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Age-related changes in gaze sampling strategies during obstacle navigation

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Abstract

Background: Appropriate coordination of gaze behavior and body motion is essential for navigating cluttered environments. This is often complicated by having to contend with a concurrent secondary task, like engaging in a conversation or looking for relevant landmarks. However, there is little evidence of how aging and multitasking affects how gaze is deployed during obstacle navigation to guide our movements. *Research question*: How do gaze patterns differ between young and older adults when navigating around a series of obstacles under dual-task conditions? *Methods*: 17 young adults and 17 older adults navigated around vertically-oriented obstacles in isolation (i.e., single-task condition) and while engaging in a concurrent backward-counting or visual search task (i.e., dual-task conditions). In the visual search condition, participants had to identify the location of an object (i.e., a black shape on a tile) along the perimeter of the pathway, simulating a landmark. We quantified the spatial-temporal pattern of gaze to obstacles relative to body position, as well as the frequency and duration of gaze fixations to obstacles, route-planning features, and landmarks. *Results*: We found that older adults transferred gaze away from obstacles earlier and contacted obstacles more frequently than young adults. However, the proportion of fixation number and duration to obstacles did not differ between groups in any condition. In addition, older adults had to allocate gaze to landmarks to a greater extent in the visual search condition—at the expense of fixating route-planning areas—to maintain similar search performance in the dual-task condition compared to the single-task condition. *Significance*: Older adults use different gaze strategies and have greater difficulty under dual-tasking conditions than young adults when navigating around a series of obstacles. We suggest that deficits in visual working memory and/or divided attention may explain these results.

Keywords: locomotion; obstacle avoidance; gaze; older adults; vision

1. Introduction

When navigating the world, we need to acquire relevant visual information about the environment while planning our future route and avoiding obstacles in our path [1,2]. Appropriate spatial-temporal allocation of gaze is required to successfully perform these tasks. Most research in this area has focused on stepping over a single obstacle, showing for instance, that people tend to fixate the obstacle during the approach but not when executing the step to avoid it [3]. On the other hand, when walking through an array of stationary obstacles, young adults frequently gaze at the end goal, presumably relying on peripheral vision to monitor obstacle position with respect to the body [2]. However, the probability to fixate an obstacle is greater when the obstacle is moving, and the risk of collision is high [4].

Aging appears to affect gaze patterns during walking [5]. This is evident with a variety of tasks, including stepping to targets, walking up and down stairs, and circumventing a single obstacle [6-9]. For example, older adults delay looking away from an obstacle when lifting the trail foot over it [6]. This prolongs the fixation on the obstacle during the step over and reduces the available time to sample future locations ahead, which may be particularly problematic when dealing with multiple obstacles. Although young and older adults spend a similar amount of time fixating a single obstacle to navigate around, older adults spend more time fixating the ground beyond the obstacle and young adults spend more time fixating the wall ahead [7].

Multitasking increases cognitive load and can impact gait, particularly as we age [10,11]. Age-related changes in gait under dual-task conditions are typically reflected in reduced walking speed [10,11]; performance on the secondary task is frequently degraded as well. In more complex walking tasks, like those involving obstacle avoidance, age-related changes are also observed. For example, in a simulated street-crossing task that involved walking on a treadmill and performing a concurrent auditory or verbal task, older adults at higher risk of falling collided with more cars and walked slower [12]. Older adults at higher risk of falling also shift gaze away from an obstacle they must step over sooner than young adults when having to count backwards at the same time [13]. In addition, older adults walk slower and maintain a larger distance from a single obstacle to avoid, particularly when having to remember an auditory message presented during the task [14]. However, there is little evidence of how aging and multitasking affects how gaze is deployed while navigating through an array of several obstacles in the travel path.

