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The impact of aging and repetition on eye movements and recognition memory

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ABSTRACT

The modulation of gaze fixations on neural activity in the hippocampus, a region critical for memory, has been shown to be weaker in older adults compared to younger adults. However, as such research has relied on *indirect* measures of memory, it remains unclear whether the relationship between visual exploration and *direct* measures of memory is similarly disrupted in aging.ß The current study tested older and younger adults on a face memory eye-tracking task previously used by our group that showed that recognition memory for faces presented across variable, but not fixed, viewpoints relies on a hippocampal-dependent binding function. Here, we examined how aging influences eye movement measures that reveal the amount (*cumulative sampling*) and extent (*distribution of gaze fixations*) of visual exploration. We also examined how aging influences direct (*subsequent conscious recognition*) and indirect (*eye movement repetition effect*) expressions of memory. No age differences were found in direct recognition regardless of facial viewpoint. However, the eye movement measures revealed key group differences. Compared to younger adults, older adults exhibited more cumulative sampling, a different distribution of fixations, and a larger repetition effect. Moreover, there was a positive relationship between cumulative sampling and direct recognition in younger adults, but not older adults. Neither age group showed a relationship between the repetition effect and direct recognition. Thus, despite similar direct recognition, age-related differences were observed in visual exploration and in an indirect eye-movement memory measure, suggesting that the two groups may acquire, retain, and use different facial information to guide recognition.

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Recognition memory; eye movements; aging; relational memory; hippocampus

Introduction

Previous research has established that aging is associated with changes in memory (Naveh-Benjamin et al., 2004; Old & Naveh-Benjamin, 2008) that lead to impaired performance on tasks such as free recall, cued recall, and recognition (Craik & Rose, 2012). These impairments are predominantly due to older adults' difficulty remembering novel

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Supplemental data for this article can be accessed here.

relations among items, and to a lesser extent, due to their difficulty remembering the items themselves (Old & Naveh-Benjamin, 2008). At the neural level, changes in memory may be linked to structural and functional changes in specific regions of the medial temporal lobe (MTL) such as the hippocampus (Bettio et al., 2017; Grady, 2012; Grady & Ryan, 2017; Olsen et al., 2017). For instance, hippocampal volumes are smaller in older adults compared to younger adults (Jack et al., 2000, 1998; Raz, 2000) and these volume reductions are associated with declines in hippocampal-dependent cognition (Driscoll et al., 2003; Ezzati et al., 2015), such as relational memory (Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000). Compared to younger adults, older adults have exhibited lower functional magnetic resonance imaging (fMRI) responses within the hippocampus during the encoding of items (e.g., words and faces; Dennis et al., 2007; Fischer et al., 2010; Liu et al., 2018) and during relational memory tasks which require linkages across items (e.g., face-name pairs and word triads; Addis et al., 2014; Salami et al., 2012). Thus, age-related changes to hippocampal volume and function may be associated with an age-related deficit in relational memory.

Aging is also associated with changes in visual exploration at encoding, which may be related to some of the observed age-related behavioral and functional changes to the hippocampus described above. For example, compared to younger adults, older adults typically make more gaze fixations during the viewing of visual stimuli, such as faces (Firestone et al., 2007; Heisz & Ryan, 2011) and scenes (Ryan et al., 2007; Wynn et al., 2021). Increased visual exploration by older adults may reflect an unconscious attempt to leverage the oculomotor system in order to compensate for a declining hippocampal system (Liu et al., 2018; Ryan et al., 2020). Using a face processing Liu et al. (2017, 2018) found that although the number of gaze fixations made to a novel face was positively related to hippocampal activation in younger adults, this relationship was significantly weaker in older adults. Moreover, in younger adults, an increased number of gaze fixations made during the initial viewing of a novel face was related to larger decreases in hippocampal activation upon subsequent presentations of the same face (i.e., repetition suppression); however, in older adults, the relationship with gaze fixations and repetition suppression was not observed with subsequent presentations of the same face. The work by Liu et al. (2017, 2018) suggests that some aspects of eye movement behavior may be associated with hippocampal function, which, in turn, may be associated with the expression of memory – at least indirectly. This work also suggests that aging disrupts the relationship between visual exploration and memory formation.

Despite these intriguing Liu et al. (2017, 2018) did not examine the relationship between eye movement measures of visual exploration and *direct* measures of memory (subsequent conscious recognition) in their younger and older adult samples. Thus, it remains unclear whether the relationship between eye movement behavior and direct expressions of memory is similarly weakened in aging. Therefore, in the current study, we compared younger and older adults on the relationship between an eye movement measure that reveals the amount of visual exploration (*cumulative sampling* – total number of fixations made to a face) and a direct measure of memory (subsequent conscious recognition). We also compared the two age groups on an eye movement measure that reveals the extent of visual exploration (*distribution of gaze fixations* – discrete regions sampled within a face). Finally, we compared the two age groups on the relationship between an indirect eye movement measure of memory (*eye movement*

repetition effect- fewer fixations to repeated, compared to novel, faces) and subsequent conscious recognition during an explicit surprise memory test. Examining the aforementioned relationships enables us to determine whether, compared to younger adults, older adults engage in different eye movement behavior (as revealed by the eye movement measures of visual exploration) in order to compensate for a declining hippocampal system and to support direct and indirect memory performance.

Specific anatomical structures in the anterior MTL cortex have been suggested to be involved with individual face representations (Collins & Olson, 2014), whereas the hippocampus has been suggested to form relations among those faces (Konkel & Cohen, 2009). This finding may be particularly evident when faces are tested from varying viewpoints, as faces viewed from different viewpoints may require the relational binding function of the hippocampus. Previous work by Olsen et al. (2015), Olsen et al. (2016) examined how different aspects of viewing behavior are linked to hippocampal function and subsequent conscious recognition of faces viewed from different viewpoints at encoding and retrieval. In their study, H.C., a woman with developmental amnesia due to hippocampal system compromise, and age-matched young adult control participants incidentally encoded individual faces that either varied in their presentation viewpoint or remained in a fixed viewpoint across study repetitions. Compared to the control participants, H. C. demonstrated relatively intact conscious recognition for faces that were repeatedly studied and tested from the same viewpoint but impaired recognition for faces studied and tested from different viewpoints. This finding suggests that face recognition is differentially supported by the hippocampus and neocortex depending on the presentation viewpoint of faces during encoding (fixed or variable viewpoints). More specifically, such findings suggest that the hippocampus binds the salient features of a face into a flexible memory representation that can accommodate variability in encoding conditions (Olsen et al., 2012). It is also important to note that these representations do not appear necessary for direct perception of the face, but rather recognition of that face when it is later presented in a different viewing context. For example, A. C. Lee et al. (2005) found that selective hippocampal lesions did not impair perceptual discrimination of faces shown from different viewpoints. Taken together, these findings suggest that although the hippocampus is not necessary for the ability to distinguish between different face views presented *simultaneously* to the participant, it does become critical for integrating different features (and views) of a stimulus presented at different timepoints into a lasting memory representation. In other words, the hippocampus supports the integration and updating of a face representation across viewpoints presented across disparate events (Olsen et al., 2015, 2012).

Another finding by Olsen et al. (2016) was that a greater number of cumulative gaze fixations during encoding was associated with better performance on a direct measure of memory (i.e., conscious recognition) for the young adult control participants. However, this relationship was not observed for H.C., suggesting that visual exploration (here, cumulative eye movement sampling) is related to hippocampal function and later recognition memory (Damiano & Walther, 2019; Henderson et al., 2005). Furthermore, examination of the eye movement repetition effect – an indirect expression of memory that occurs when repeated stimuli are viewed with fewer fixations relative to novel stimuli (Althoff & Cohen, 1999) – revealed that H.C. showed an intact repetition effect for faces viewed from fixed viewpoints, but not for faces from varied viewpoints. Notably, Olsen

et al. (2016) found that the magnitude of the eye movement repetition effect was not related to the later recognition of faces for either H.C. or the control participants, suggesting that either multiple memory representations are formed by the hippocampus to support different types of memory performance, or distinct aspects of information within the same memory representation are not available for conscious appraisal (also see, Smith and Squire (2017) for repetition effects outside of awareness when information is incidentally encoded). Together, findings from the eye movement measures of visual exploration (cumulative sampling), as well as the direct (recognition memory) and indirect (eye movement repetition effect) measures of memory suggest that the hippocampus may be important for binding memory representations across repetitions, particularly when the to-be-bound information is not presented in the identical format across repetitions (Olsen et al., 2015, 2012).

