Aging and the rate of visual information processing

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Multiple methods exist for measuring how age influences the rate of visual information processing. The most advanced methods model the processing dynamics in a task in order to estimate processing rates independently of other factors that might be influenced by age, such as overall performance level and the time at which processing onsets. However, such modeling techniques have produced mixed evidence for age effects. Using a time-accuracy function (TAF) analysis, Kliegl, Mayr, and Krampe (1994) showed clear evidence for age effects on processing rate. In contrast, using the diffusion model to examine the dynamics of decision processes, Ratcliff and colleagues (e.g., Ratcliff, Thapar, & McKoon, 2006) found no evidence for age effects on processing rate across a range of tasks. Examination of these studies suggests that the number of display stimuli might account for the different findings. In three experiments we measured the precision of younger and older adults' representations of target stimuli after different amounts of stimulus exposure. A TAF analysis found little evidence for age differences in processing rate when a single stimulus was presented (Experiment 1). However, adding three nontargets to the display resulted in age-related slowing of processing (Experiment 2). Similar slowing was observed when simply presenting two stimuli and using a post-cue to indicate the target (Experiment 3). Although there was some interference from distracting objects and from previous responses, these age-related effects on processing rate seem to reflect an age-related difficulty in processing multiple objects, particularly when encoding them into visual working memory.

Introduction

In the study of cognitive aging, one influential perspective has been that information processing speed underlies age-related decline (Salthouse, 1996). When information processing speed is taken into account the relationship between age and cognitive ability is substantially reduced. For example, Salthouse (1991) showed that, not only does processing speed predict a moderate proportion of the variance in cognitive ability, but processing speed appears to mediate the relationship between age and higher order cognitive functioning. There are a range of measures of processing speed. Some, such as digit symbol coding, are cognitively complex. Other more simple measures, such as four-choice reaction time are also predictive of cognitive ability in older adults (e.g., Brown, Brockmole, Gow, & Deary, 2012). It has been suggested however, that psychophysical measures of perceptual speed, such as the inspection time required to discriminate between two objects (Deary, Johnson, & Starr, 2010) or pattern comparison (Salthouse, 1994) are more predictive of neural processing speed and cognitive ability, indicating that the extent of cognitive involvement in the processing speed measure is key. Recent research has suggested that anterior white matter integrity, and the efficiency with which neural networks can communicate might underlie the relationship between perceptual speed and cognitive ability (Bucur et al., 2008; Deary et al., 2006). Understanding the exact nature of age-related declines in processing speed is therefore an important area of research. As visual cognition is very age-sensitive (Brown et al., 2012; Jenkins, Myerson, Joerding, & Hale, 2000), this paper focuses upon establishing the extent to which

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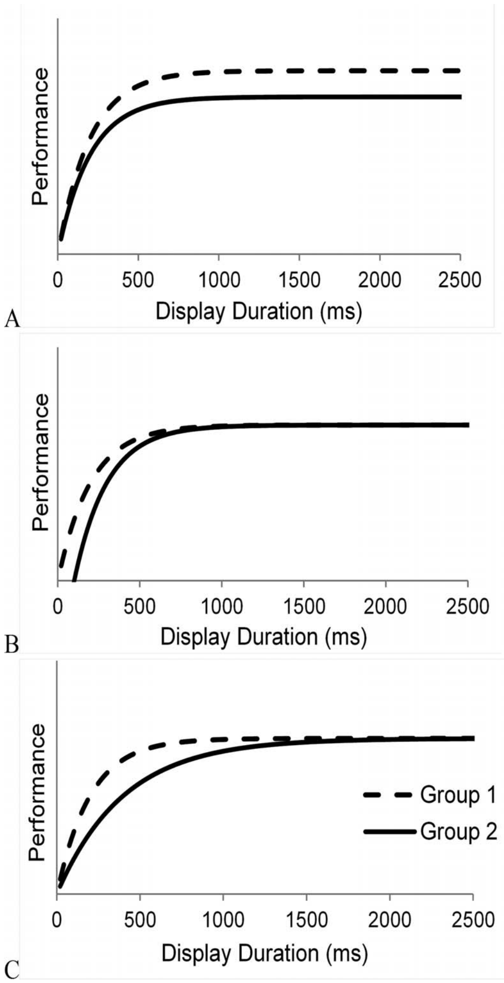

Figure 1. Idealized time-accuracy functions using Equation 1, displaying a difference in asymptote (A), take-off (B), and processing rate (C).

older adults exhibit a deficit in the speed of processing visual information.

Measuring processing speed

A variety of methodologies can be utilized in order to examine age-related differences in visual information processing. For example, one can measure the accuracy in a task after the information has been presented under different encoding time conditions (e.g., Beigneux, Plaie, & Isingrini, 2007; Lecerf & Roulin, 2006; Vaughan & Hartman, 2010), measure the time taken to respond to a visual stimulus (e.g., Deary, Allerhand, & Der, 2009; Gregory, Nettelbeck, Howard, & Wilson, 2008; Hultsch, MacDonald, & Dixon, 2002; Jenkins et al., 2000), or equate the presentation duration needed to reach a set level of performance (e.g., Edwards et al., 2006; Owsley, 2013). These measures have typically indicated slower processing for older adults but there are multiple factors that contribute to these differences. Older adults may take longer to bring their attention to bear on the task, have lower levels of discrimination, or have problems with the task methodology, particularly if a complex task is administered via a computer. Older and younger adults also display different biases in decision making. In time sensitive studies, older adults have been shown to optimize accuracy over speed in a range of tasks (Ratcliff, 2008; Starns & Ratcliff, 2010). This bias may have a biological basis; the striatum hypothesis has suggested that differences in speed accuracy trade-off may reflect an age-related reduction of white matter integrity in certain corticostriatal tracts (Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Forstmann et al., 2011). Performance differences in RT/accuracy tasks may therefore reflect a combination of this accuracy-over-speed strategy alongside any effects of slowed processing.

It has therefore been acknowledged that experiments assessing RT or accuracy differences alone cannot disentangle the factors contributing to age-related differences in processing speed (Kliegl et al., 1994; Ratcliff, Thapar, & McKoon 2007; Verhaeghen, Kliegl, & Mayr, 1997). To establish a purer measure of processing speed it is necessary to examine the dynamics of performance in a particular task. Two key methodologies that have been applied to this issue are the time accuracy function analysis (TAF; Kliegl et al., 1994) and the diffusion model approach (Ratcliff, Thapar, and McKoon, 2001). Importantly TAF analysis specifically examines speed of processing. In comparison, the diffusion model is a model of the dynamics of the decision process, and thus while it does estimate the speed of processing, it is a much more general model (Ratcliff, 1978).

Estimating processing speed by modeling the dynamics of performance

The time accuracy function (TAF) procedure allows for the independent measurement of processing dynamics, separated from influences of absolute performance. In the TAF procedure the duration of a visual display is manipulated and participants produce a response for the particular task after the display offsets. The function determining how performance changes over time can then be examined. Figure 1 shows examples of such functions. Each panel shows hypothetical data for two groups of participants, Groups 1 and 2. The following model can then be fit to this function (although note that in the diffusion model [Ratcliff, 1978] an alternative formula can be used to model these functions);

$$\text{Performance}(t) = \lambda\left(1 - e^{-\beta(t-\delta)}\right), \text{for } t > \delta, \text{else } 0 \quad (1)$$

in which t is time, δ is the intercept or the time at which responding is no longer at chance (the "take-off" point), and λ is the asymptotic level of performance. The rate of processing is given by β, which determines the rate at which performance rises from chance. The mean processing time can be calculated by $1/\beta$.

Each panel of Figure 1 shows how differences in each parameter yield different patterns in the time course of performance (Reed, 1976). In Figure 1A the groups differ in their asymptotic level of performance, with Group 1 outperforming Group 2 as display duration increases. In Figure 1B the groups differ in take-off time, which is the time for processing to rise above chance levels. This may be caused by differences in the time taken to onset processing rather than reflecting slower processing. Finally, Figure 1C shows a difference in processing rates, with Group 1 showing faster processing such that performance rises faster from chance levels as display duration increases. The advantage of the TAF methodology is that it enables a purer estimate of processing speed than standard accuracy or RT designs, because the estimate is not contaminated by performance levels or the time taken to start processing. Indeed, this approach has been used to model the time course of performance and gain estimates of visual information processing rates in a variety of tasks such as perceptual categorization, visual search, recognition, and word identification (Brockdorff & Lamberts, 2000; Carrasco & McElree, 2001; Guest & Lamberts, 2010, 2011; Kent, Howard, & Gilchrist, 2012; see Kent, Guest, Adelman, and Lamberts, 2014, for a review).

The TAF procedure is also ideal for examining potential differences in information processing across age groups. For example, Verhaeghen, Vandenbroucke, and Dierckx (1998) used a word list recall task and reported large differences in processing speed between younger and older adults (see also Verhaeghen et al., 1997, for similar results using mental arithmetic). In the study of visual cognition, Kliegl et al. (1994) reported age-related slowing in several tasks using multi-object arrays in which participants were asked to assess whether there were feature differences between two sets of four objects. Greater age-related slowing was shown when participants also had to mentally rotate one of the sets of objects in order to complete the feature comparison, providing strong evidence for age-related differences in visual information processing. However, this finding has been contradicted by those of Ratcliff and colleagues, who used a diffusion model approach to estimate visual information processing speed. While the TAF approach specifically examines the speed of perceptual processing the diffusion model is a model of the decision process, and although it can evaluate the quality of evidence as a result of limited perceptual processing, it is a much more general model.