In the present study, we tested the hypothesis that gaze patterns differ between young and older adults when having to walk around a series of vertical obstacles, particularly under dual-task conditions. We also expected performance on the secondary task to decline in the older adult group. Thus, young and older adults performed the obstacle negotiation task in isolation (i.e., single-task condition) and while engaging in a concurrent counting or visual search task (i.e., dual-task conditions). The search task is an ecologically valid task in that it mimics situations encountered when walking, like looking for relevant landmarks while having to prevent collisions with objects. Because vision is required for both the gait and cognitive task, it leads to structural interference [15]. We chose a counting dual task because it is commonly used, is a well-defined and quantitative verbal fluency task similar to having a conversation, and gait changes associated with it are an indicator of fall risk in older adults [16].

2. Method

2.1 Participants

17 older adults (5 females; age = 71.8 ± 6.8 years, range = 65 – 86 years) and 17 young adults (7 females; age = 22 ± 2.3 years) from the community and university campus voluntarily participated in the study. Inclusion criteria included: visual field mean deviation score better than -2 dB in both eyes as determined by frequency-doubling technology (Humphrey 710 FDT Visual Field Instrument; Carl Zeiss Meditec, Inc.); aged ≥65 years (older adults) or between 18 – 35 (young adults); and no known neurological, muscular, or joint disorder that could affect walking. Participants wore their habitual corrective lenses if applicable (3 young and 8 older adults). The Office of Research Ethics at Simon Fraser University approved the study, and participants provided informed written consent prior to participating.

2.2 Protocol

Participants performed an obstacle negotiation task under single- and two dual-task conditions [17], the order of which was randomized. There were 12 walking trials per condition (36 trials total). For each condition, participants walked along a 4.5-m long and 1.25-m wide path to an ‘‘end gate’’ consisting of two vertical poles (height = 25 cm; diameter = 6 cm) after circumventing four vertical poles (height = 165 cm; diameter = 3.5 cm). We positioned poles 60 cm from each other in the anterior-posterior (AP) direction and varied pole and end gate positions in the medial-lateral (ML) direction on a trial-to-trial basis using one of four randomized configurations. An opaque board occluded vision before trial initiation. We instructed participants to walk at a self-selected speed, to navigate the course without stopping, to take the simplest path through the poles without any part of their body going outside the path's borders, and to avoid contact with the poles. Participants started walking immediately once cued.

In the count dual-task condition, participants walked while counting backward out loud by threes. In the visual search dual-task condition, participants had to identify the location of a shape at the end of each trial after being asked by an experimenter. In this condition, we positioned four tiles (20 x 15 cm) on the ground, two on each side of the path, each with a different black shape on a white background. We randomly varied the sequence of shapes (cross, triangle, circle, and square) on a trial-to-trial basis.

Participants performed the count and visual search task prior to walking (i.e., baseline single-tasks conditions). For the count single task, participants counted out loud by threes for a total of 10 seconds in each of three trials while seated. For the visual search single task, participants viewed the shapes for 5 seconds while standing, before having their vision blocked in each of 12 trials.

Participants also performed the Useful Field of View (UFOV) test (17-inch touch monitor with 75-Hz refresh rate; version 7.0.2; Visual Awareness Research Group, Inc., Punta Gorda, FL). Participants sat 50 cm from the screen and performed all three subtests.

2.3 Data collection

A high-speed, head-mounted, mobile eye-tracker (model H6-HS; Applied Science Laboratories, Bedford, MA) recorded gaze position at 120 Hz. A video camera mounted on the eye tracker recorded the participants' view of the path at 30 Hz. We used the system's standard 9-point calibration method to calibrate the eye tracker, with calibration points located on the walkway. Two Optotrak Certus (Northern Digital, Inc., Waterloo, Canada) cameras, synchronized with the eye tracker, recorded (at 120 Hz) the time-varying positions of infrared-emitting diodes placed on the obstacles and participant's body, including the head, chest, and bilaterally on the heels, mid-feet, and tip of shoes.

2.4 Data and Statistical Analysis

We low-pass filtered kinematic data using a 4th-order Butterworth algorithm at 6 Hz, then calculated gait speed between the first and last obstacle using the chest marker. We also quantified the number of obstacle collisions, defined as a noticeable sway or shift in position of the obstacle or it falling to the ground after contact with the body (and verified visually by two experimenters). We performed a mixed-model (group x condition) ANOVA to determine differences in gait speed. We used a Poisson regression generalized linear model with a log link function for collisions per trial. Due to the lack of non-zero factor levels in the data, we converted group and condition into a single factor with six levels for this analysis.