To date, the aging literature has reported that older adults exhibit greater visual sampling (i.e., more fixations) during the viewing of faces compared to younger adults (Firestone et al., 2007; Liu et al., 2018) and that, despite this increase in fixations, the positive association between gaze fixations and memory formation may be disrupted in older adults (Liu et al., 2018). Moreover, some studies have found that, compared to younger adults, older adults exhibit a different distribution of gaze fixations to facial features (Firestone et al., 2007; C. Y. Chan et al., 2018), whereas others have found that the two age groups are similar in distribution of fixations (Liu et al., 2018). In addition, compared to younger adults, older adults exhibit diminished eye movement repetition effects during the viewing of faces from fixed viewpoints (Heisz & Ryan, 2011) and are worse at recognizing faces in general (Boutet & Faubert, 2006; Boutet et al., 2015; Crook & Larrabee, 1992; Konar et al., 2013). The aforementioned studies have used face stimuli presented from the same viewpoint. Olsen et al. (2015), Olsen et al. (2016) showed that memory for faces presented across different viewpoints depended on an intact hippocampal system, but that memory for faces viewed multiple times from the same viewpoint could be supported by the neocortex. Therefore, as even healthy aging is typically associated with reduced hippocampal integrity, the present study examined older adults' memory for faces presented at varying viewpoints in an effort to assess age-related changes in the relational binding function of the hippocampus.

To examine how aging may influence eye movement measures of visual exploration (cumulative sampling and distribution of gaze fixations), as well as the indirect (repetition effect) and direct (subsequent conscious recognition) expressions of memory on a task that varies the extent of hippocampal involvement, we used the same experimental task as Olsen et al. (2015), Olsen et al. (2016). Furthermore, we assessed whether there was a relationship between older adults' performance on the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005), and their eye movement behavior and indirect/direct memory performance. The MoCA is a brief cognitive screening test that has high sensitivity and specificity in detecting mild cognitive impairment and predicting future conversion to Alzheimer's disease. Lower MoCA scores are associated with smaller volumes in the MTL, including the hippocampus, among older adults (O'Shea et al., 2016; Olsen et al., 2017), and one study has linked lower MoCA scores to changes in the pattern of viewing of faces (C. Y. Chan et al., 2018). More specifically, C. Y. Chan et al. (2018) found that, compared to older adults with higher MoCA scores, older adults with lower MoCA scores exhibited a more holistic eye movement pattern during facial processing. However,

C. Y. Chan et al. (2018) did not manipulate the viewpoint of the facial stimuli in their study, and they also did not examine the eye movement repetition effect. Here, we add to this work by assessing the relationship between MoCA scores, eye movement behavior (cumulative sampling and distribution of gaze fixations), and indirect (repetition effect)/direct (recognition memory) measures of memory in older adults.

Based on the aforementioned prior work, we made the following predictions. We predicted that older adults would generally show impaired direct recognition, but particularly for faces presented from variable viewpoints. Furthermore, we predicted that, compared to younger adults, older adults would demonstrate greater cumulative sampling and possibly a different distribution of gaze fixations during encoding due to age-related hippocampal compromise. We also predicted that the relationship between cumulative sampling and direct recognition would be disrupted in older adults, especially for faces presented across variable viewpoints, as was observed in amnesic case H.C. Additionally, we predicted smaller age-related eye movement repetition effects (indirect measure of memory) for faces presented across different viewpoints compared to faces presented in fixed viewpoints, similar to amnesic case H.C. (Olsen et al., 2016). Moreover, we predicted that there would be no significant relationship between the magnitude of the eye movement repetition effect and successful direct recognition (also see, Olsen et al., 2016; Smith & Squire, 2017) for either age group. Finally, we predicted that lower MoCA scores would be related to changes in eye movement behavior (e.g., greater cumulative fixations, changes in distribution of gaze fixations), as well as direct (e.g., poorer recognition) and indirect (e.g., weaker repetition effect) expressions of memory among older adults (Olsen et al., 2017; C. Y. Chan et al., 2018). Altogether, this work examined differences in eye movement behavior (cumulative sampling and distribution of gaze fixations), and indirect (repetition effect) and direct (overt reports) measures of memory using a task that varied the extent to which successful performance required hippocampal function. The current study extends previous work on aging and eye movements through a comprehensive assessment of the differential influence of aging on both direct *and* indirect expressions of memory as indicated by the eye movement behavior of younger and older adults. This research advances our knowledge about the neural underpinnings of eye movement behavior, as well as indirect and direct expressions of memory, which will be a step toward understanding overall cognitive variability across the lifespan.

Methods

Participants

Participants were 38 younger adults (21 female; *M* age = 23.10, age range: 18–35 years, *M* education = 15.39 years, education range: 12–19 years) and 35 older adults (26 female; *M* age = 74.77, age range: 61–86 years, *M* education = 15.71 years, education range: 12–22 years). All participants were healthy individuals, community-dwelling, and living in the greater Toronto area. Participants were recruited from the participant database at the Rotman Research Institute or from the "Adult Volunteer Pool" in the Department of Psychology at the University of Toronto. All participants were screened using a background questionnaire to determine their eligibility. All participants were fluent in English and were checked for normal or corrected-to-normal vision using an ETDRS chart.

Exclusion criteria included history of neurological disorder, psychological problem, learning disability, diabetes, significant concussion or loss of consciousness, color blindness, substance abuse, stroke, heart attack, cardiac arrest, or chemotherapy.

Several of the younger adult participants experienced technical difficulties during the experimental session (n = 6) or received incorrect experimental instructions (n = 1) and were subsequently excluded from the analyses. The final sample of younger adult participants consisted of 32 individuals (19 Female; M age = 22.91, M education = 15.31) in the study phase analyses and 31 individuals (19 Female; M age = 22.80, M education = 15.30) in the recognition phase analyses. One older adult participant did not finish the experiment and was excluded from the study. The final sample of older adult participants consisted of 34 individuals (26 female; M age = 74.90, age range: 61–86 years, M education = 15.76 years, education range: 12–22 years).

The MoCA was administered to the older adult participants (M score = 25.24, SD = 1.96). Based on the traditional recommended cutoff score of 26/30 (Damian et al., 2011), 16 older adults failed the MoCA, and 18 older adults passed it. Also, based on the more conservative but more specific MoCA passing cutoff score of 23/30 (Carson et al., 2018), 3 older adults failed the MoCA, and 31 older adults passed it. In the current study, we used the MoCA as a continuous variable in our analyses. There was no difference in years of education between older and younger adults (t = −.59, p = .56). All participants gave informed written consent and received compensation for their participation following standard procedures at the Rotman Research Institute. Ethics approval was obtained for this research from the Research Ethics Board of the Rotman Research Institute.

Apparatus and classification of fixations

Face stimuli were shown on a 21" Asus monitor with a refresh rate of 75 Hz. A head mounted Eyelink II eye tracker (SR Research Ltd., Ottawa, ON, Canada) with 500 Hz temporal resolution was used to record monocular eye movements. Participants were seated 24 inches away from the monitor. At the start of the experiment, a 9-point calibration procedure was conducted. If required, drift correction (>2°) was also conducted before the administration of each trial. Acceleration and velocity thresholds were set to detect saccades greater than 0.5° of visual angle. The right eye of participants (or left eye, if tracking error of the right eye was larger than 1° of visual angle during calibration) was tracked throughout the experiment. The built-in Eyelink saccade-detector heuristic was used to determine saccades. A blink was defined as periods of three or more samples in a saccade-detector signal sequence that were missing. Fixations were defined as the samples remaining after the categorization of blinks and saccades; no minimum duration for fixation definition was applied.