Since its inception, the diffusion model has been successfully applied to numerous psychological tasks and is one of the most advanced models of decision processes (Ratcliff, 1978; Ratcliff & Rouder, 2000; Ratcliff & Starns, 2013). The diffusion model assumes that, over time, evidence in favor of a particular response accumulates, and a response is provided once this evidence reaches a particular criterion. Response time is therefore influenced by how conservative or liberal the response criteria are and how quickly information accumulates in favor of a particular response (the drift rate). Importantly, the drift rate is determined by the amount of information that is extracted from the stimulus, and thus represents the rate of visual information processing. Response times are also influenced by nondecision components, such as the time for response execution (see Ratcliff et al., 2006, for a technical specification of the model applied to aging).

Typically the decision bound model is fit to correct and error RT distributions, and accuracy rates allow it to disentangle speed accuracy trade-offs. Thus, age-related differences in perceptual and decision processes can be isolated. Ratcliff and colleagues have used the diffusion model to investigate such age-related differences across a large range of tasks, including brightness discrimination (Ratcliff, Thapar & McKoon, 2003, 2006), letter discrimination (Thapar, Ratcliff, & McKoon, 2003), distance and numerosity discrimination (Ratcliff et al., 2001; Ratcliff, 2008), lexical decision tasks (Ratcliff, Thapar, Gomez, & McKoon, 2004; Ratcliff et al., 2007) and word recognition (Ratcliff, Thapar, & McKoon, 2004, 2007). Across these tasks there are several relatively consistent findings; older adults tend to adopt a more conservative decision criterion and have a longer nondecision component (see Ratcliff et al., 2007, for a summary). However, the majority of tasks show no evidence for an age-related difference in drift rate, suggesting that older and younger adults do not differ in the rate at which they process visual information. One exception was for masked letter discrimination, for which older adults had a significantly slower drift rate. Ratcliff et al. (2007) suggested that this was due to psychophysical deficits in older adults' ability to perceive high spatial frequency stimuli (Spear, 1993). In comparison, in memory tasks older adults have recently been shown to exhibit markedly slower drift rates in associative word recognition, and a small slowing in drift rates in item recognition (Ratcliff, Thapar, & McKoon, 2011; see also Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008).

Inconsistent findings about the existence of age-related differences in the rate of visual information processing are therefore apparent. In numerous studies, Ratcliff et al. (2006) found no evidence for this whereas, in comparison, Kliegl et al. (1994) showed that older adults process visual information at a slower rate than younger adults. This mixed evidence is difficult to interpret due to the different methodologies utilized. Kliegl et al. (1994) used a TAF procedure in which display duration was manipulated, whereas Ratcliff et al. (2006) typically present a stimulus for a fixed period of time. Ratcliff (2008) is an exception in which display duration was manipulated by using a signal to respond procedure, and data were modeled assuming a mixture of processes that did or did not terminate before the onset of the response signal. The task was a numerosity judgment and the results supported previous conclusions; there was no evidence for age-related differences in drift rates. Thus, differences in findings cannot simply be attributed to whether or not display duration was manipulated.

Another key distinction between the Ratcliff and Kliegl studies is the number of objects to be processed. In the Kliegl et al. (1994) study participants either had to compare two pictures of four objects and determine whether they were the same or different, or perform the same task whilst mentally rotating one of the pictures by 90 degrees. In comparison, the majority of studies by Ratcliff et al. have used a single stimulus involving, for example, identification of a single letter or word, estimation of the brightness of a patch of black and white pixels, or estimation of distance between two dots. An exception is numerosity judgment (Ratcliff, 2008; Ratcliff et al., 2001, 2006). In these tasks multiple dots were presented (e.g., 31-70 in Ratcliff, 2008) and participants estimated whether there were a small or large number of dots onscreen. Although this task involves multiple objects, numerosity can be thought of as a judgment along a single dimension (Krueger, 1984). In addition, it is possible that other unidimensional cues such as the density or luminosity of the display could have been used to determine numerosity. For example, density judgments have been shown to tap into surface perception processes which are known to operate efficiently (Rodriguez,Valdes-Sosa, & Freiwald, 2002) and assessment of global summary statistics of the visual field appears to be very attentionally efficient (Saiki & Holcombe, 2012). These numerosity tasks may therefore be interpreted as a judgment about a single dimension that does not necessarily require processing of complex (e.g., identity) information across multiple objects.

It is possible, then, that a key difference between the Kliegl et al. (1994) study and the studies of Ratcliff et al. (e.g., Ratcliff et al., 2006) is the number of objects from which complex visual information needs to be processed. Certainly, in a number of visual tasks, older adults appear to perform worse when multiple objects are presented in the display (Jost, Bryck, Vogel, & Mayr, 2011; Madden, Gottlob, & Allen, 1999; Peich, Husain, & Bays, 2013; Sekuler & Ball, 1986). However, it is unclear whether this is because additional items reduce overall performance levels or influence the rate of information processing.

Another key difference between the Kliegl et al. (1994) and Ratcliff et al. studies is in terms of the modeling of the decision process. The TAF procedure does not explicitly model the dynamics of the decision process, whereas the diffusion model does. It is therefore possible that, as decision dynamics are not modeled, the TAF procedure does not adequately estimate visual information processing rates. Alternatively, it is possible that in two alternative forced-choice (2AFC) designs (as in the studies by Kliegl et al., 1994; and Ratcliff et al., 2007), the decision component makes it more difficult to reliably estimate the rate of visual information processing. Although diffusion models have been designed to disentangle these effects, another useful methodology is to reduce the decision element of the task as much as possible. This is the approach we adopted. In the three experiments reported, the stimuli were Gabor patches of a random orientation. After stimulus offset, participants used a method of adjustment to rotate points onscreen to directly report their perception of the orientation. This technique enables measurement of the precision with which visual information was represented, increasing the sensitivity of the paradigm to measure the visual information that has been processed at particular time points. Using the TAF methodology, stimulus duration was manipulated, yielding a time course function of precision. The information accumulation model was then fit to these data to estimate differences in processing dynamics. A diffusion model analysis was not considered appropriate due to the physical time participants required to make the adjustment and because the adjustment method allowed for fine grained responses ($<1^\circ$), yielding too many potential responses (>180) and thus making implementation of a diffusion model unwieldy.

With all of the above issues in mind, we completed a series of three studies to reevaluate whether older and younger adults differ in the rate of visual information processing. In Experiment 1 we examined whether age-related differences in visual information processing are evident when participants are presented with a single stimulus. In Experiments 2 and 3, multiple stimuli were presented and participants either had to dismiss irrelevant items (Experiment 2) or, after display offset, were queried to report one of the targets by means of a postcue (Experiment 3).

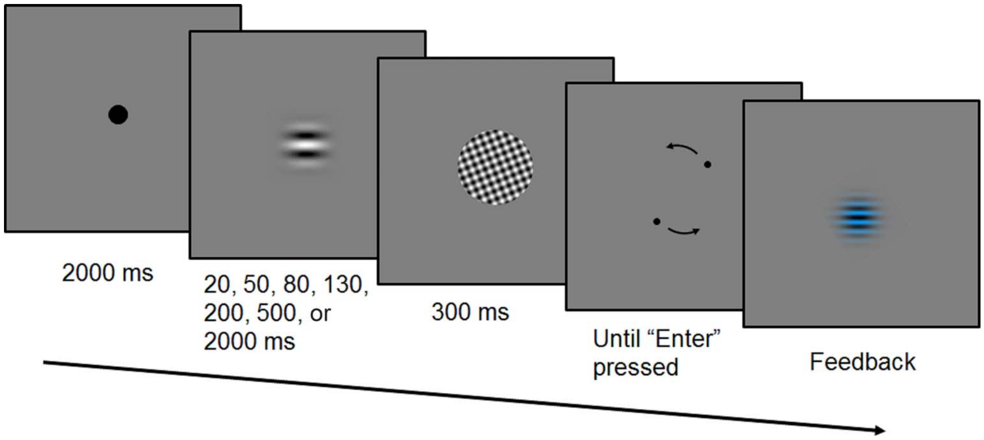

Figure 2. Example of a trial from Experiment 1.

Experiment 1

Experiment 1 consisted of a simple visual task in which participants were presented with a Gabor patch for a given duration and then asked to report its orientation. If age does influence speed of visual processing (Kliegl et al., 1994) then a clear age-related processing rate difference should be observed.

Method

Participants

Participants comprised 18 healthy young participants (mean age = 20.6 years; range = 19–26; $SD = 1.5$) with a mean number of 16.0 years of education ($SD = 1.65$). Using the Test of Premorbid Functioning (TOPF; Pearson Education, Inc., 2009), younger adults had a mean estimated verbal IQ of 102.44 (range = 90–117; $SD = 6.86$). There were 18 healthy older participants, recruited from the local community, with a mean age of 71.6 years (range = 65–86; $SD = 7.24$), a mean number 13.9 years of education ($SD = 3.69$). Their mean verbal IQ was 107.94 (range = 75–127; $SD = 13.55$). There was no significant difference in estimated IQ between age groups, $t(25.91) = 1.54$; $p = 0.14$, although younger adults had significantly more education than the older adults, as is typically seen in aging literature due to cohort effects, $t(24.99) = -3.01$; $p = 0.006$ (t adjusted in both tests due to inequality of variances). In order to screen for unhealthy cognitive decline, older participants additionally completed the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975). The mean MMSE score was 28 (range = 24–30; $SD = 1.71$) indicating that all participants were cognitively healthy (Folstein et al., 1975). All participants reported normal or corrected-to-normal vision and were given either research credits or a £5 store voucher for their time.