We calculated vector gaze position at each time point from the horizontal and vertical components of the gaze data after filtering (12-Hz low-pass, 4th-order Butterworth algorithm). We defined saccade onsets and offsets as the times when angular eye rotation exceeded or fell below 100 °/s for a minimum of 16 ms [18]. Periods >66 ms between a saccade offset and a subsequent saccade onset defined fixations on an area of interest [18]. We used the 30 Hz video mounted on the eye tracker with gaze location superimposed on the image to verify the location of fixations.

To indicate how far ahead participants fixated to plan their route, we calculated a spatial gaze distance (SGD) score and a spatial-temporal gaze distance (STGD) score [17]. The details of these measures are explained in the legend of Figure 1. We compared SGD and STGD scores across groups, conditions, and segments using separate mixed-model ANOVAs.

We next quantified the proportion of the number of fixations and the proportion of gaze fixation time to route-planning features (ground, gap between obstacles), obstacles, and shapes (if applicable). In addition, we calculated the interval between a gaze shift away from an obstacle and the time at which the AP chest position crossed past it (gaze obstacle-crossing interval). Because some participants fixated an obstacle more than once, we used the last gaze shift away from the obstacle before crossing. A negative interval indicates gaze transfer away before crossing the obstacle. To determine differences in these measures, we used separate mixed-model (group x condition) ANOVAs. Separate two-tailed t-tests determined differences between groups for the shape proportion analysis.

For the counting task, for each trial, we determined the total correct responses in a number sequence and normalized this by the trial's duration. Normalization accounts for group differences in walking speed and times for completing the baseline versus walking conditions. For the visual search task, we determined the total number of correctly identified shape locations across trials. We then calculated dual task cost (DTC) as [10,17]:

$$DTC = \frac{(Dual\ Task - Single\ Task)}{Single\ Task}$$

Separate two-tailed t-tests determined differences between groups for the count and search DTC measures.

We used an alpha level of 0.05 for all statistical analyses. For all ANOVAs, we included participant as a random effect, and used Tukey's post hoc tests when we found significant main effects or interactions.

3. Results

3.1 Gait speed and obstacle collisions

Older adults walked slower (0.86 ± 0.16 m/s) than young adults (1.03 ± 0.18 m/s) (group main effect: $F_{1,32} = 9.4$, $P = 0.004$). Both groups walked faster in the single-task condition and slower in the count dual-task condition (condition main effect: $F_{2,64} = 38.7$, $P < 0.0001$). However, all gaze measures are independent of gait speed.

Older adults contacted obstacles significantly more than young adults ($\chi^2 = 55.1$, $p < 0.0001$). Young adults contacted obstacles only four times in the search condition (0.020 ± 0.036 collisions/trial). Older adults contacted obstacles in all three conditions (collisions/trial: single task = 0.039 ± 0.067; count = 0.066 ± 0.081; search = 0.060 ± 0.058) for a total of 32 collisions.

3.2 Gaze patterns

Participants fixated further ahead early in the path (approximately 4 segments ahead during the single- and count dual-tasks, and 3 segments ahead during the search dual-task) and decreased gaze distance near the end (Fig. 1B). We found no group differences in SGD ($F_{1,32} = 0.4$, $P = 0.535$) or STGD ($F_{1,32} = 0.4$, $P = 0.544$). However, we found a significant interaction for SGD (condition x segment: $F_{8,448} = 7.3$, $P < 0.0001$). As shown in Fig. 1C, we found similar results for STGD (condition x segment: $F_{8,448} = 4.7$, $P < 0.0001$).