Stimuli

Face stimuli were the same as those used in our previous work (Olsen et al., 2015, 2016); Figure 1. They were created by FaceGen Modeler's *Generate* function (Singular Inversions, Toronto, ON, Canada). Face/head models were lifelike, three-dimensional, and posed with a neutral expression or with a slight smile (80 males, 80 females). Furthermore, a wide range of facial properties were used (e.g., skin tone, eye color, facial shapes, feature shapes/sizes, and

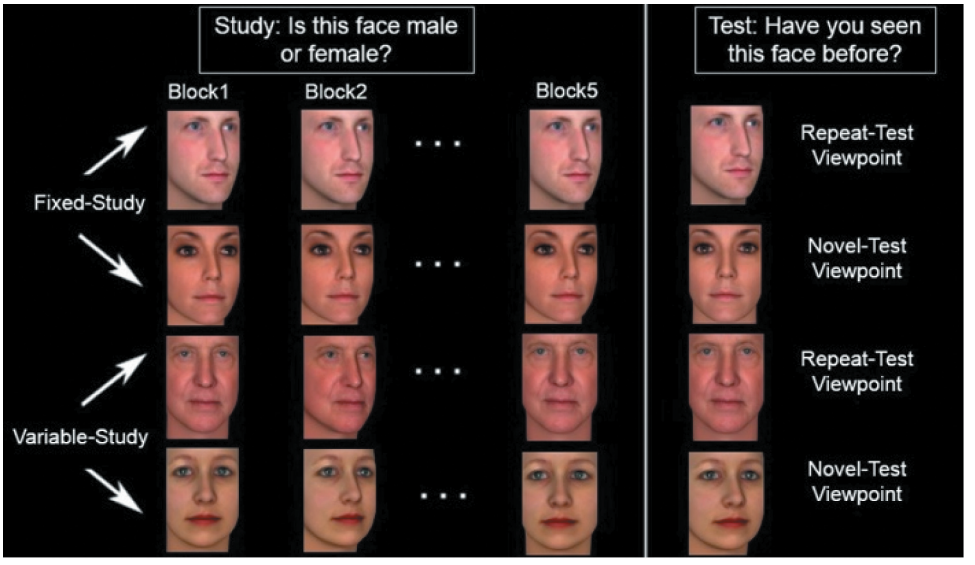

Figure 1. Task design (adapted from Olsen et al., 2015). Left panel (Study phase): The study phase consisted of five study blocks. 80 faces were presented in each block. Each face was displayed for four seconds, once per block, and participants made a gender judgment. 40 faces were presented from the identical viewpoint (fixed-study viewpoint) and 40 faces were shown from five different viewpoints (variable-study viewpoint) across the five study blocks. The presentation order of the viewpoint condition (fixed-study vs. variable-study) was randomized across trials within each block. Right panel (Test phase): The Surprise recognition memory test was administered five minutes after the fifth study block and consisted of 80 previously studied faces and 80 non-studied faces. The presentation order of the viewpoint condition (repeat-test vs. novel-test) was randomized across trials. Among the previously studied faces, half were shown from a repeat-test viewpoint and half were shown from a novel-test viewpoint. For faces studied from variable-study viewpoints, the repeat-test viewpoint was the same as the viewpoint used in the fifth study block. During the test phase, participants made a memory judgment using a 5-point recognition confidence scale (1 = sure new, 2 = probably new, 3 = don't know, 4 = probably old, 5 = sure old).

age). Moreover, using the FaceGen Modeler software, skin textures were manipulated in order to increase the appearance of realism. In order to manipulate viewing angles in a controlled manner, face stimuli were computer generated. This manipulation allowed for comparison with previous literature on facial memory and amnesia with the current study. A total of 960 pictures were generated. Each face ($n = 160$) was positioned in 6 different viewpoints (0° (front view), 5°, 10°, 15°, 20°, 25°). Face images were turned to the participants' right. All faces were cropped so that the top of the head, some of the neck, and ears were not visible. All images measured 316 mm (width) x 405 mm (height) pixels. The crop box used was identical for all face images and positioned horizontally approximately 15 pixels above the eyebrows. Gender ratings were collected by Olsen et al. (2015) from a separate group of younger adult participants ($n = 12$), to ensure that the computer-generated faces could be accurately distinguished as male ($M = .99$, $SD = .01$) or female ($M = .98$, $SD = .02$) even without the presence of hair.

Experimental design and procedure

The task used in the present study was the same as described in Olsen et al. (2015). Participants completed and signed a consent form and a background information form before beginning the experiment. Participants completed two experimental phases: a study phase during which participants incidentally encoded faces while their eye movements were recorded, followed by a surprise recognition memory test phase (Figure 1). In the study phase, the participants were asked to indicate whether the face they saw on the screen was male or female using the left and right arrow keys on a computer keyboard. Response times were recorded for each participant, and their eye movements were tracked while they studied the faces during the five blocks of the study phase. In each study block, the same eighty faces (half female) were displayed one at a time, for four seconds each. Forty faces (20 female) were presented in the identical viewpoint (fixed-study condition) across study blocks and forty faces (20 female) were shown from varying viewpoints (variable-study condition) across study blocks. For example, if a face was shown in the variable-study condition, a participant could have seen it from the following viewpoints: block 1 = 5° rotated, block 2 = 20° rotated, block 3 = 25° rotated, block 4 = 10° rotated, block 5 = 0° rotated (front view); see, Figure 1. Faces were assigned to the fixed-study and variable-study conditions as counterbalanced across participants. The presentation order of the viewpoint condition (fixed-study vs. variable-study) was randomized across trials within each block.

After the fifth study block, participants were given a five-minute break. Before participants started the test phase, they were told that some of the previously shown faces would be presented in a different viewpoint and that they should make their decisions based on facial identity rather than viewpoint. Then, participants were asked to respond out loud to the experimenter whether or not they had viewed the face during the study phase using a five-point confidence scale: 1 = sure new, 2 = probably new, 3 = don't know, 4 = probably old, 5 = sure old. Participants responded out loud rather than on a computer keyboard in order to reduce the likelihood that they would look down at the keyboard while making their responses, which may otherwise cause the eye-tracker to lose signal or cause a shift in the calibration. Participants were asked to make their decisions as quickly and accurately as possible while the face was still displayed on the screen. In the test phase, 160 faces were shown to the participants: 80 previously viewed and 80 new faces. Each face was displayed one at a time, for three seconds. Half of the 40 faces that were studied from the fixed-study viewpoint were shown again at test in the same viewpoint (**fixed-study/repeat-test viewpoint condition**); for the other half of the studied faces that were viewed from the fixed-study viewpoint, the viewpoint at test changed by 15 degrees (**fixed-study/novel-test viewpoint condition**). Half of the 40 faces previously studied in the variable-study condition were tested in the same viewpoint as in the 5th block of the study phase (**variable-study/repeat-test viewpoint condition**); the other half were shown in viewpoints rotated 15 degrees away from their viewpoints in the 5th study block of the study phase (**variable-study/novel-test viewpoint condition**). The presentation order of the viewpoint condition (repeat-test vs. novel-test) was randomized across trials. Front view (0°) and side view (5°-25°) faces were shown equally across the fixed-study and variable-study, novel-test and repeat-test, viewpoint conditions, such that face viewpoint was not diagnostic of condition in either the study or the test block. In the

test phase, faces were viewed as studied versus non-studied faces, and as repeat-test viewpoint and novel-test viewpoint test probes, in a counterbalanced fashion across participants.

Statistics

For each participant, eye movement and response time data were obtained from SR Data Viewer and imported into R Studio (version 1.1.463). All analyses were performed using the R programming language (R Core Team, 2021). Trials for which no response was provided were excluded from analyses. Study trials that were less/greater than 3 standard deviations from the mean of the response time and number of fixations for each condition and participant (i.e., outlier trials) were excluded. The total number of trials for each participant was 400. There were no significant differences in the proportion of average excluded trials for younger (RT: *M* trials = 3.87; number of fixations: *M* trials = 1.57) versus older (RT: *M* trials = 3.35; number of fixations: *M* trials = 1.80) adults. See supplementary materials for a more thorough description of the response time analyses and results.

For the face memory test, the following measures were calculated: hits (the proportion of previously presented faces from the study phase that participants correctly classified as "old"); misses (previously presented faces that were incorrectly classified as "new"); correct rejections (novel faces that were correctly classified as "new"); false alarms (novel faces that were incorrectly classified as "old"); and response bias (participants' tendency to judge faces as being "old"). A measure of sensitivity (d-prime) was determined for each of the four test probe conditions for each participant: fixed-study/repeat-test viewpoint, fixed-study/novel-test viewpoint, variable-study/repeat-test viewpoint, and variable-study/novel-test viewpoint.

The proportion of fixations to the specific facial features was also investigated. Each face stimulus was divided into 4 regions: eyes, nose, mouth, and outer face (excluding eyes, nose, mouth regions). The "emmeans" package (Lenth et al., 2020) was used to obtain pairwise comparisons for all combinations of age group (younger adults and older adults) and facial region (eyes, nose, mouth, and outer face) in R studio. The emmeans package automatically adjusts for multiple comparisons.