Stimuli and materials

Stimuli were presented on a 17.5-in. 1024 × 768 pixel CTX EX951F monitor (Chuntex Electronic Co., Ltd., Taipei, Taiwan) with a refresh rate of 100 Hz. Participants viewed the display in a dimly lit room with a viewing distance of 57 cm. The experiment was written using VisionEgg (Straw, 2008; http://www.visionegg.org). Target stimuli were Gabor patches (sinusoidal luminance gratings in a Gaussian envelope) with a random orientation and a spatial frequency of 1.39 cycles/° and $\sigma = 0.77°$. The mask was a randomly oriented circular plaid comprising two orthogonally superimposed sinusoidal luminance gratings each with a spatial frequency of 1.39 cycles/° with a diameter of 6.18°.

Design and procedure

At the start of each trial, a circular black fixation point subtending 0.80° was presented at the center of the screen for 2000 ms on a mid-gray background. This was then replaced with the target grating which was presented for 20, 50, 80, 130, 200, 500, or 2000 ms. The presentation duration was randomized on each trial. Upon stimulus offset the mask was presented in the target location for 300 ms. After mask offset, participants were prompted to report the orientation of the target. Participants adjusted the orientation of a pair of black markers by using key presses to rotate the markers clockwise or anticlockwise (see Figure 2 for an example). The appearance of these markers was delayed until after the participant had started to make their response to avoid interference between the initial vertical alignment of the markers and the orientation held in memory. Markers were presented 3.16° from the center of the screen as if marking the edge of an invisible circle. Participants used the up and down keys to make adjustments of 1°, and used the left and right keys to make further adjustments of 0.3° to refine their response. After the adjustment participants pressed the

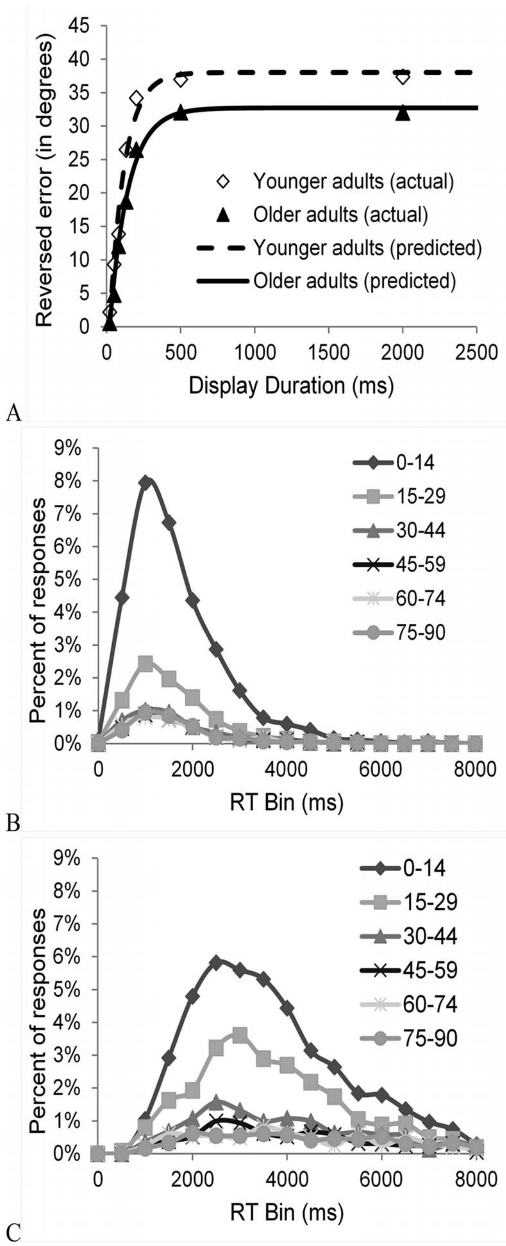

Figure 3. (A) Predicted and observed reversed error magnitude (in degrees) for older and younger adults in Experiment 1. (B, C) Percentage of errors in each error magnitude bin (errors measured in degrees) at each 500 ms RT bin for younger (B) and older (C) adults.

enter key to enter their response (providing a measurement of response time). Participants were instructed to respond as accurately as they could and also to respond relatively quickly (to prevent long trials). After responding, participants received feedback in the form of the target grating, but colored blue to distinguish from the first target presentation. The space bar was pressed to start the next trial, enabling participants to take a break between trials if they wished.

The experiment consisted of two blocks containing 119 trials each, with 34 trials per cell of the design. Thus, each participant completed 238 trials. At the beginning, each participant practiced until they felt comfortable with the procedure (typically around 10 trials).

Results and discussion

The data of each participant was trimmed by excluding responses that were longer than 8300 ms (allowing for ample time, approximately 8 s, to make an adjustment before submitting the response by pressing the space bar) and responses that were longer than two standard deviations from each participant's mean RT. If this criterion led to exclusion of a large number of trials for a participant (e.g., more than 60% of trials) that participant was excluded from analysis. This led to the exclusion of one older participant. Of the remaining participants, trimming resulted in 7.8% of the data being excluded from analysis.

On every trial, error magnitude was calculated which is the absolute difference between the reported and correct orientation. For example, if the participant reports an orientation of 57° clockwise of vertical, but the correct orientation was 42° clockwise of vertical, then this response yields an error magnitude of 15°. This yields a total error range of 0–90°, with 45° reflecting chance responding. To aid with interpretation in relation to the prior literature in which higher scores indicate greater precision we calculated mean errors at each stimulus duration and subtracted these from 45 (the chance rate). On this scale a score of 0 indicates a score equivalent to chance and a score of 45 indicates perfect responding.

Figure 3 shows this reversed error for each stimulus duration and for each condition (the time accuracy function, TAF). As can be seen, younger adults generally produced more precise responding than older adults, with this difference evident even from the shortest stimulus duration. A 2 (age: young or old) × 7 (stimulus durations: 20, 50, 80, 130, 200, 500, or 2000 ms) mixed ANOVA was conducted on response errors, with age as the between-subjects factor and stimulus duration as the within-subjects factor. There was a significant effect of stimulus duration, $F(6, 198) = 201.34$, $MSE = 63.28$, $p < 0.001$, with smaller response errors when the stimulus was presented for longer durations, and a significant effect of age, $F(1, 33) = 6.38$; $MSE = 218.85$, $p = 0.017$, with older participants performing worse than younger participants. Interestingly, the interaction between age and stimulus duration was not significant, $F(6, 198) = 1.67$; $MSE = 63.28$, $p = 0.169$, indicating similar age effects at each stimulus duration. This suggests that performance differences between groups reflect differences in overall task ability rather than a difference in the rate at which information was processed and assimilated into the target representation.

To examine the pattern of errors produced at different RTs, RTs were binned into sixteen 500-ms bins from 0–8000 ms, and reversed error magnitudes were placed into six 15° error bins from 0–90°. Figure 3 shows the percentage of responses in each error bin at each RT bin. Younger adults clearly showed faster responding than older adults, with the majority of responding in the first 3000 ms and the peak of responses occurring around 1000–1500 ms. For older adults, the time taken to respond varied much more, with a peak around 2500–3000 ms but large numbers of responses still being given after 6000 ms. Importantly, for both the younger and older adults, the pattern of RTs was similar for each error bin, with the peaks all occurring within the same region. Thus although older adults were slower overall, there was not a pattern of slow, large errors, which would suggest delayed responding led to significant deterioration of the stimulus representation. The observed differences in asymptotic performance between older and younger adults can therefore be interpreted primarily as older adults having a less precise stimulus representation.

Model fitting

Model fitting was completed by maximizing the adjusted R^2 statistic given by:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (d_i - \hat{d}_i)^2/(n-k)}{\sum_{i=1}^{n} (d_i - \bar{d})^2/(n-1)}, \tag{2}$$

In this equation n is the number of data points (stimulus durations), k the number of parameters, d_i is the observed data, $\hat{d}_i$ refers to the predicted value, and $\bar{d}$ the overall mean. A simple shifted exponential rise-to-asymptote function was fit to the time accuracy functions, whereby

$$\text{reversed error}(t) = \lambda\left(1 - e^{-\beta(t-\delta)}\right), \text{for } t > \delta, \text{else } 0 \tag{3}$$

Two methods were used for model fitting. The first method entailed fitting the model to data for each individual subject in order to derive parameters for each individual. Statistical tests were then performed on these parameter estimates to assess differences. The second method entailed fitting the model to data for each age group and performing model comparisons to examine the extent to which parameters differed between older and younger participants.

Individual parameter estimates

The model was fit to reversed response error data from each individual. Estimated parameters for participants from the younger and older groups are shown in Table 1A and 1B respectively. An independent samples t test was performed to compare parameter estimates from both age groups. The groups differed in asymptote parameters, $t(33) = 4.57$; $p = < 0.001$, with younger adults having a higher asymptote and thus demonstrating more precise overall responding. However, there was no difference between groups in processing rate, $t(33) = 1.41$; $p = 0.17$, or take-off, $t(33) = -0.57$; $p = 0.58$.