Older adults shifted gaze away from a particular obstacle approximately 0.35s earlier than young adults before crossing it (Fig. 2; group effect: $F_{1,32} = 6.4$, $P = 0.016$), though we found no effect of condition (condition: $F_{2,63} = 3.1$, $P = 0.051$; group x condition: $F_{2,63} = 2.9$, $P = 0.063$). Young adults directed more fixations to route-planning features than older adults in the search dual-task (by ~11%), but not in the other conditions (Fig. 3A; group x condition: $F_{2,64} = 14.9$, P <

0.0001). Both groups allocated a lower proportion of fixation time to route-planning features during the search dual-task (group x condition: $F_{2,64} = 11.4$, $P < 0.0001$) (Fig. 3B). In addition, for both groups, the proportion of fixations ($F_{2,64} = 17.5$, $P < 0.0001$) and the proportion of fixation time ($F_{2,64} = 6.4$, $P = 0.003$) allocated to obstacles was reduced in the search dual-task compared to the other conditions (Fig. 3C,D). During the search dual-task, older adults made a greater proportion of fixations ($t_{32} = 5.1$, $P < 0.0001$) and spent a greater proportion of fixation time ($t_{32} = 3.8$, $P = 0.0006$) on the shapes than young adults (Fig. 4).

3.3 Dual-task costs and UFOV scores

Although older adults performed worse in the search dual-task condition (Fig. 5A; $t_{32} = 2.9$, $p = 0.006$), we found no differences between groups in search DTC ($t_{32} = -1.5$, $p = 0.147$). We also found no difference in count DTC ($t_{32} = -1.0$, $p = 0.314$) between groups (Fig. 5B). As shown in Table 1, UFOV scores differed between groups for the divided attention and selective attention subtests as well as overall scores.

4. Discussion

Appropriate coordination of gaze behavior and body motion is essential for navigating cluttered environments, despite other competing demands for attention. However, there is little evidence of how aging and multitasking affects how gaze is deployed during obstacle navigation. In this study, we found that, when navigating through an array of vertically-oriented obstacles, older adults transferred gaze away from them earlier and contacted them more frequently than young adults. Older adults also had to allocate gaze to landmarks (i.e., shapes) to a greater extent—at the expense of fixating route-planning areas—to maintain a similar search performance level in the dual-task condition compared to the single-task condition.

Trajectory modifications during obstacle avoidance require a balance between acquiring upcoming environmental information and monitoring limb/body position. The gaze distance measures show that both young and older adults fixated future locations rather than prioritizing obstacles in their immediate vicinity. These results are consistent with previous studies showing that when negotiating vertical obstacles people tend to fixate on end-goal locations to guide locomotion [2]. Older adults shifted gaze away from obstacles earlier relative to when they passed them compared to younger adults. These earlier shifts suggest that older adults prioritized the acquisition of visual information from other obstacles or route-planning features, rather than from the obstacle that they were approaching. Similarly, when sequential precision foot placements are required [20], or one must step over an obstacle under dual-task conditions [13], older adults at a higher risk of falling look away from a target or obstacle sooner than younger adults or older adults at low risk of falls. To successfully circumvent the obstacles, online information about body trajectory relative to the obstacle positions can be acquired through peripheral vision, without direct fixations [2,21].

The search dual-task condition necessarily impacts gaze, as participants had to momentarily direct gaze away from the main path to look at the shapes. This leads to structural interference [15] and simulates situations of daily living, like having to negotiate a busy sidewalk while scanning for a particular store. In this condition, both groups reduced the number of fixations to obstacles and route-planning features. They also prioritized closer path locations (lower SGD). Previous studies demonstrate that multitasking influences the allocation of gaze during walking [17,22,23]. For example, young adults decreased the number of fixations directed to stairs when also dealing with a visual reaction time task [23]. As one of our primary findings, we showed that older adults allocated a greater proportion of fixations (32% vs 19%) and fixation time (28% vs 16%) on the shapes in the search dual-task condition than younger adults. The obstacle and shape locations are both stored within a visual-spatial memory representation [24], and thus compete for the same cognitive resources. The increased gaze scrutiny of the shapes may have allowed the older adults to maintain similar search performance compared to the single-task condition.