For within-subject analyses comparing study phase viewing measurements and subsequent memory (correct/hits or incorrect/misses recognition responses), generalized mixed effects linear regression was performed using the glmer function from the "lme4" package and "lmerTest" package (Kuznetsova et al., 2017; Pinheiro et al., 2022) in R Studio, with subject and item specified as random factors. Subsequent memory was a binary outcome as the participant either made the correct response or did not. The subsequent memory variable only takes into account the previously studied faces (unlike the d-prime variable mentioned above). The logit link function was used in the glmer models. Furthermore, study condition (fixed-study viewpoint, variable-study viewpoint), test condition (repeat-test viewpoint, novel-test viewpoint), age group (*categorical variable*-younger adults and older adults), and the eye movement measure (cumulative sampling and/or the repetition effect) were entered as fixed effects. The maximal model always included the eye movement measure (i.e., cumulative sampling or repetition effect) and age group (*categorical variable*-younger and older adult participants) as interaction terms, age group and study condition (fixed-study viewpoint, variable-study viewpoint) as

interaction terms, and study condition and test condition (repeat-test viewpoint, novel-test viewpoint) as interaction terms, and subsequent memory was modeled as the outcome variable. For all other within subject analyses (no binary outcome), the lmer function was used. Cumulative sampling is the total number of fixations that a participant makes to a face across study blocks. The repetition effect is defined by a decrease in the number of fixations that are made to a face that is repeated across blocks.

For between-subject analyses (see supplementary material) examining the relationship between recognition memory (d-prime) and study phase viewing measurements (i.e., cumulative sampling and repetition effect), linear models were performed using the lm function in R Studio. The maximal model for the between-subject analyses always included the eye movement measure (i.e., cumulative sampling or repetition effect) and age group (*categorical variable*-younger and older adult participants) as interaction terms, age group and study condition (fixed-study viewpoint, variable-study viewpoint) as interaction terms, and study condition and test condition (repeat-test viewpoint, novel-test viewpoint) as interaction terms, and d-prime was modeled as the outcome variable.

Finally, linear models were used to examine the relationship between recognition memory (d-prime) and MoCA in older adults, as well as the relationship between eye movement behavior (i.e., cumulative sample, distribution of gaze fixations, and repetition effect) and MoCA in older adults. MoCA and age (older adults only) were included as continuous variables in these models.

For all between- and within-subject analyses, we performed a likelihood ratio test using the "anova" function in R Studio. p-values were obtained by likelihood ratio tests of the maximal model with the effect in question against the model without the effect in question. Lastly, in order to report the contribution of the main effect of a specific factor that is part of a significant interaction, we compared a depleted model with *the specific factor of interest removed* to a depleted model with *the interaction removed* and not to the maximal model (with interaction terms). This was because a comparison involving the model with interaction terms would include both the contribution of the interaction and the main effect if we compared it directly (Barr, 2013; Bates et al., 2015).

Results

Visual exploration

Cumulative sampling

We predicted that compared to younger adults, older adults would exhibit greater cumulative sampling during the encoding of faces, especially for faces viewed at variable-study viewpoints. Cumulative gaze fixations were calculated for each participant by summing the mean number of fixations made during each block (Figure 2A). A linear model indicated that there was a significant difference in cumulative sampling between younger and older adults ($F = 61.24$, $p < .001$); older adults viewed faces with a higher cumulative number of fixations for both fixed-study and variable-study viewpoints ($t = -7.83$, $p < .001$). Study condition ($F = .002$, $p = .97$), and the interaction between age group and study condition ($F = .03$, $p = .86$) were not significant predictors of cumulative sampling among younger and older adults.

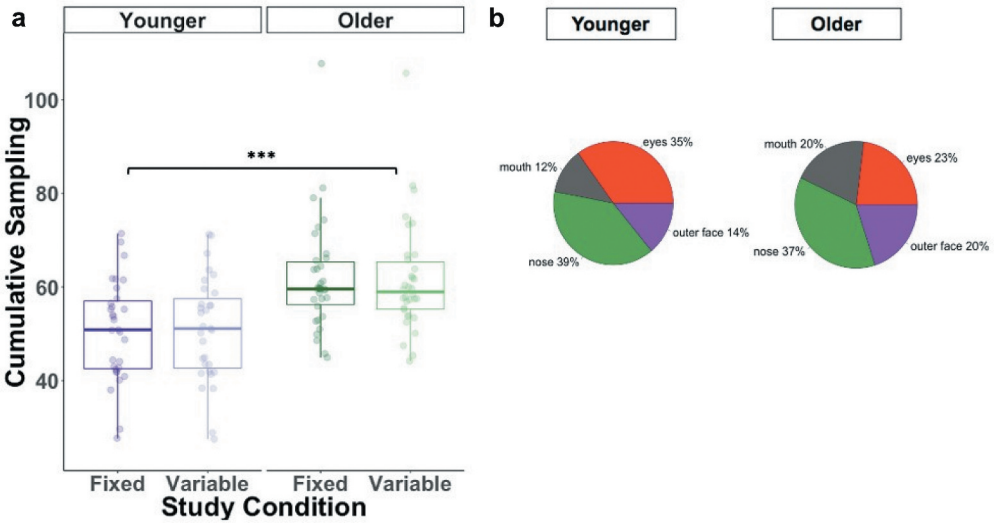

Figure 2. A. The total (cumulative) number of fixations made across the five study blocks plotted for fixed-study viewpoint faces and variable-study viewpoint faces for the younger adults and older adults. B. The proportional distribution of fixations across face regions is shown for the two age groups. Asterisks indicate a significant main effect between older and younger adults, *** $p < .001$.

Distribution of gaze fixations

To investigate whether, compared to younger adults, older adults would demonstrate a different distribution of gaze fixations during the encoding of faces, the proportion of fixations made to specific facial features was examined (Figure 2B). Each face stimulus was divided into 4 regions: eyes, nose, mouth, and outer face (excluding eyes, nose, mouth regions). Younger adults looked at the eye region ($t = -9.52$, p two-tailed $< .0001$) and nose ($t = -2.08$, p two-tailed $= .04$) significantly more than older adults. Conversely, older adults looked at the mouth ($t = 7.09$, p two-tailed $< .0001$) and outer face ($t = 4.51$, p two-tailed $< .0001$) significantly more than younger adults. Therefore, older adults showed an overall increase in sampling behavior compared to younger adults, and the nature of the sampling behavior (i.e., distribution of gaze fixations across face features) also differed from that of younger adults.

Indirect measures of memory

Eye movement repetition effect

A mixed effects linear regression analysis examined the effect of age group, study condition, and block on the number of fixations on a trial-by-trial basis. In this model, study condition, age group, and block, were entered as fixed effects and subject and item were entered as random effects. There was a significant main effect of block ($\chi^2(4) = 728.39$, $p < .001$); the number of fixations significantly decreased across blocks for both younger and older adults (Figure 3A, Table 1). There was a significant main effect of age group ($\chi^2(1) = 15.07$, $p < .001$); older adults made more fixations per trial across blocks. There was a significant interaction between block and age group ($\chi^2(4) = 73.25$, $p < .001$);

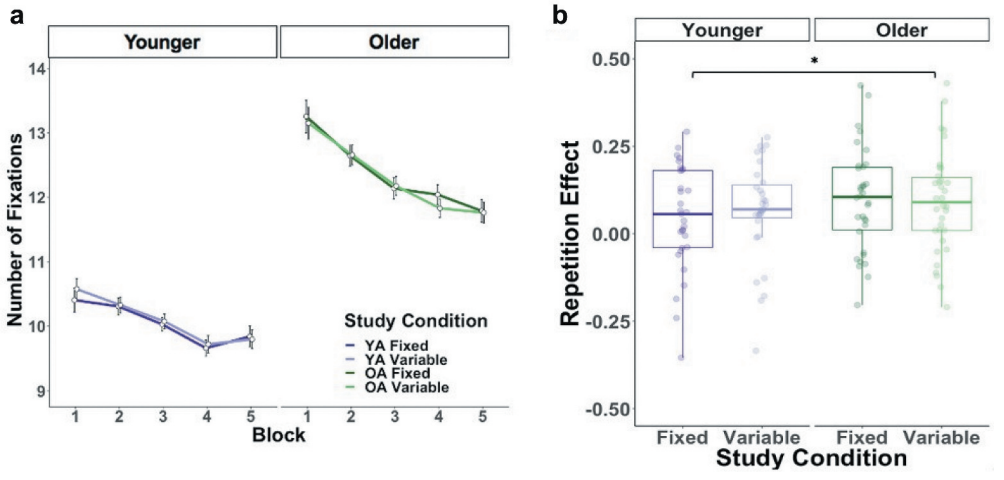

Figure 3. A. The average number of fixations made to a face by younger adults and older adults during each study block, plotted separately for fixed-study viewpoint faces and variable-study viewpoint faces for younger adults (YA Fixed, YA Variable) and older adults (OA Fixed, OA Variable). Error bars denote 95% confidence intervals. B. The magnitude of the repetition effect ([block 1 fixations – block 5 fixations]/block 1 fixations) for fixed-study viewpoint faces and variable-study viewpoint faces for younger adults and older adults. Asterisk indicates a significant main effect between older and younger adults, * $p < .05$.