Model comparisons

Models were fit to data from all individual data simultaneously. Adjusted R^2 was calculated for each participant, and an overall adjusted R^2 was then derived by averaging the adjusted R^2 from all participants. Although an alternative method of modeling mean data from each age group is possible, this would require fitting relatively few data points (seven per condition) whereas this approach assesses the fit for seven data points per participant. In fact, both modeling procedures resulted in the same "best" model, although we report only results from the former methodology.

The most restricted model assumed that older and younger participants had the same asymptote, processing rate, and take-off parameters ($1\lambda\ 1\beta\ 1\delta$). The most general model assumed that older and younger participants differed on all these parameters ($2\lambda\ 2\beta\ 2\delta$). Model fits for all permutations of shared/unique parameters between age groups were examined. The best fitting model was, $2\lambda\ 2\beta\ 1\delta$,which yielded an R^2 of 0.79. The fits of the model are shown in Figure 3. As is evident, the model provided a very good account of the data. Parameter estimates from this model are shown in Table 2. In agreement with the analysis of parameters estimated for each individual, the model indicated that younger adults had a higher asymptote, demonstrating more accurate responding, with parameter values similar between modeling approaches. In contrast, the best fitting model from the model comparisons suggested that younger participants had a faster processing rate than older adults, whereas this was not the case when assessing individual parameter estimates. Further examination shows that this processing rate advantage was relatively small. Comparing the mean processing time ($1/\beta$) between groups reveals that the difference in processing rates yielded a difference between the mean processing times of 26 ms only. Moreover, the second best model assumed older adults and younger adults had identical processing rates, and this fit the data only slightly worse (an R^2 difference of

Parameter	Mean	SD	1	2	3	4	5	6	7	8
A										
Asymptote (λ)	38.08	2.46	34.93	38.31	37.03	35.54	41.08	41.06	35.91	40.11
Processing rate (β)	.01375	.01074	.00673	.02050	.00797	.01101	.00929	.00938	.00644	.00889
Take off (δ)	24.44	14.68	32.87	13.92	44.59	0	27.33	33.49	15.9	21.06
R^2	.93	.05	.94	.97	.91	.93	.98	.91	.89	.85
B										
Asymptote (λ)	33.15	3.81	26.73	28.51	34.85	35.74	33.24	32.67	32.75	28.84
Processing rate (β)	.00969	.00511	.00536	.00205	.01782	.01771	.01186	.00344	.01082	.00928
Take off (δ)	28.30	24.72	12.57	108.4	25.96	24.63	34.1	5.983	19.15	1.898
R^2	.94	.05	.94	.96	.99	.98	.85	.94	.94	.93

Table 1. (Continued)

0.0005), again suggesting that any difference in processing rates between older and younger adults in the task was relatively small.

In summary, in Experiment 1 we used a simple visual perception task requiring observing and responding to a single stimulus. Rather than using a more complex 2AFC task which incorporates a decision-making component, participants simply reproduced the stimulus orientation as best they could. This provides a direct measure of the precision of participants' stimulus representations. A clear age effect in overall accuracy was observed, with more accurate responding by younger adults, indicating a better ability to store a more precise, finer-grained representation of the target object. This supports previous evidence suggesting that visual short-term memory is age-sensitive (e.g., Beigneux et al., 2007; Brown et al., 2012; Jenkins et al., 2000; Johnson, Logie, & Brockmole, 2010; Logie & Maylor, 2009). In particular, in the context of a visual feature binding task, Peich et al. (2013) also investigated fidelity of visual short-term memory representations in older adults using a precision-based measure, and showed that aging was associated with less accurate reproductions of orientation from memory.

Despite this overall difference in performance there was relatively limited evidence for an age difference in processing dynamics. No differences were observed in the time at which processing started. Although there was some evidence of faster visual information processing in younger adults, this was limited; there was no interaction between age and duration in the ANOVA on response error magnitude and no evidence for a difference in rates when comparing parameters derived for individuals from each group. Moreover, any processing rate difference was very small in magnitude. The results of Experiment 1 therefore support Ratcliff et al. (e.g., Ratcliff et al., 2006) who have found limited evidence for age differences in the rate of visual information processing in tasks in which a single object or dimension needed to be processed.

Experiment 2

Experiment 2 was again designed to assess the speed of processing of a target object, but in a context that contained additional items. This addressed the possibility that processing speed deficits are more problematic for older adults in more cognitively complex circumstances, specifically when more items require processing. Experiment 2 was therefore similar to Experiment 1 except that there were four objects in each stimulus display. Three of these objects were nontargets and shared the same spatial frequency as one another. The task was to report the orientation of the target object which had a unique spatial frequency. Spatial frequency can be used to guide attention efficiently and in parallel (Wolfe & Horowitz, 2004). Experiment 2 therefore examined the rate at which visual information about a target object could be processed in a simple search array.

Method

Participants

Participants comprised 18 healthy young adults (mean age = 21.94 years, range = 19–28; *SD* = 2.60) with a mean of 16.44 years of education (*SD* = 1.71), and a predicted verbal IQ (TOPF) of 100.5 (range = 90–119; *SD* = 7.86). There were 19 older participants (mean age = 70.53; range = 65–82; *SD* = 5.48) with a mean of 13.68 years of education, a TOPF-estimated verbal IQ

Group	Asymptote (λ)	Processing rate (β)	$1/\beta$	Take off (δ)
Younger adults	38.00	0.00991	101	19.70
Older adults	32.72	0.00790	127	19.70

Table 2. Parameter estimates derived from model comparisons for younger adults (A) and older adults (B) in Experiment 1.

Parameter	9	10	11	12	13	14	15	16	17	18
A										
Asymptote (λ)	38.24	41.4	38.63	41.43	33.98	37.25	40.96	37.74	35.45	36.34
Processing rate (β)	.00803	.00580	.04049	.03891	.01111	.01142	.02651	.00903	.00719	.00872
Take off (δ)	4.11	25.78	0	15.66	31.95	37.85	15.43	46.79	29.41	43.73
R^2	.93	.88	.99	1.00	.97	.93	.99	.97	.91	.83
B										
Asymptote (λ)	25.02	32.29	35.01	34.95	37.95	34.92	35.31	37.38	37.44	
Processing rate (β)	.00473	.01670	.01316	.00608	.01412	.00775	.01268	.00536	.00588	
Take off (δ)	18.82	26.48	0.764	23.16	19.77	31.89	33.28	40.66	53.65	
R^2	.95	.98	.99	.93	.89	.82	.97	.92	.97	

Table 1. Continued. Parameter estimates for younger adults (A) and older adults (B) in Experiment 1 for each participant (indicated by the top row).

of 109.05 (range = 97–127; $SD = 9.69$), and a mean MMSE of 28 (range = 26–30; $SD = 1.29$). Younger adults had significantly more years in education, $t(35) = 3.16$; $p = 0.004$, while the older adults had a higher estimated IQ, $t(35) = 2.94$; $p = 0.006$ (this can often be seen in the aging literature, e.g., Brown & Brockmole, 2010). Importantly, this is in the opposite direction of any aging effects in the experiment, and likely reflects that the younger adults have yet to develop their verbal knowledge fully.

Stimuli, materials, design, and procedure

Experiment 2 was identical to Experiment 1 with the following exceptions. The fixation point was a white disc measuring 0.40°. Instead of a single target stimulus, four Gabor patches were presented simultaneously with their centers on the corners of an imaginary square with corners 5.42° from fixation. Out of the four gratings, the target was defined as the only grating that differed in spatial frequency from the other three, which all shared the same spatial frequency (i.e., the target was the spatial frequency singleton in the display). The location of the target grating was randomly selected on each trial. On each trial, the target spatial frequency was randomly selected from one of four values: 3.68, 1.84, 1.23, and 0.92 cycles/°. One of the remaining three values was then randomly selected for the other three nontarget gratings. These spatial frequency values were selected to be suprathreshold even for older adults who show some loss in contrast sensitivity at very high spatial frequencies (see Owsley, 2011).

All four gratings were displayed simultaneously and for a duration randomly selected on each trial, either 20, 50, 80, 130, 200, 500, or 2000 ms. Each grating was then masked as in Experiment 1. After the disappearance of the masks, participants attempted to report the orientation of the target. After submitting their response, they were given feedback in the same way as Experiment 1 (see Figure 4). Participants were given practice trials until they were comfortable to continue (typically around 10 trials). They then completed 210 trials (30 trials per display duration),

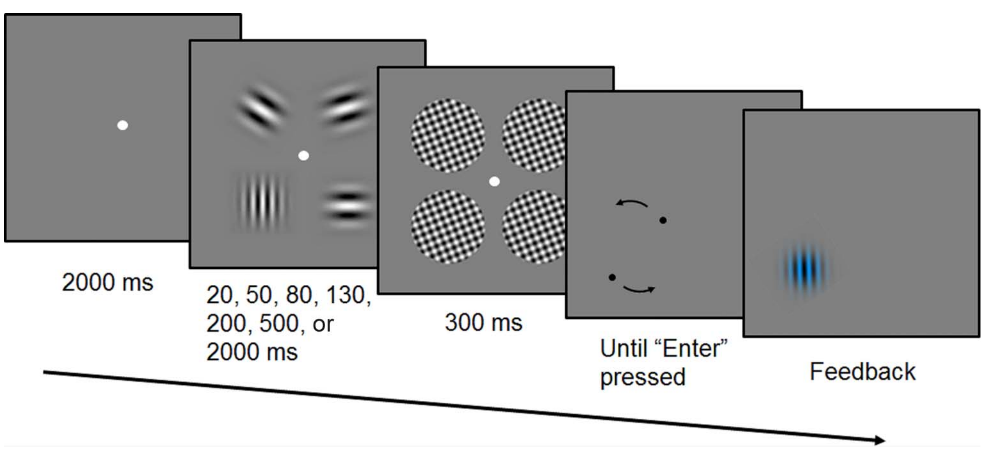

Figure 4. Example of a trial from Experiment 2. On each trial four stimuli were presented briefly then masked. Three of the stimuli (nontargets) shared the same spatial frequency, thus the target had a unique spatial frequency. In the example above, the target was at the bottom left. After response, feedback (the correct orientation) was shown at the target location.

