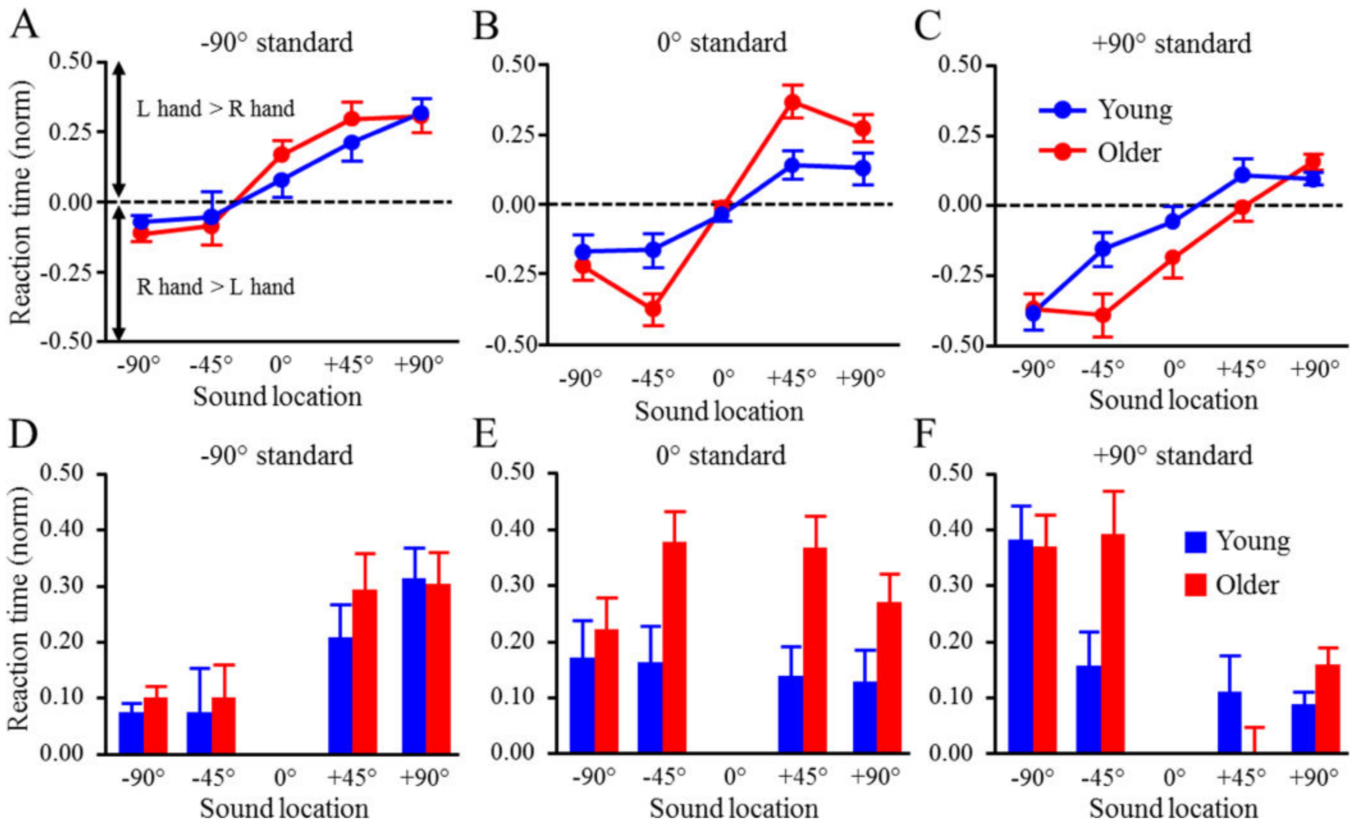

Figure 3.

Simon effects as a function of standard location and stimulus locations. Locations are absolute values relative to midline (negative left, positive right). Reaction times for normalized left hand minus right hand responses are shown in A-C to visualize results across all 5 locations. The difference in normalized reaction times between non-corresponding and corresponding trials at lateral locations are shown in D-F. The overall Simon effect was significantly larger for older vs. younger subjects when the standard was at 0°. Lateral standards had a complex interaction involving group, mainly at the +90° standard condition. For the lateral standard conditions Simon effects were significantly smaller in the hemispace ipsilateral to the standard location. Error bars = SEM.