Table 1. Number of fixations (SE). mean number of fixations made during the study phase for each block, split by study condition and age condition.

Age Group	Younger	Younger	Older	Older
Study Condition	Fixed	Variable	Fixed	Variable
Block 1	10.41 (0.18)	10.58 (0.16)	13.26 (0.25)	13.15 (0.25)
Block 2	10.31 (0.13)	10.33 (0.12)	12.65 (0.16)	12.66 (0.15)
Block 3	10.03 (0.10)	10.08 (0.11)	12.14 (0.17)	12.18 (0.15)
Block 4	9.66 (0.12)	9.72 (0.13)	12.04 (0.16)	11.83 (0.14)
Block 5	9.84 (0.16)	9.80 (0.15)	11.79 (0.17)	11.76 (0.16)
Mean Number of fixations across blocks	10.05 (0.09)	10.10 (0.09)	12.38 (0.12)	12.32 (0.12)
Eye movement repetition effect (%)	4.76	6.82	9.72	9.04

older adults made more fixations in each block. There was no main effect of study condition on fixation count ($\chi^2(1) = .07$, $p = .79$) and there was no interaction between study condition and block ($\chi^2(4) = 2.21$, $p = .70$).

Furthermore, we predicted that older adults would exhibit smaller age-related eye movement repetition effects for faces presented across variable-study viewpoints compared to faces presented in fixed-study viewpoints. The magnitude of the eye movement repetition effect was computed as a proportion of block 1 fixations to account for any baseline differences in viewing ([block 1 fixations-block 5 fixations]/block 1 fixations) for each participant (Figure 3B). An eye movement repetition of .0476 indicates that on average, a participant made 4.76% fewer fixations during the 5th block compared to the 1st block. A linear model indicated that there was a significant main effect of age group ($F = 4.36$, $p = .04$); the magnitude of the repetition effect was greater for older

adults compared to younger adults for both study conditions ($t = -2.09$, $p < .05$). The main effect of study condition ($F = .11$, $p = .74$), and the interaction between age group and study condition ($F = .55$, $p = .46$) was not significant.

Direct measures of memory

Recognition memory

Using a linear model, d-prime was determined for each of the four test probe conditions: fixed-study/repeat-test viewpoint, fixed-study/novel-test viewpoint, variable-study /repeat test-viewpoint, and variable-study/novel-test viewpoint, for each participant. The model included an interaction between study condition and age group, as well as an interaction between study condition and test condition. D-prime was the outcome variable of interest; hit rate, false alarm rate, and response bias were also examined. The effect of test viewpoint was significant ($F = 5.84$, $p = .02$); recognition accuracy was higher in the repeat-test viewpoint than the novel-test viewpoint for both younger and older adults. The interaction between study condition and age group ($F = .26$, $p = .61$), the main effect of study viewpoint ($F = .23$, $p = .63$), the interaction between study viewpoint and test viewpoint ($F = 3.39$, $p = .07$), and the effect of age group ($F = .06$, $p = .80$) were all non-significant predictors of d-prime. A linear model indicated that there was a significant main effect of age group on hit rate ($t = -4.0$, $p < .001$); which was driven by a higher hit rate among older adults compared to younger adults across all conditions. There was also a significant main effect of age group on false alarm rate ($t = -3.51$, $p < .001$); older adults made more false alarms to novel faces (incorrectly classified novel faces as "old"). These patterns of results lead to a significant main effect of age group on response bias ($t = 6.72$, $p < .001$); older adults were more biased toward judging faces as "old" across all conditions. Altogether, age group did not significantly impact the direct measure of recognition (d-prime). Next, we examined whether aging influenced the relationship between the amount of visual exploration and recognition memory.

Cumulative sampling and recognition memory

We predicted that the relationship between cumulative sampling and subsequent recognition memory would be disrupted in older adults, especially for faces presented across variable viewpoints. To examine whether increased visual sampling for particular faces was related to better recognition memory of those same faces (i.e., to examine the effect of visual sampling within subjects), a generalized linear mixed model regression analysis examined the effect of visual sampling (measured by the number of fixations) on subsequent memory (correct and incorrect memory responses). The subsequent memory variable only takes into account the previously studied faces. See supplementary material for the between-subject analyses. High and low confidence responses were collapsed into correct memory responses (hits; 4 and 5 on the confidence scale) and incorrect memory responses (misses; 1 and 2 on the confidence scale). The main effect of test viewpoint was significant ($\chi^2(1) = 12.51$, $p < .001$); recognition accuracy was better in the repeat-test viewpoint than in the novel-test viewpoint. The interaction between study and test viewpoint was significant ($\chi^2(1) = 10.77$, $p < .01$); accuracy was better in the fixed-study

/repeat-test viewpoint. The interaction between study condition and age group (χ^2 (1) = .53, p = .47), the main effect of age group (χ^2(1) = 2.59, p = .11), and the main effect of study viewpoint (χ^2(1) = 1.63, p = .20) were all non-significant.

However, the main effect of cumulative sampling was significant (χ^2(1) = 7.97, p = .005), which indicated that the faces that received a greater number of fixations during the study phase were better remembered. There was a significant interaction between cumulative sampling and age group which indicated that this positive association was not the same in younger and older adults (χ^2(1) = 4.95, p = .03). This interaction was driven by a robust positive relationship in younger adults between cumulative fixations made across study blocks and correct memory responses (Odds Ratio = 1.03, 95% CI [1.01, 1.05]). The relationship between cumulative fixations and correct memory responses was absent in older adults (Odds Ratio = 1.00, 95% CI [0.99, 1.02]; Figure 4A and B; refer to Table 2 for the effects of all factors of the reduced model arrived at via model comparison). These patterns of results were similar even when using the standardized *full range* of the 5-point recognition confidence scale as the dependent variable (see supplementary material). Finally, using *separate* models for each block of the study phase, we conducted the same

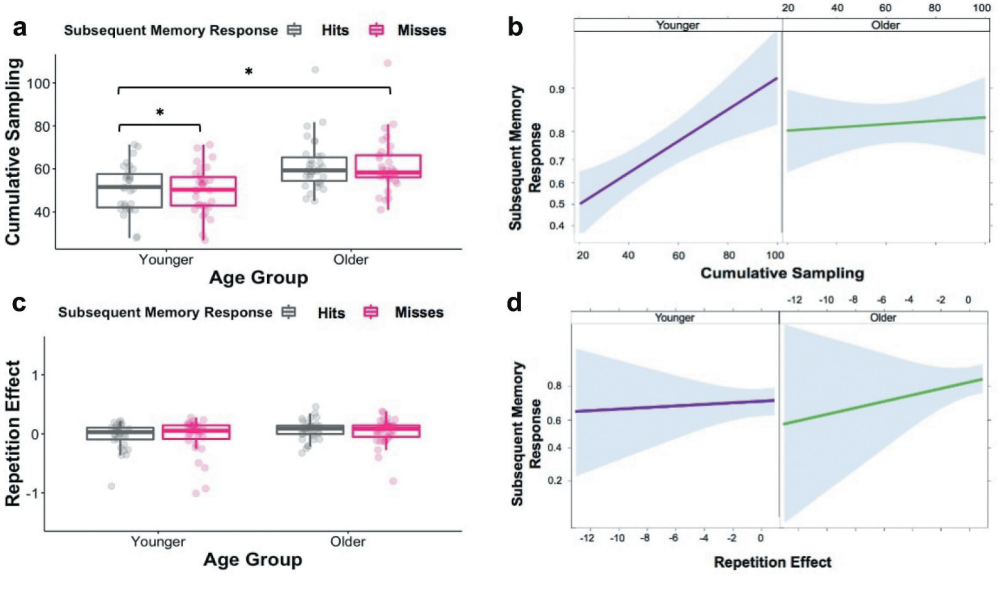

Figure 4. A. Cumulative sampling as a function of subsequent memory response plotted separately for younger adults and older adults. Hits (correct memory responses) are plotted in gray and misses (incorrect memory responses) are plotted in pink. B. The association between cumulative sampling and subsequent memory response among younger adults and older adults. Lower subsequent memory response values reflect a greater proportion of misses and higher values reflect a greater proportion of hits. C. Repetition effect as a function of subsequent memory response plotted separately for younger adults and older adults. Hits (correct memory responses) are plotted in gray and misses (incorrect memory responses) are plotted in pink. B. Lower subsequent memory response values reflect greater a proportion of misses and higher values reflect a greater proportion of hits. D. The association between repetition effect and subsequent memory response among younger adults and older adults. Asterisks indicate a significant main effect between older and younger adults, * $p < .05$.