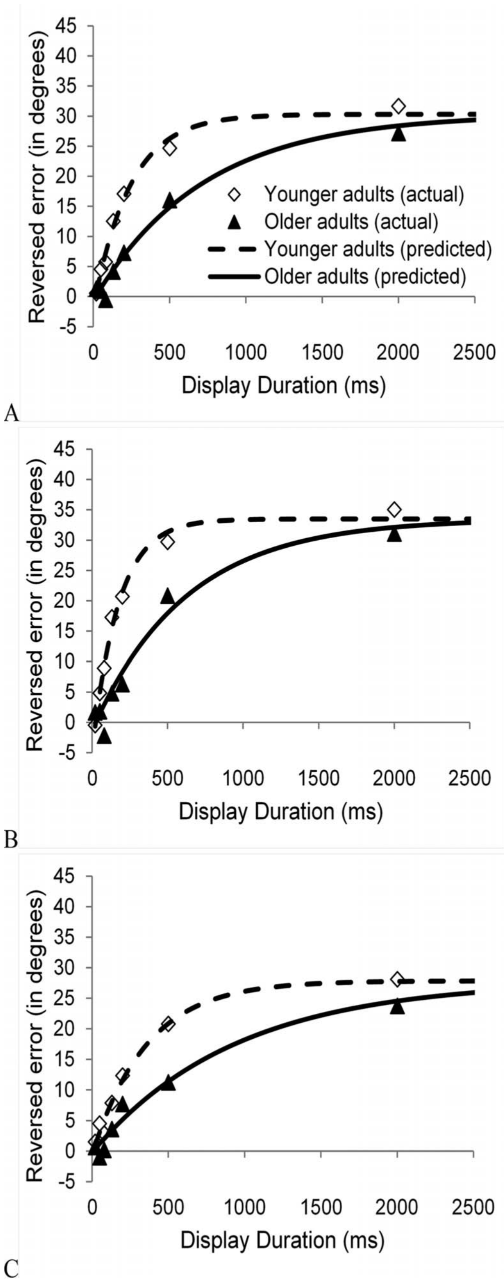

Figure 5. Predicted and observed reversed error magnitudes for older and younger adults in Experiment 2. Panel (A) includes data from all trials whereas panels (B) and (C) comprise data from trials in which there was a large (B) or small (C) difference between the spatial frequency of the unique target and the distracting items.

which were presented in a randomized order and in two blocks of 105 trials.

Results and discussion

Data were trimmed in the same way as in Experiment 1 leading to one older participant being removed from analysis because more than 70% of their data points were removed during trimming. An additional three older participants were also excluded from analysis as they were still performing at chance at the longest stimulus duration, indicating an inability to perform the task within these parameters. Of the participants remaining, trimming resulted in 5.6% of the data being excluded from analysis.

Figure 5 displays reversed response error magnitudes for the overall data and also data broken down by whether there was a relatively large or small difference between the spatial frequencies of the target and nontargets. A large difference was classed as a difference of greater than 1.8 cycles/° and comprised approximately half the trials. There are several striking aspects of the data. At the longest stimulus duration older and younger adults reached a similar level of precision, with younger adults being slightly more precise. Importantly, however, the time course of performance differed dramatically, with younger adults showing a much faster rise to asymptotic precision, indicative of a difference in processing rate. A 2 (age: young or older) $\times$ 7 (stimulus durations: 20, 50, 80, 130, 200, 500, or 2000 ms) mixed-design ANOVA was conducted on reversed response errors with age as the between subjects factor and stimulus duration as the within subjects factor. There was an effect of age, $F(1, 31) = 15.52$, $MSE = 124.94$, $p < 0.001$, indicating that younger adults responded more precisely than older adults. There was also an effect of stimulus duration, $F(6, 186) = 119.89$, $MSE = 42.46$, $p < 0.001$, with more precise responding as stimulus duration increased. Crucially, there was also a significant interaction between age and stimulus duration, $F(6, 186) = 3.74$, $MSE = 42.46$, $p = 0.005$.

Using the same methodology as in Experiment 1, RTs and errors were binned to examine how response precision changed as a function of RT. Figure 6 shows the percentage of responses in each error bin and each RT bin. As in Experiment 1, younger adults showed much faster responding with a peak in the 500–1500 ms range and the majority of responses within 3000 ms. For older adults, responses were much more spread over the full range of response times, with a peak of responses within 3000–4500 ms. Importantly, the pattern of responding over the RT bins did not differ for different error bins. Thus, although older adults responded much more slowly, they did not tend to produce lots of larger errors at longer RT bins. This indicates that delaying responding did not lead to significant deterioration of their stimulus representation, and suggests that this could not primarily explain any age difference in performance.

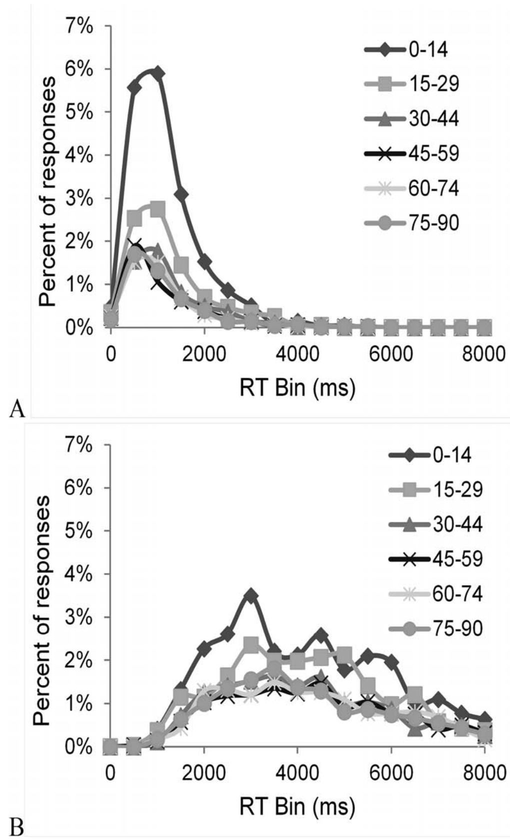

Figure 6. Percentage of errors in each error magnitude bin (errors measured in degrees) at each 500 ms RT bin for (A) younger and (B) older adults in Experiment 2.

Individual parameter estimates

The model was fit to reversed error magnitude data from each individual. Estimated parameters for participants from the young and old groups are shown in Table 3A and 3B respectively. An independent samples t test was performed to compare parameter estimates between the old and young groups. The age groups differed in processing rate parameters only, $t(31) = 3.57$; $p = 0.001$, with younger adults having a faster processing rate.

Model comparisons

The same modeling methodology as Experiment 1 was used. The best fitting model was, $1\lambda\ 2\beta\ 1\delta$, which yielded an adjusted R^2 of 0.92. The TAFs produced by the model are shown in Figure 5 and fit the data well. Parameter estimates from the best fitting model are shown in Table 4. Unlike in Experiment 1, there was clear agreement between the different modeling methodologies, both of which indicated an advantage in processing rate for younger adults, with no other age differences between parameters observed. Moreover, mean values of parameters derived from each modeling methodology were similar, the exception being for the take-off parameter, which was predicted to be smaller when estimated through modeling comparisons.

Given the large differences found in asymptotic performance in Experiment 1 and previous findings (e.g., Peich et al., 2013), it is surprising that asymptotic performance did not appear to differ between age groups. Closer inspection of the data however does show that at all levels younger adults were more accurate than older adults, and the mean asymptotes calculated from individual parameter estimates trend in this direction. It is possible that a difference in the estimated asymptote parameters was not found because the data are not fully conclusive as to whether performance at the last display duration was at asymptotic levels. In case conclusions regarding age-related differences in processing rates were in part caused by assuming the same asymptotic level of performance for both groups, we compared fits between the $2\lambda\ 2\beta\ 1\delta$ and the $2\lambda\ 1\beta\ 1\delta$ models, which both assume different asymptotes. The $2\lambda\ 2\beta\ 1\delta$ model fit the data better, again supporting the conclusion that processing rates differed between age groups.

Modeling comparisons were also completed for trials in which there was a large or small difference between the spatial frequencies of the target and non-targets. In both instances, the same $1\lambda\ 2\beta\ 1\delta$ model provided the best fit of the data yielding an R^2 of 0.87 for the large difference condition and an R^2 of 0.89 for the small difference condition. Parameters estimated from this model are shown in Table 5. These are revealing in that, although in both cases younger adults show a processing advantage, this is most marked when there is a small difference between target and distractor spatial frequencies. For younger adults processing rates were around 3.6 times larger than older adults when there was a small target-distractor difference but only 2.6 times larger than older adults when there was a large target-distractor difference.