There are at least three possible explanations for the effects of aging in the visual search condition. First, peripheral visual loss, which may occur with age, can affect the allocation of gaze in this task [17]. However, we found normal visual field scores in our older adults. Second, aging may reduce spatial working memory capacity [25,26]. Visual information regarding the environment kept in working memory allows for proper limb trajectory over or around objects. For example, when stepping over an obstacle, visual information acquired before straddling the obstacle for a period of time can be retained for at least 120 s before resuming the step [27]. Gaze allocation may rely on this memory representation [27-30]. For instance, when searching for targets in a virtual environment, the plan to fixate a particular location initially depends on memory rather than on the current visual information [29]. Faster decay of visual memory can increase uncertainty of the visual scene, thus increasing the need to re-fixate environmental features to update previously stored information. Indeed, environmental uncertainty affects the decision of where and when to look during walking: greater target uncertainty increases gaze allocation on stepping targets, and the increased gaze times are associated with reduced foot-placement error [18]. Third, the older adults may have had greater difficulty selecting or dividing attention. This is supported by the UFOV scores (see Table 1).

In conclusion, aging affects gaze patterns and dual-task performance while navigating through obstacles. We propose that a combination of visual working memory and selective/divided attention deficits due to aging may partially explain these results. Additional research in complex, cluttered environments is needed.

Conflict of interest statement: None.

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Figure Legends

Figure 1. Gaze distance measures for each condition and group across the five segments included in the analysis. To determine the spatial gaze distance (SGD) score, we first divided the walking path into seven segments. We determined which segment(s) participants fixated relative to the anterior-posterior chest marker location until they walked past the fourth obstacle (representing the first five segments). We assigned an SGD score to each fixation based on the number of segments ahead the participant fixated. For the spatial-temporal gaze distance (STGD) score, we multiplied the SGD for each fixation by the fixation duration divided by the time the participant spent walking in the current segment. The SGD and STGD scores are then averaged for each segment. Larger values for these measures indicate that the participant allocates gaze further ahead (SGD) for a greater amount of time (STGD). (A) An example of how gaze distance is scored. Here, the participant is walking through segment 1 (S1). (B) Spatial gaze distance scores. (C) Spatial-temporal gaze distance scores. Data are represented as mean ± SE.

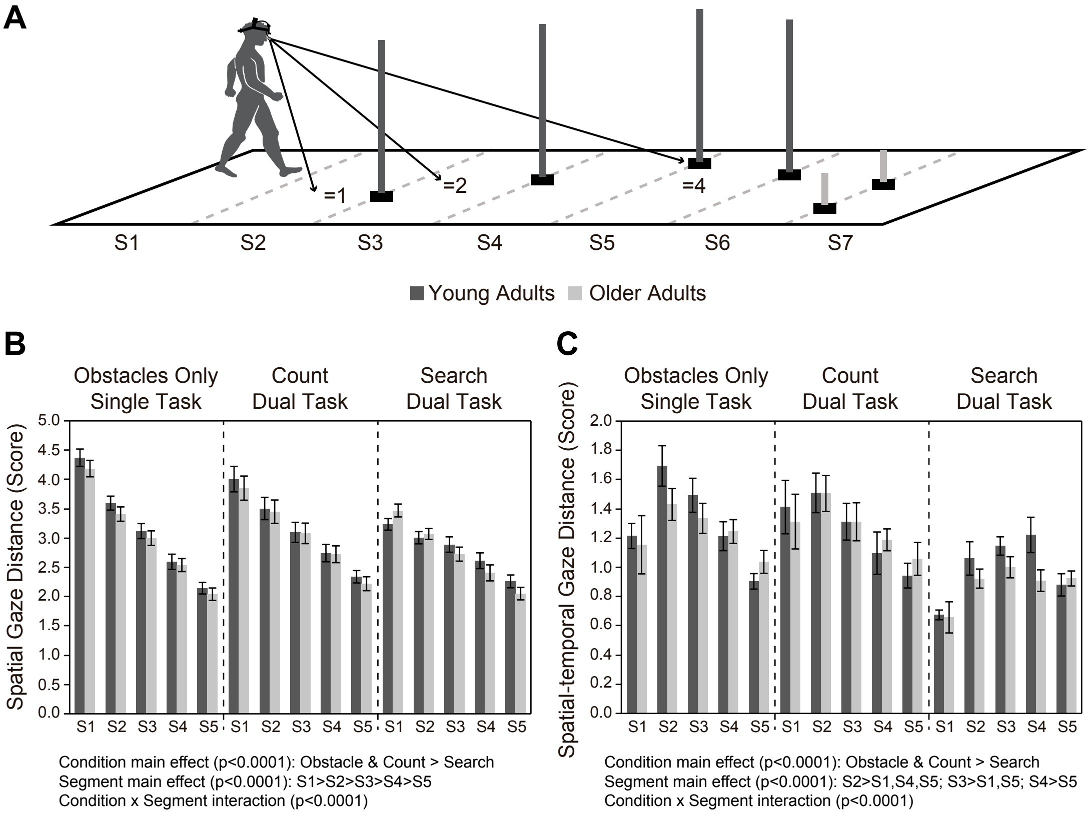
Figure 2. Gaze obstacle-crossing interval for each condition and group. Negative intervals indicate gaze transfer away before crossing the obstacle. Data are represented as mean ± SE. Individual participant data are also shown. * Statistically significant post hoc test based on a group main effect ($P < 0.05$).