Table 2. Recognition accuracy by cumulative sampling, age group, study viewpoint, and test viewpoint on a trial-by-trial basis.

	β	SE	z	p
(Intercept)	1.12	0.56	1.98	0.05*
Cumulative Sampling	0.003	0.009	0.40	0.69
Age Group	−1.93	0.72	−2.68	0.007 **
Study Viewpoint	0.15	0.11	1.39	0.16
Test Viewpoint	0.53	0.11	4.85	<.001 ***
Cumulative Sampling x Age Group	0.03	0.01	2.24	0.02*
Study Viewpoint x Test Viewpoint	−0.51	0.15	−3.31	<.001 ***
Total observations = 4262				
		Variance		*SD*
Random Effect for Participant (Intercept)		0.95		0.98
Random Effect for Item (Intercept)		0.37		0.61
Model equation: Subsequent Memory ~ Cumulative Sampling X Age Group + Study Viewpoint X Test Viewpoint + (1 | Subject) + (1 | Image)				

Note: Subsequent memory is modeled by comparing hits versus misses for a given face.

analyses as mentioned above and found that the pattern of results were similar to those discussed here (see supplementary material): whereas younger adults showed a relationship between the amount of visual exploration; older adults did not.

Eye movement repetition effects and recognition memory

The relationship between the eye movement repetition effect and subsequent recognition memory was assessed across younger and older adults for each of the study/test viewpoint condition. We predicted that there would be no significant relationship between the magnitude of the eye movement repetition effect and successful recognition for either age group. Generalized mixed effects linear regression was used to examine whether eye movement repetition effects among younger adults, compared to older adults, were larger for subsequently remembered (correct response/hits) versus forgotten faces (incorrect response/misses) using a within subject analysis (Figure 4C and D). See supplementary material for the between-subject analyses. The main effect of the eye movement repetition effect on memory was not significant ($\chi^2(1) = .52$, $p = .47$), which indicated that there was no consistent relationship between the repetition effect magnitude and the ability to recognize a previously studied face. The main effect of age group was significant ($\chi^2(1) = 5.31$, $p < .05$); older adults correctly responded "old" on more trials than younger adults. There was no significant interaction between the repetition effect and age group ($\chi^2(1) = .31$, $p = .58$). Test viewpoint was significant ($\chi^2(1) = 12.43$, $p < .001$); participants were more accurate when faces were tested in the repeat-test viewpoint. The interaction between study and test viewpoint was significant ($\chi^2(1) = 11.11$, $p < .001$); there was a larger recognition advantage for repeat-test viewpoint faces that were studied in the fixed-study viewpoint condition. The interaction between study condition and age group ($\chi^2(1) = .55$, $p = .46$), and the main effect of study viewpoint was not significant ($\chi^2(1) = 1.61$, $p = .21$). Therefore, the within-subjects analyses indicated that the magnitude of the eye movement repetition effect does not reliably relate to subsequent recognition memory in a consistent manner in younger or older

Table 3. Recognition accuracy by repetition effect, age group, study viewpoint, and test viewpoint on a trial-by-trial basis.

	β	SE	z	p
(Intercept)	1.33	0.20	6.65	<.001 ***
Repetition Effect	0.04	0.06	0.73	0.47
Age Group	−0.62	0.26	−2.35	0.02 *
Study Viewpoint	0.15	0.11	1.43	0.15
Test Viewpoint	0.53	0.11	4.87	<.001 ***
Study Viewpoint X Test Viewpoint	−0.51	0.15	−3.35	<.001 ***
Total observations = 4262				
		Variance		*SD*
Random Effect for Participant (Intercept)		1.00		1.00
Random Effect for Item (Intercept)		0.36		0.60
Model equation: Subsequent Memory ~ Repetition Effect + Age Group + Study Viewpoint X Test Viewpoint + (1 | Subject) + (1 | Image)				

Note: Subsequent memory is modeled by comparing hits versus misses for a given face.

adults (refer to Table 3 for the effects of all factors). We found the same pattern of results using the standardized *full range* of the 5-point recognition confidence scale as the dependent variable (see supplementary material).

MoCA and age

We predicted that lower MoCA scores would be related to changes in eye movement behavior (e.g., greater cumulative fixations, changes in distribution of gaze fixations to facial features), as well as direct (e.g., poorer recognition) and indirect (e.g., weaker repetition effect) expressions of memory among older adults. To investigate this prediction, a linear model was used to examine linkages between MoCA scores and d-prime across older adult participants. To examine the contribution of age (*continuous variable*) in this relationship, we added age as a covariate in the model. Furthermore, although we used age as a continuous variable in our MoCA models, in Figure 5, we split the older adults into two age subgroups to more clearly visualize the effect of age on these relationships. Based on the median older adult age of 75, we split the older adults into a young-old (< 74 years old) subgroup and old-old (75 years old <) subgroup.

The linear model included MoCA scores, age, study condition, test condition, cumulative sampling, and the eye movement repetition effect as predictor variables, and d-prime as the outcome variable. There was no significant relationship between d-prime and MoCA scores (F = .46, p = .50; Figure 5A). There was a marginal relationship between d-prime and age (F = 3.19, p = .08). Cumulative sampling (F = 1.32, p = .25), repetition effect (F = .57, p = .45), study condition (F = .0003, p = .99), and test condition (F = 3.16, p = .08) did not significantly improve model fit. Refer to Table 4 for the effects of all factors.

Moreover, a linear model was used to examine the relationship between cumulative sampling (outcome variable) and MoCA scores across older adult participants (Figure 5B). In this model, MoCA scores and age were included as predictor variables. There was no significant relationship between cumulative sampling and MoCA scores among older adults (F = 1.40, p = .24), as well as no significant relationship between cumulative sampling and age (F = .63, p = .43; refer to Table 5 for the effects of all factors). In addition, a linear model was used to examine the relationship between the proportion of gaze

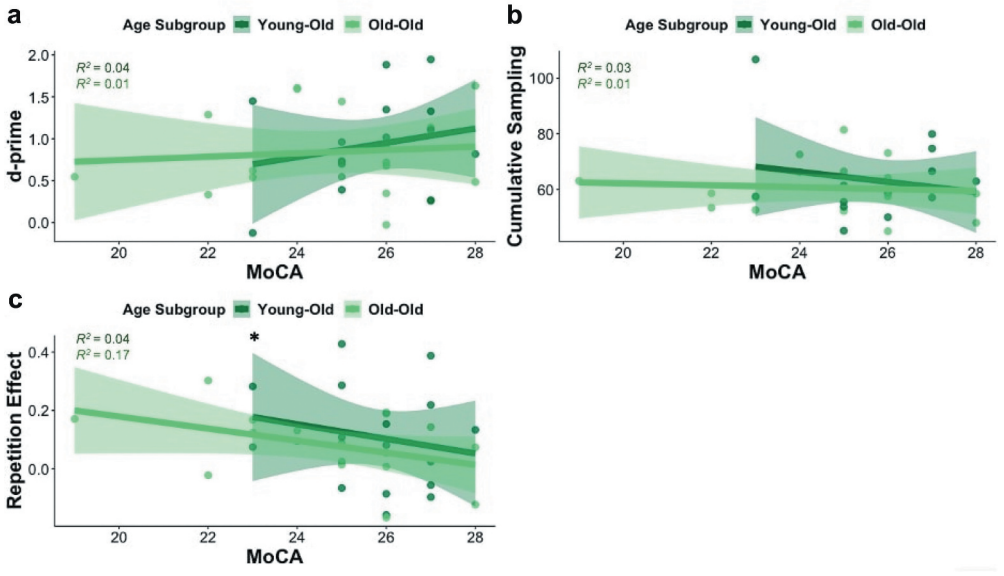

Figure 5. A. Correlation between MoCA and d-prime split by age subgroup (for visualization). B. Correlation between MoCA and cumulative sampling split by age subgroup. C. Significant correlation between MoCA and the repetition effect split by age subgroup.

Table 4. Recognition accuracy by MoCA scores, age (older adults only), cumulative sampling, repetition effect, study viewpoint, and test viewpoint.