Overall, Experiment 2 yields several interesting findings. Three forms of evidence including ANOVA and parameters estimated from two modeling methodologies suggest a difference in the rate of processing between age groups. When there are additional items in the display, older adults exhibit clear slowing in the rate of visual information processing. Combined with Experiment 1, this suggests that age-related deficits in the rate of visual information processing are only evident when there are multiple items to be processed. As such, this may reconcile the findings of Kliegl et al. (1994), who showed clear age-related differences in processing in tasks requiring processing of multiple objects, with those of Ratcliff et al. (2006), who found little evidence for such age-related differences in studies involving processing of a single object or dimension.

Parameter	Mean	SD	1	2	3	4	5	6	7	8
A										
Asymptote (λ)	32.82	5.59	30.06	23.95	30.62	24.33	27.55	32.51	37.86	31.99
Processing rate (β)	.00500	.00273	.00355	.00982	.00652	.00623	.00608	.00397	.00527	.00474
Take off (δ)	32.08	43.14	31.17	38.38	29.93	11.50	42.52	28.30	16.77	63.32
R^2	.94	.10	.98	.97	.97	.96	.96	.99	.95	1.00
B										
Asymptote (λ)	30.28	7.52	37.54	22.35	27.56	28.03	19.19	32.79	45.00	19.05
Processing rate (β)	.00216	.00166	.00086	.00132	.00208	.00194	.00506	.00259	.00039	.00166
Take off (δ)	49.95	51.43	0	42.7679	16.9135	78.0554	57.5844	0	0	157.848
R^2	.96	.03	.89	.97	.98	.97	.97	.95	.98	.98

Table 3. (Continued)

As the task required search for, and processing of, the target it is possible that older adults found it more difficult to find the target. This is doubtful given that the display contained only four items and that spatial frequency can efficiently guide search in parallel (see Wolfe & Horowitz, 2004) as well as the effect of grouping. Indeed, no age differences in the take-off parameter were observed, suggesting this was not the case, and supporting previous research showing no age-related decline in the ability to guide attention to perceptual features (Madden et al., 1999).

It is possible however that older adults adopted a different strategy, perhaps processing the display serially rather than in parallel. McElree and Carrasco (1999) produced models of parallel and serial processing of display information in visual search specifically for TAFs. When performance rises slowly as a function of processing time, serial search is characterized by an S-shape function (as duration increases performance initially shows a gradual improvement, then much faster improvement, followed by more gradual improvement again). Despite showing a relatively slow climb to asymptote, there is little evidence for an S-shaped function for older adults, suggesting a serial search strategy was not adopted. Indeed, the model fit to the data assumes continuous accumulation of target information and this provided a very good account of the data.

Why, then, did older adults show a reduced rate of visual information processing? Given the good fit of the TAF function assuming continuous accumulation of target information and the lack of evidence for slower attentional guidance, we interpret the slower processing in terms of older adults finding it harder to focus limited capacity attentional resources. Attention is a flexible resource (Alvarez & Franconeri, 2007; Howard & Holcombe, 2008) and evidence suggests that older adults have reduced attention capacity (for a review see Zanto & Gazzaley, 2014). In Experiment 1 a single object was presented allowing for attention to be easily focused. In comparison, in Experiment 2, multiple objects were presented making it harder to focus attention and leading to a slowing of processing for older adults. In visual search there is evidence that older adults have to over-use top down control due to deficient bottom up processes (Madden, 2007; Madden et al., 2007), potentially resulting in increased processing demands. Consistent with this notion, we found a larger age-related deficit in processing rate when the nontarget items were more similar to the target in terms of spatial frequency, potentially because older adults found it harder to focus their processing resources on the target.

Group	Asymptote (λ)	Processing rate (β)	$1/\beta$	Take off (δ)
Younger adults	30.32	0.00416	241	15.65
Older adults	30.32	0.00140	720	15.65

Table 4. Parameter estimates derived from model comparisons in Experiment 2.

Experiment 3

Experiment 2 required considerable online processing in terms of searching for the target during stimulus presentation. However, tasks with multiple objects sometimes require considerable offline processing such that information from multiple objects needs to be retained until there is an indication as to which is relevant. Peich et al. (2013) demonstrated that under

Spatial frequency difference	Group	Asymptote (λ)	Processing rate (β)	$1/\beta$	Take off (δ)
Large	Younger adults	33.50	0.00581	173	23.34
	Older adults	33.50	0.00162	621	23.34
Small	Younger adults	27.86	0.00283	355	8.69
	Older adults	27.86	0.00105	935	8.69

Table 5. Parameter estimates derived from model comparisons in Experiment 2.

Parameter	9	10	11	12	13	14	15	16	17	18
A										
Asymptote (λ)	40.81	45.00	33.41	24.73	34.48	37.40	32.57	33.98	35.99	33.60
Processing rate (β)	.00072	.00046	.00586	.00143	.00536	.00212	.00581	.00443	.01020	.00745
Take off (δ)	0.00	0.00	28.35	185.57	0.00	62.53	0.00	5.39	12.11	21.66
R^2	.93	.97	.94	.99	.84	.96	.56	.97	.92	.99
B										
Asymptote (λ)	28.38	31.67	26.71	34.06	39.72	32.92	29.23			
Processing rate (β)	.00239	.00149	.00589	.00099	.00089	.00176	.00309			
Take off (δ)	66.3734	116.891	20.1794	0	8.26615	101.061	83.28			
R^2	.95	.96	.99	.96	.93	.97	1.00			

Table 3. Continued. Parameter estimates for younger adults (A) and older adults (B) in Experiment 2 for each participant (indicated by the top row).

such circumstances an age-related decline in precision is observed. In their experiment, one or three stimuli were shown and then, following a mask, one of the objects was probed. Their analysis of the distribution of errors suggested an age-related decline in working memory resources used to store visual information. However, they did not examine whether this influenced the rate of visual information processing. In Experiment 3 we therefore examined the influence of having to process and retain information from two objects, one of which was subsequently probed after stimulus offset.

Method

Participants

There were 16 young participants with a mean age of 23.56 years (range = 20–29; $SD = 2.83$), a mean number of 16.88 years of education ($SD = 1.86$), and a mean verbal IQ (TOPF) of 102.50 (range = 92–119; $SD = 8.96$). There were also 18 cognitively healthy older adults with a mean age of 69.11 years (range = 65–82; $SD = 4.76$), a mean of 13.33 years of education ($SD = 3.77$), a mean verbal IQ (TOPF) of 108.22 (range = 94–127; $SD = 10.58$), and a mean MMSE score of 28.17 (range = 26–30; $SD = 1.29$). Younger adults had significantly more years of education, $t(32) = 3.40$; $p = 0.002$) but there was no reliable difference in estimated IQ, $t(32) = -1.69$; $p > 0.10$.

Stimuli, materials, design, and procedure

Experiment 3 was similar to Experiment 1 except that, in this experiment, participants were required to attempt to encode the orientations of two targets and, after display offset, were probed to report the orientation of one of the targets. Experiment 3 was therefore identical to Experiment 1, with the following exceptions. The fixation point was a black disc measuring 0.40° and remained visible until the response phase. Instead of a single target stimulus, two circular sinusoidal Gabor luminance patches were presented simultaneously in adjacent positions with the center of the targets 5.45° on either side of the fixation point. The two stimuli were the same size and spatial frequency as in Experiment 1. Participants were instructed to attend to both targets, and informed that they would be required to report one of the two at the end of the trial with equal probability. Upon offset of the masks, a small white circular post cue measuring 0.71° was presented either 1.05° left or right of the fixation point to indicate which of the two stimuli was being probed. The probe remained onscreen until the participant began the response adjustment (see Figure 7). After submitting their response, participants were given feedback as per Experiment 1.

Displays were presented for either, 20, 50, 80, 130, 200, 1000, or 2000 ms. There were 30 trials for each display duration, totaling 210 trials in two blocks of 105, with the order of trial presentation randomized. Participants were given some practice (typically around 10 trials) before commencing the experiment.

Results and discussion

Data were trimmed using the same method as in Experiment 1. This led to the exclusion of one older participant for whom over 50% of trials were removed, and another two older participants who remained near chance performance throughout. Of the participants remaining, trimming resulted in 5% of the data being excluded.