Figure 3. Obstacles and route-planning gaze fixations across groups and conditions. (A) Proportion of route-planning fixations across groups and conditions. (B) Proportion of route-planning fixation times. (C) Proportion of obstacle fixations across groups and conditions. (D)

Proportion of obstacle fixation times. Data are represented as mean ± SE. Individual participant data are also shown. *Statistically significant post hoc test based on a condition x group condition interaction ($P < 0.05$). **Statistically significant main effect of condition ($P < 0.05$).

Figure 4. Gaze fixations on shapes. (A) Proportion of fixations on shapes between groups. (B) Proportion of fixation time on shapes between groups. Data are represented as mean ± SE. Individual participant data are also shown. *Statistically significant difference ($P < 0.05$).

Figure 5. Dual-task performance. (A) Visual search performance (percent correct across trials) and dual-task cost. (B) Counting performance (normalized to trial duration) and dual-task cost. Data are represented as mean ± SE. Individual participant data are also shown.


A
=1
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S1
S2
S3
S4
S5
S6
S7
Young Adults
Older Adults
B
Obstacles Only Single Task
Count Dual Task
Search Dual Task
Spatial Gaze Distance (Score)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
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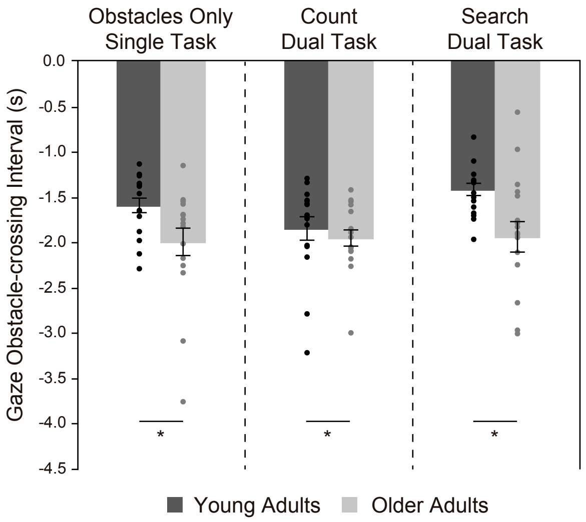
S1 S2 S3 S4 S5 S1 S2 S3 S4 S5 S1 S2 S3 S4 S5
Condition main effect (p<0.0001): Obstacle & Count > Search
Segment main effect (p<0.0001): S1>S2>S3>S4>S5
Condition x Segment interaction (p<0.0001)
C
Obstacles Only Single Task
Count Dual Task
Search Dual Task
Spatial-temporal Gaze Distance (Score)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
S1 S2 S3 S4 S5 S1 S2 S3 S4 S5 S1 S2 S3 S4 S5
Condition main effect (p<0.0001): Obstacle & Count > Search
Segment main effect (p<0.0001): S2>S1,S4,S5; S3>S1,S5; S4>S5
Condition x Segment interaction (p<0.0001)