	β	SE	t	p
(Intercept)	1.24	1.39	0.89	0.37
MoCA	0.02	0.03	0.68	0.50
Age	−0.02	0.01	−1.79	0.08
Cumulative Sampling	0.005	0.005	1.03	0.30
Repetition Effect	0.06	0.40	0.15	0.88
Study Viewpoint	0.002	0.11	0.02	0.99
Test Viewpoint	0.19	0.11	1.78	0.08

Model Equation: D-Prime ~ MoCA + Age + Cumulative Sampling + Repetition Effect + Study Viewpoint + Test Viewpoint

Table 5. Cumulative sampling by MoCA scores and age (older adults only).

	β	SE	t	p
(Intercept)	88.58	22.54	3.93	<0.001 ***
MoCA	−0.66	0.56	−1.18	0.24
Age	−0.14	0.17	−0.79	0.43

Model Equation: Cumulative Sampling ~ MoCA + Age

fixations to facial features (outcome variable), MoCA scores (predictor variable), age (predictor variable), and facial region of interest (i.e., eyes, mouth, nose, outer face – predictor variable; refer to Table 6 for the effects of all factors). There was no significant interaction between facial region of interest and MoCA scores (F = .54, p = .65), and no significant main effect of MoCA scores on proportion of fixations to facial features (F = .41, p = .80). However, there was a significant interaction between facial region of interest and age (F = 4.28, p < .01) on proportion of fixations to facial features. This interaction

Table 6. Proportion of fixations to facial features by MoCA scores, age (older adults only), and facial region of interest (eyes, mouth, nose, outer face).

	β	SE	t	p
(Intercept)	1.21	0.41	2.98	0.003 **
Region of Interest (mouth)	−1.22	0.57	−2.12	0.04 *
Region of Interest (nose)	−1.30	0.57	−2.26	0.03 *
Region of Interest (outer face)	−1.33	0.57	−2.31	0.02 *
MoCA	−0.01	0.01	−1.09	0.28
Age	−0.009	0.003	−3.01	0.003**
Region of Interest (mouth)*MoCA	0.01	0.01	1.00	0.32
Region of Interest (nose)*MoCA	0.01	0.01	0.95	0.34
Region of Interest (outer face)*MoCA	0.02	0.01	1.14	0.26
Region of Interest (mouth)*age	0.01	0.004	2.50	0.01*
Region of Interest (nose)*age	0.01	0.004	3.33	0.001 **
Region of Interest (outer face)*age	0.01	0.004	2.69	0.008 **

Model Equation: Proportion of fixations ~ Region of Interest*(MoCA + Age)

Table 7. Repetition effect by MoCA scores and age (older adults only).

	β	SE	t	p
(Intercept)	1.38	0.26	5.30	<0.001 ***
MoCA	−0.03	0.006	−4.36	<0.001 ***
Age	−0.008	0.002	−3.88	<0.001 ***

Model Equation: Repetition Effect ~ MoCA + Age

indicated that as age increased, older adults looked at the nose, mouth, and outer face with a greater proportion of fixations, but viewed the eye region with a lower proportion of fixations. Moreover, there was an overall significant main effect of age on proportion of fixations to facial features ($F = 3.21$, $p = .02$).

Lastly, a linear model was used to examine the relationship between the repetition effect (outcome variable), MoCA scores (predictor variable), and age (predictor variable; Figure 5C). There was a significant negative relationship between the repetition effect and MoCA ($F = 15.04$, $p < .001$), as well as the repetition effect and age ($F = 19.02$, $p < .001$; refer to Table 7 for the effects of all factors). Therefore, the older adults with the highest MoCA scores exhibited a weaker eye movement repetition effect compared to the older adults with lower MoCA scores. Moreover, older adults in the old-old subgroup with higher MoCA scores exhibited weaker eye movement repetition effects than the young-old subgroup. Despite this, there was surprisingly no relationship between the MoCA scores and recognition performance, which may be explained by the fact that the MoCA tests a variety of cognitive processes, making it a coarser measure of cognition.

Discussion

In the current study, we examined how aging influences visual exploration and both indirect and direct expressions of memory on a face recognition task that varies the extent of hippocampal involvement across conditions. Prior work from Olsen et al. (2015), Olsen et al. (2016) found that when faces were studied across different (i.e., variable) viewpoints, recognition memory for these faces required the hippocampal system. However, when faces were studied across identical (i.e., fixed) viewpoints, specific regions outside of the

hippocampus, presumably within the MTL cortex, could support memory for these faces. Thus, the hippocampal system was critical for the formation of flexible associations of facial features across space and time in order to successfully form single face memory representations. In the current study, we used the same task as Olsen et al. (2015), Olsen et al. (2016) and monitored eye movements in a group of healthy older adults who varied in their risk of developing mild cognitive impairment, as defined by their scores on the Montreal Cognitive Assessment (MoCA), and in a group of healthy younger adults.

In general, aging was not associated with poorer direct recognition performance for either fixed-study or variable-study viewpoint faces. However, aging was associated with an overall increase in visual exploration: older adults made more gaze fixations across blocks (cumulative sampling) than younger adults, and differed in their distribution of gaze fixations across the facial features relative to younger adults. These differences in the *manner* of encoding (i.e., cumulative gaze fixations and distribution of gaze fixations to facial features) between younger adults and older adults suggests that the amount and/or quality of the information acquired by the eyes may have differed between the two age groups (Wynn et al., 2021). Moreover, cumulative sampling was positively related to subsequent recognition performance for the younger adults, but not for the older adults. The magnitude of the eye movement repetition effect was greater among older adults compared to younger adults for both study conditions, once again suggesting that the two age groups acquire and represent information differently. However, for both younger and older adults, eye movement repetition effects expressed during encoding were not related to subsequent recognition memory. Finally, although the MoCA was not predictive of recognition memory, cumulative sampling, or the distribution of gaze fixations for the older adults, it was negatively associated with the magnitude of the eye movement repetition effect. Together, these findings suggest that although older adults may be able to encode enough information to support both direct (subsequent conscious recognition) and indirect (repetition effect) expressions of memory, the information underlying direct recognition and the repetition effect may fundamentally differ between younger and older adults.

Recognition memory

Based on previous research with older adults (Boutet & Faubert, 2006; Crook & Larrabee, 1992; Hildebrandt et al., 2010; Konar et al., 2013), and impaired direct recognition performance exhibited by H.C. on the same task used in our current study (Olsen et al., 2015, 2016), we predicted that older adults would generally have poorer recognition performance than younger adults, especially for faces studied across variable-study viewpoints (Habak et al., 2008; Y. Lee et al., 2012; Meinhardt-Injac et al., 2014). However, there were no age differences in face recognition for either fixed-study or variable-study viewpoint faces. One explanation for this finding may be that H.C. had more hippocampal compromise than the older adults in our study. Therefore, it may be concluded that the changes in viewpoint were enough to disrupt H.C.'s encoding and subsequent recognition, but not enough to negatively impact recognition performance for the older adults in our study, who did not have an amnestic disorder or a dementia diagnosis. Future work could assess the relationship between hippocampal volumes and recognition for faces studied under multiple viewpoints to better understand the influence of the hippocampal system on cognitive function in aging.

Cumulative sampling and recognition memory

Previous studies with younger adults have shown that the number of fixations made to items, including faces, is positively related to subsequent recognition memory (Damiano & Walther, 2019; Henderson et al., 2005; Olsen et al., 2016; J. P. K. Chan et al., 2011). Other work has shown that healthy older adults (Firestone et al., 2007; J. P. K. Chan et al., 2011) and older adults at risk for mild cognitive impairment (Yeung et al., 2013) tend to make more fixations than younger adults. In the current study, older adults made more fixations to faces compared to younger adults in both fixed-study and variable-study conditions. For younger adults, cumulative sampling was positively correlated with recognition; faces that received a greater number of fixations across the encoding phase were more likely to be remembered than faces that received fewer fixations. In contrast, for older adults, more fixations did not translate into better recognition memory. Thus, the relationship between viewing behavior and subsequent recognition memory was weakened in aging. This finding may suggest that increased sampling behavior by older adults may reflect an unconscious attempt to leverage the oculomotor system to upregulate- and compensate for- a declining hippocampal system (Liu et al., 2018; Ryan et al., 2020).