Reversed response error magnitudes are shown in Figure 8. There were clear age differences in asymptotic performance, with older adults performing much worse than younger adults, even at the longest display duration. Less clear is whether there were processing rate differences, as these are difficult

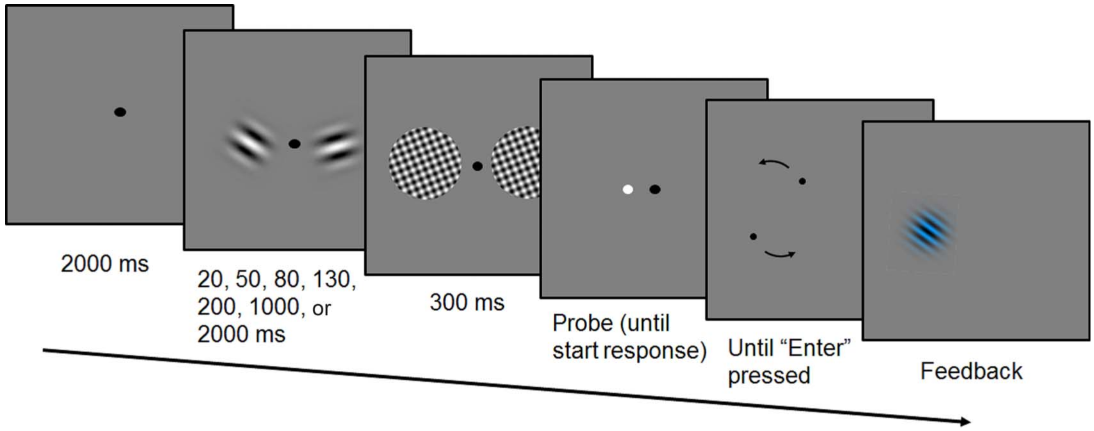

Figure 7. Schematic of procedure from Experiment 3. Two stimuli were presented for a given duration and then masked. A probe then indicated the target object whose orientation participants had to report.

to assess visually if asymptotic performance differs. A 2 (age: young or old) × 7 (stimulus durations: 20, 50, 80, 130, 200, 1000, or 2000 ms) mixed-design ANOVA was conducted on response errors with age as the between subjects factor and stimulus duration as the within subjects factor. There was a significant effect of age, $F(1, 29) = 31.13$, $MSE = 3874.80$, $p < 0.001$), a significant effect of stimulus duration, $F(6, 174) = 144.82$, $MSE = 4985.10$, $p = < 0.001$, and a significant interaction between age and stimulus duration, $F(6, 174) = 6.58$, $MSE = 4279.99$, $p < 0.001$.

Using the same methodology as in Experiment 1, RTs and errors were binned to examine how response precision changed as a function of RT. Figure 8 shows the percentage of responses in each error bin and each RT bin. Younger adults showed much faster responding with a peak in the 1000–2000 ms RT bin and the majority of responses within 5000 ms. Compared to Experiments 1 and 2, RTs tended to be longer and much more spread for younger participants. This is probably due to delaying response preparation until onset of the probe. For older adults, responses were much more spread over the full range of response times with the distribution similar to that observed in Experiment 2. The peak of responding occurred within 3000–4500 ms. Importantly, the pattern of responding over the RT bins did not seem to differ for different error bins. Thus, although older adults responded much more slowly, they did not tend to produce lots of larger errors at longer RT bins.

Individual parameter estimates

The model was fit to reversed response magnitude data from each individual. Estimated parameters for participants from the young and older groups are shown in Table 6. An independent samples t-test was performed to compare parameter estimates from the older and younger groups. The age groups differed in asymptote precision, $t(29) = 3.84$; $p = 0.012$, and processing rate, $t(29) = 3.88$; $p < 0.001$, with older adults having a lower asymptote and a slower rate of processing. Take-off parameters did not significantly differ, $t(29) = 1.81$; $p = 0.12$.

Model comparisons

As in Experiment 1, models with all permutations of shared/unique parameters between age groups were examined. The best fitting model was, $2\lambda\ 2\beta\ 1\delta$, which yielded an adjusted R^2 of .90. The TAFs produced by the model are shown in Figure 8 and clearly fit the data well. Parameter estimates from the best fitting model are shown in Table 7. There was clear agreement between the different modeling methodologies, both of which indicated a higher asymptote and faster processing for younger adults. Generally, parameter estimates generated from these two methodologies were similar.

Experiment 3 differed from Experiment 1 in the introduction of an additional display stimulus that needed to be processed and maintained in working memory. While in Experiment 1 there was little evidence for age-related processing rate differences, Experiment 3 found clear evidence for processing rate differences, with older adults showing slower processing. Thus, by introducing a single additional stimulus *to be remembered* (as distinct from introducing nontarget stimuli whose orientations were to be ignored, as in Experiment 2), the cognitive demands of the task sufficiently increased to impact the rate at which older adults could form and maintain representations of the objects.

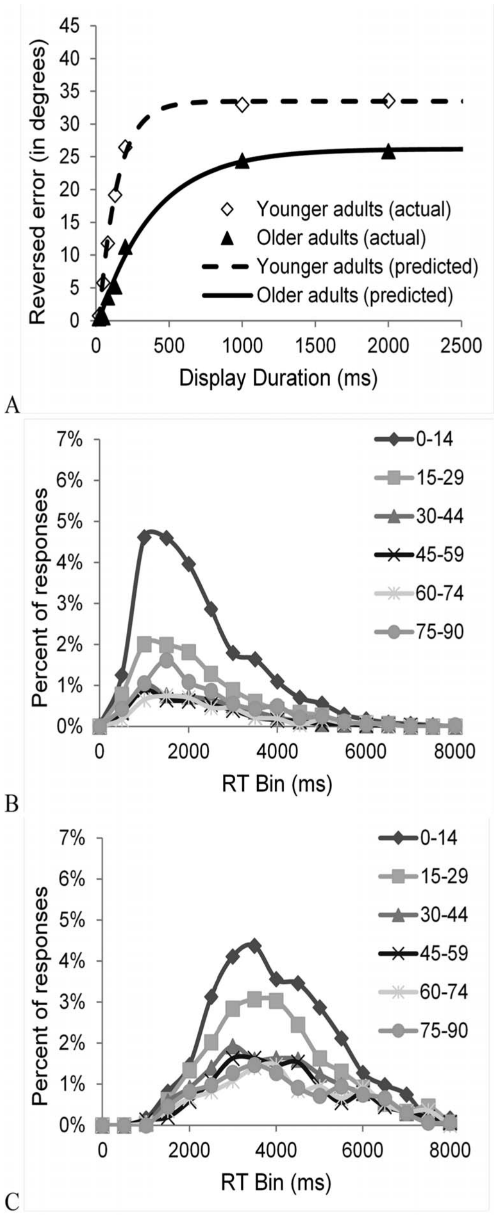

Figure 8. (A) Predicted and observed reversed error magnitudes for older and younger adults in Experiment 3. (B, C) Percentage of errors in each error magnitude bin (errors measured in degrees) at each 500 ms RT bin for younger (B) and older adults (C) in Experiment 3.

Interference

As there were two stimuli in Experiment 3 which had to be processed and held in memory it is possible that performance differences were due to older adults experiencing interference between these representations. That is, older adults may not have been able to successfully ignore information about a previously relevant stimulus after the postcue rendered one of them irrelevant. This interference may account for differences in asymptotic performance but also processing rate differences. That is, the degree of interference may have been magnified when processing time was short. Alternatively processing may have been slowed by the process of keeping the two representations separate during encoding. Table 8 shows the mean similarity of each response relative to the nonqueried object orientation for older and younger adults. This varies from 0° (identical responding) to 90° (maximally different responding) with a value of 45° indicating no influence of the nonqueried object. Interestingly, younger adults' responses appeared to be biased away from the nonqueried object, whereas older adults tended to be biased towards the orientation of the nonqueried object. Although this effect was small, it was reliable, with a 2 (age: young or old) × 7 (stimulus durations: 20, 50, 80, 130, 200, 1000, or 2000 ms) mixed-design ANOVA on these similarity scores showing a significant effect of age only. $F(1, 29) = 5.06$, $MSE = 125.37$, $p = 0.032$. This may reflect an age-related deficit for ignoring previously relevant information. However, the lack of interaction suggests that this cannot account for any processing rate differences observed.

General discussion

To date, studies into age-related differences in the rate of visual information processing have produced mixed findings. In a wide range of studies Ratcliff et al. (2006) analyzed two-alternative forced choice (2AFC) decision tasks using diffusion modeling and found limited evidence for an age-related difference in the rate of visual information processing. In contrast, using the TAF methodology to assess processing differences, Kliegl et al. (1994) found evidence of such a difference. In three studies we attempted to resolve these differences. Rather than using 2AFC tasks, we estimated the precision of participants' stimulus representations by asking participants to replicate the target orientations. Additionally, we used time accuracy function (TAF) methodology, which allows separate analysis of the processing speed and accuracy task elements and, thus, disambiguation of the core mechanisms underlying age-related deficits.

In Experiment 1, in which only a single stimulus had to be reported, little evidence was observed for age-related differences in the rate of processing. In contrast, as additional demands were introduced via presenting more objects that either needed to be processed online at object presentation (Experiment 2), or maintained until a postcue (Experiment 3), then age-related processing rates became evident. As Ratcliff et al. (2001, 2003, 2004, 2006, 2007) tended to use single objects or tasks that required assessment of a single

Parameter	Mean	SD	1	2	3	4	5	6	7	8
A										
Asymptote (λ)	33.57	3.68	30.65	31.80	35.66	33.79	35.78	35.65	38.08	27.41
Processing rate (β)	.00918	.00461	.01377	.00454	.00618	.00355	.00882	.00608	.00703	.00292
Take off (δ)	23.44	17.30	28.81	41.87	27.19	70.61	25.55	17.08	30.76	0.00
R^2	.93	.04	.94	.95	.95	.96	.89	.95	.89	.98
B										
Asymptote (λ)	28.81	4.22	24.50	34.23	33.82	29.09	22.10	30.34	25.14	30.20
Processing rate (β)	.00350	.00291	.00097	.00190	.01003	.00405	.00491	.00167	.00753	.00751
Take off (δ)	45.35	54.00	26.34	58.36	21.25	57.91	32.17	0.00	0.00	43.20
R^2	.96	.07	.99	.97	.71	.99	.98	.97	.96	.98

Table 6. (Continued)

dimension, while Kliegl et al. (1994) used tasks requiring processing the identity of multiple (four) display objects, the present findings help to resolve their previous, apparently contradictory findings. Accordingly, we have shown that processing rate differences are reliably observed only when participants are required to process information from multiple (two or four) objects.