Figure 1


Obstacles Only
Single Task
Count
Dual Task
Search
Dual Task
Gaze Obstacle-crossing Interval (s)
0.0
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Young Adults
Older Adults

Figure 2

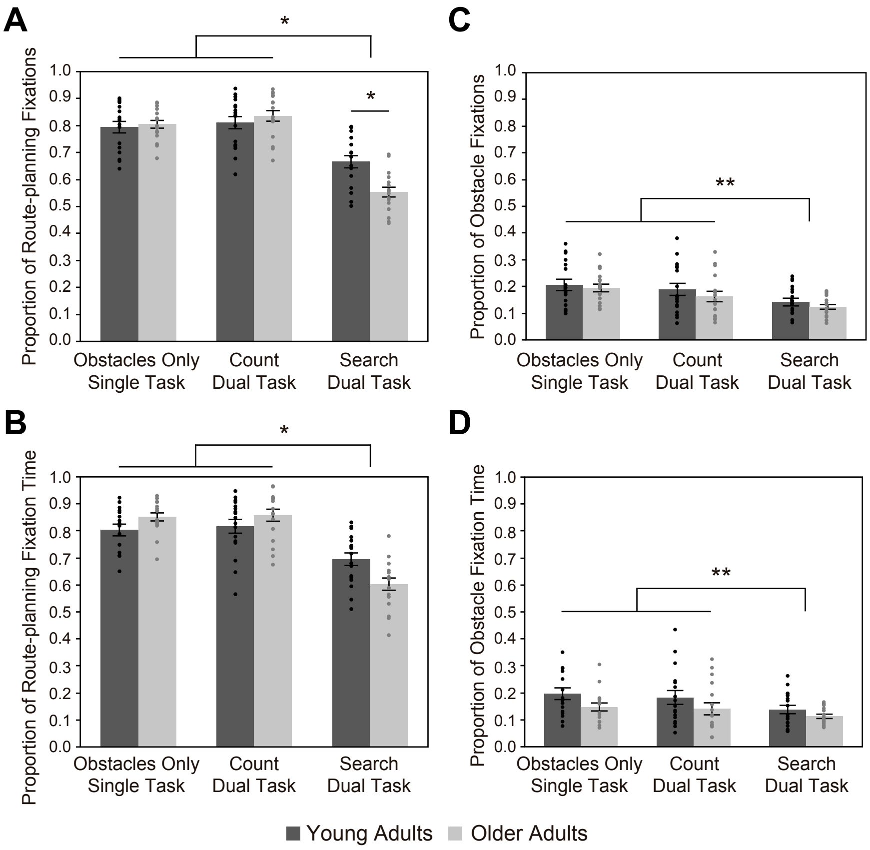

A
B
C
D
*
**
Proportion of Route-planning Fixations
Proportion of Route-planning Fixation Time
Proportion of Obstacle Fixations
Proportion of Obstacle Fixation Time
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Obstacles Only Single Task
Count Dual Task
Search Dual Task
Young Adults
Older Adults