Increased sampling may have supported recognition memory of older adults such that their performance was similar to that of younger adults. However, the connection between the number of gaze fixations and the amount and quality of information extracted from those gaze fixations may have varied across older adults and even across trials within each older adult (Wynn et al., 2021), resulting in a non-significant relationship between cumulative fixations and subsequent recognition. Moreover, the relative distribution of fixations across facial features differed between younger and older adults; specifically, older adults looked at the mouth and outer face region significantly more than younger adults. This finding corroborates previous studies that have found that, compared to younger adults, older adults exhibit a different distribution of gaze fixations to facial features (Firestone et al., 2007; C. Y. Chan et al., 2018). However, others have found that the two age groups are similar in distribution of fixations (Liu et al., 2018). In Liu et al. (2018), participants viewed faces from a single viewpoint; however, in the current study, older adults viewed faces from multiple viewpoints. This may be one reason as to why we observed age-related differences in the allocation of fixations to facial features in the current study. Moreover, unlike the facial stimuli used by Liu et al. (2018), the facial stimuli in the current study were cropped so that no hair was visible, which may be another reason why we observed age-related differences in the distribution of fixations on facial features.

Eye movement repetition effects and recognition memory

The role of the hippocampal system in eye movement repetition effects and subsequent recognition memory has been extensively debated. Whereas some studies reported that eye movement repetition effects were hippocampal-dependent and that they required explicit/conscious recognition (Smith & Squire, 2008), others have shown that repetition effects were hippocampal-independent and occurred in the absence of explicit recognition (Althoff & Cohen, 1999; Ryan et al., 2000). Consistent with the latter set of studies, the current work found no

significant relationship between successful direct recognition and the magnitude of the eye movement repetition effect (also see, Olsen et al., 2016; Smith & Squire, 2017) for either age group. These results are also consistent with work by Smith and Squire (2017) who found that when participants viewed scenes without the expectation of memory testing, as was the case in the current study, both healthy controls and memory-impaired individuals with MTL damage demonstrated an eye movement repetition effect, and the repetition effect did not predict explicit memory performance. Our results therefore provide further evidence that repetition effects are an expression of memory that may not necessarily be available to subsequent conscious appraisal.

There is evidence from previous studies that, compared to younger adults, older adults sometimes demonstrate diminished eye movement repetition effects (Heisz & Ryan, 2011; Liu et al., 2018), even when the viewpoint of the face is maintained across repetitions. However, contrary to our predictions, we found that the magnitude of older adults' eye movement repetition effects was greater than that of younger adults for both fixed-study and variable-study viewpoint faces. This finding is consistent with research conducted by Yeung et al. (2013), who showed that older adults at risk for cognitive decline failed to differentiate between previously-seen objects relative to lure novel objects with many overlapping features, causing them to view the novel objects as though they had been previously seen (i.e., fewer fixations to novel objects). This false recognition was present to a lesser extent in their healthy older adult sample. These findings were attributed to atrophy of the perirhinal cortex and a subsequent increased reliance on memory for the individual object features, which overlapped across the visually-similar novel and previously-seen objects and were thus all familiar at the feature level. Although we did not explicitly manipulate the faces in our study to have a high degree of perceptual overlap, given inherent visual similarity and overlapping features across human faces, a similar explanation may underpin the current results. That is, forming less-differentiated memory representations may have led to erroneous or heightened recognition signals (as evidenced by the higher false alarm rate and higher response bias among the older adults) for individual facial features, thus explaining the larger eye movement repetition effect we observed in older adults relative to younger adults.

The larger repetition effects among older adults can also be explained by the finding that they made more gaze fixations overall across the study blocks, especially during the initial study blocks. Therefore, older adults' larger repetition effects may indicate that they had more "room" for a steeper decline in fixations across blocks. Likewise, there may be a floor effect among younger adults in the magnitude of their eye movement repetition effects. In addition, the trend that we observed in our study regarding the repetition effects has also been observed in studies of reaction time (Kane et al., 1994; Stoltzfus et al., 1993). These studies have found that older adults show larger response priming effects because they start off more slowly and have more "room" to increase their response speed. By contrast, younger adults start with a much faster reaction time, and ultimately reach a point at which they cannot complete their responses any faster. Similarly, in our study, compared to younger adults, older adults had larger priming effects (see supplementary material) and larger repetition effects for the same reason provided by the studies of reaction time.

MoCA and age

We found no relationship between the MoCA and recognition memory, which may be due to the fact that the MoCA assesses a broad variety of cognitive processes. Given that MoCA scores decrease with age (Malek-Ahmadi et al., 2015) and that the older adult participants fell within a relatively large age range, we included age as a covariate in the models examining relationships between direct recognition memory, our eye movement measures, and MoCA performance. As with the MoCA, age did not predict direct recognition memory. Furthermore, we found no significant relationship between either the MoCA and cumulative sampling, or between age and cumulative sampling. Although there was no significant relationship between the MoCA and proportion of fixations to facial features, there was a significant interaction between facial region of interest (eyes, nose, mouth, outer face) and age, as well as a significant overall relationship between proportion of fixations to facial features and age. Thus, as age increased, older adults exhibited a change in the pattern of gaze fixations to facial features (i.e., they looked at the mouth, nose, and outer face more than the eyes). Again, this finding is in line with previous studies that have found that, compared to younger adults, older adults exhibit a different distribution of gaze fixations to facial features (Firestone et al., 2007; C. Y. Chan et al., 2018). However, as mentioned previously, some studies have found similar spatial distributions of fixations across younger and older adults (Liu et al., 2018). Based on the results of the current study, we suggest that some of this inconsistency across studies may be related to the fact that Liu et al. (2018) and Firestone et al. (2007) did not assess the relationship between the MoCA, age, and distribution of facial features. Therefore, it is hard to know whether the findings from the current study are consistent or not with previous findings. Although C. Y. Chan et al. (2018) assessed the MoCA and eye movement behavior, they did not examine the distribution of fixations to individual facial features per se; instead, the authors examined eye movement patterns interpreted to reflect "holistic" vs. "analytic" processing which may not necessarily align with the analyses conducted here. Furthermore, Chan and colleagues did not examine the effect of age within the older adult group, which makes it difficult to directly compare these findings to the current results. Future studies should consider age as an important factor when investigating the relationship between the MoCA and proportion of fixations to facial features.

In addition, there was a significant negative relationship between both the MoCA and the eye movement repetition effect, and between age and the repetition effect. Specifically, older adults with higher MoCA scores exhibited weaker eye movement repetition effects, whereas older adults with lower MoCA scores exhibited larger repetition effects. This is consistent with previous work demonstrating that older adults with lower MoCA scores were worse at differentiating between previously-seen objects relative to visually similar novel lure objects, as evidenced by reduction in viewing to both the familiar and novel objects (Yeung et al., 2013). This work was interpreted to reflect the fact that older adults with low MoCA scores were falsely recognizing the visually similar novel objects as familiar and viewing them as though they had been previously seen. Interestingly, in our study, the oldest participants in the older adult group with higher MoCA scores exhibited weaker eye movement repetition effects than the relatively young older adults, suggesting that cognitively intact older adults can perform more like their younger counterparts.

Conclusion

Aging influences visual exploration, and these viewing differences may reflect underlying age-related changes in memory function. Cumulative sampling is important for the formation of conscious memories for previously studied faces. However, the current work found that despite intact direct recognition for the faces from all viewpoints, aging disrupted the relationship between cumulative sampling and subsequent recognition. This suggests that older adults may be less effective than younger adults in relationally binding visual information into a rich representation that can be subsequently used to support recognition, and thus require more fixations to achieve similar levels of recognition performance as younger adults. Although direct recognition performance was ultimately statistically indistinguishable between the two groups, the eye movement measures of visual exploration (cumulative sampling and distribution of fixations), revealed that the manner by which encoding occurs was different for older versus younger adults.

By contrast, the eye movement repetition effect was observed for both younger and older adults and was not associated with direct recognition memory for either group. The eye movement repetition effect may be hippocampal-independent, and instead may reflect the engagement of broader neocortical regions during the incidental encoding of faces. Regardless of participants' age, the memory representations reflected by the eye movement repetition effect did not support later conscious recognition.

In the current study, older adults differed from younger adults in their relative distribution of gaze fixations across face features. This suggests that the older adults may build up face representations comprised of different information, or use a different strategy, relative to younger adults. Likewise, the finding of the larger eye movement repetition effects in older adults suggests that different information may have been represented (e.g., feature-level information rather than a holistic representation of the face). Thus, although older adults' recognition performance was similar to that of younger adults, they may have acquired and used different information to support that performance. Future studies could explore the nature of the information that older adults represent in memory. Altogether, this work provides key insights into age-related differences in eye movement behavior and further clarifies the relationship between eye movements and face recognition as revealed by direct and indirect expressions of memory.

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