Figure 3

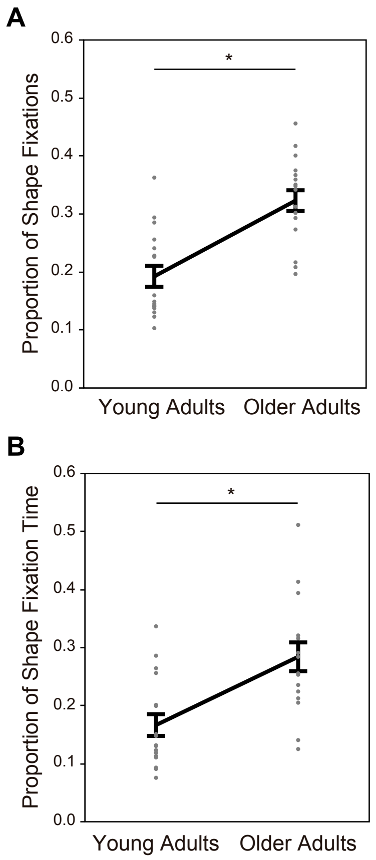
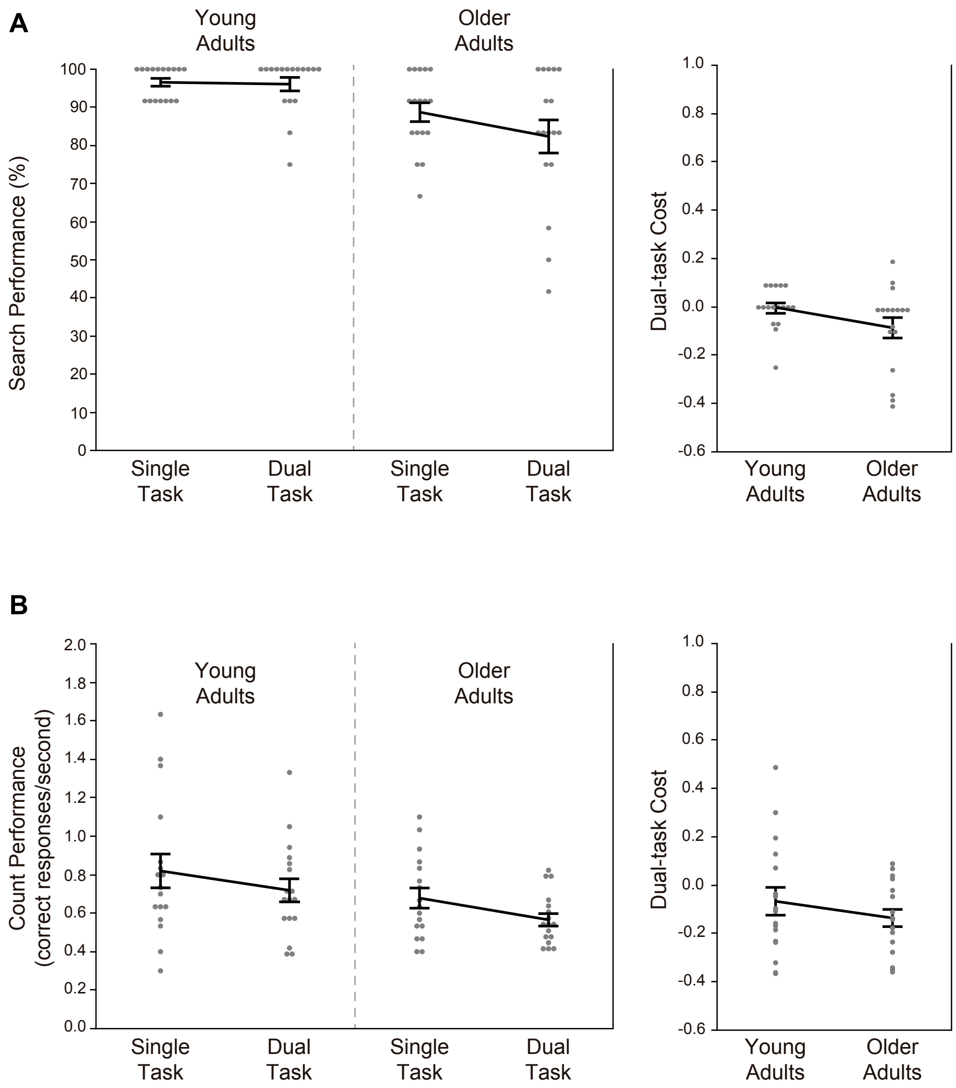

A
B
Proportion of Shape Fixations
Proportion of Shape Fixation Time
0.0
0.1
0.2
0.3
0.4
0.5
0.6
*
Young Adults
Older Adults

Figure 4



A
Young Adults
Older Adults
Search Performance (%)
100
90
80
70
60
50
40
30
20
10
0
Single Task
Dual Task
Single Task
Dual Task
Dual-task Cost
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Young Adults
Older Adults
B
Count Performance (correct responses/second)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Young Adults
Older Adults
Single Task
Dual Task
Single Task
Dual Task
Dual-task Cost
Young Adults
Older Adults

Figure 5