Age differences in asymptotic performance levels

In all Experiments older adults displayed worse overall performance and in Experiments 1 and 3 showed lower asymptotic performance. A potential cause of this performance difference is an age-related vision deficit. This is unlikely because stimuli were suprathreshold, with high contrast, with spatial frequencies in the region at which there is peak sensitivity. Although older adults do show loss in contrast sensitivity, this is typically for higher spatial frequencies than the stimuli used in Experiments 1 and 3 (see Owsley, 2011). Indeed, in Experiment 2, older adults actually performed better on trials in which the highest spatial frequency was used (the "large difference" condition, see Figure 5B). Furthermore, research on visual working memory capacity shows that older adults can perform well at lower levels of task complexity, indicating that age related deficits observed are not simply due to visual impairment (Beigneux et al., 2007; Brown et al., 2012; Johnson et al., 2010).

Group	Asymptote (λ)	Processing rate (β)	1/β	Take off (δ)
Younger adults	33.46	0.00791	126	21.57
Older adults	26.20	0.00267	374	21.57

Table 7. Parameter estimates derived from model comparisons in Experiment 3.

Another possibility is that older adults found it harder to use the adjustment method to provide their response and thus gave up more easily. Although possible, the RT data seem to speak against this, as older adults took considerably longer in responding than younger adults, but did not specifically show long, large errors. Although older adults were generally slower, at least some of this slowness is probably due to them trading off speed for accuracy relative to younger adults, that is, choosing greater confidence in their responses at a cost of slowed RT (Ratcliff, 2008; Starns & Ratcliff, 2010). A further possibility is that slowing responses led to significant decay of the object representation in VSTM, resulting in worse overall performance. Again, the absence of long, large errors speaks against this. Indeed, other research has also suggested that age-related differences in sensory processing are not due to sensory memory decay (Fabiani, Low, Wee, Sable, & Gratton, 2006).

A further possibility is that older adults suffered from greater trial-to-trial interference, either from previous responses or with previously shown stimuli. The inhibition deficit hypothesis (Hasher, Lustig, & Zacks, 2007; Hasher & Zacks, 1988) suggests that older adults have difficulties inhibiting irrelevant information. Recent research has shown that older adults exhibit a specific deficit inhibiting activation of no-longer-relevant material, and declines in prefrontal cortex functioning may underlie such a cognitive deficit (e.g., see Braver & West, 2008, for a recent review). Thus, performance differences may reflect, at least in part, inhibition deficits rather than, or in

	Mean difference between response and distractor orientation
Younger adults	45.81
Older adults	44.23

Table 8. Mean difference between response and distractor orientation in Experiment 3.

Parameter	9	10	11	12	13	14	15	16
A								
Asymptote (λ)	32.79	33.85	39.67	31.34	33.63	31.66	26.71	38.67
Processing rate (β)	.01415	.01398	.01174	.00551	.01557	.00452	.01421	.01430
Take off (δ)	26.06	19.44	30.41	19.59	20.36	0.00	0.00	17.33
R^2	1.00	.88	.90	.93	.98	.93	.87	.96
B								
Asymptote (λ)	30.49	26.34	30.54	21.79	21.79	26.86	45.00	
Processing rate (β)	.00115	.00221	.00281	.00142	.00484	.00084	.00060	
Take off (δ)	0.00	109.30	0.00	4.52	79.60	191.32	56.28	
R^2	.94	.99	.99	.98	.98	.99	.95	

Table 6. Continued. Parameter estimates for young adults (A) and older adults (B) in Experiment 3.

addition to, processing speed differences. To examine this, Table 9 shows (a) the similarity of the response on trial *n* to the target stimulus on trial *n-1,* (b) the similarity of the response on trial *n* to the response on trial *n-1,* and (c) the similarity of the target on trial *n* to the target on trial *n-1*. A clear age effect was observed only for the similarity between responses on trial *n* to the response on trial *n-1*. Older adults were more likely to assimilate to previous responses than younger adults, that is, provide responses more similar to the orientation reported on the previous trial. To follow this up, for each experiment, a *t* test on each of these variables (a, b, and c as listed above) as well as overall mean precision was completed with age as the between-subjects variable. The effect of age on assimilation toward the previous response was significant for each experiment, Experiment 1: $t(33) = 2.12$, $p = 0.041$; Experiment 2: $t(31) = 3.13$, $p = 0.004$; Experiment 3: $t(29) = 3.41$, $p = 0.002$. To examine whether this greater assimilation was caused by older adults being more likely to reproduce their previous response specifically when they felt less confident, assimilation was calculated for different error bins (error bins of 15°). For each experiment a mixed ANOVA on response assimilation, with error size (six error bins) as the within-subject factor and age as the between-subjects factor, showed no interaction between age and error size. Thus, older adults experienced difficulty inhibiting their previous responses, but this was not related to confidence. This provides some support for the notion that older adults suffer from an inhibition deficit (Braver & West, 2008; Hasher et al., 2007; Hasher & Zacks, 1988), but specifically in relation to inhibiting previous responses rather than previously encoded stimuli. Importantly, the amount of assimilation by itself cannot explain the extent of the observed age differences in response precision because on 50% of trials, assimilating to the previous response would have led to smaller error sizes, while on 50% of trials it would have caused larger error sizes.

Having ruled out a variety of causes for the age-related differences in asymptotic performance, it seems likely that this difference reflects an age difference in the precision of representations. This is consistent with Noack, Lövdén, and Lindenberger (2012) who, in a

	Mean error	Stimulus similarity (*n, n-1*)	Similarity between response *n*, and stimulus *n-1*	Similarity between response *n*, and response *n-1*
Experiment 1				
Older	26.22	45.99	41.34	38.13
Young	22.12	45.18	41.34	41.35
sig.	*			*
Experiment 2				
Older	36.90	44.02	44.48	39.80
Young	31.26	45.28	44.88	44.83
sig.	*			*
Experiment 3				
Older	34.71	44.76	42.21	39.47
Young	26.39	45.04	42.94	44.29
sig.	*			*

Table 9. Sequential effects (errors and similarities in degrees). *indicates $p < 0.05$.

change detection paradigm, found that age effects on visuospatial STM are driven by an increase in the dispersion of stimulus representations and reduced overall capacity. Peich et al. (2013) also found that older adults had less precise representations than younger adults. Interestingly, in both studies, the observed age effects were greater under conditions of higher memory load (i.e., greater than 1). Although, in the Peich et al. (2013) study, precision differences were still observed with a single object to be remembered (see also Ko et al., 2013). They also found that older adults tended to erroneously misreport features of nonqueried items. Although we found some evidence for this in Experiment 3, the effect was slight and could not explain much of the overall age difference in precision. Neither Peich et al. (2013) nor Noack et al. (2012) examined the extent of trial-to-trial interference, which we show contributes towards performance differences.

Interpreting rate differences

In the above experiments differences in processing rate between older and younger adults were interpreted in terms of age related differences in the speed of visual information processing. An issue of concern is whether the TAFs estimated were influenced by additional factors, particularly the slower responding for older adults and eye movements. Each of these is addressed in turn.

Did slower responding by older adults influence the TAF function and thus estimates of processing rate? There are very good reasons to believe not. The methodology utilized enabled participants to replicate their representation of the target orientation without interrupting decision making. As such, the only factor limiting their performance was the rate at which they could process visual information when the stimulus was displayed and before it was masked. Although other procedures control RT by forcing participants to respond upon the onset of a signal (e.g., Guest & Lamberts, 2011; Kent, Howard, & Gilchrist, 2012) these tasks can easily be completed when RT is long, hence the need to interrupt decision making and force responding in order to produce a TAF function. That was not the case here or other studies using the TAF methodology in aging (Kliegl et al., 1994; Verhaeghen et al., 1997; Verhaeghen et al., 1998; see also Guest, Kent, & Adelman, 2015 for a nonaging example). Of course, delaying responding could lead to the stimulus representation decaying. However, not only was little evidence found for this, but such decay should consistently influence performance across all stimulus durations and thus not influence estimates of processing rate.

Nevertheless, in order to check that estimates of processing rates and RT were not related we entered the asymptote, processing rate and take off parameters from participants in all three experiments into a multiple regression analysis in order to predict mean RT. The regression overall was significant, $F(3, 95) = 6.14$, $p = 0.001$), with the model accounting for 16.2% of the variance in RT ($R^2 = 0.162$). Only the asymptote showed a significant relationship with mean RT, with increasing asymptote related to decreasing RT ($b = -6.68$, $p = 0.017$). In other words, participants who were better at the task overall responded quicker. There was no evidence that processing rate was significantly related to mean RT.

In an additional analysis, we modeled older and younger adult data for which RT was similar. For both older and younger adults, responses were split into quartiles based on their RTs. Taking the mean RT for quartile 1 (the fastest quartile) for older adults, a quartile for younger adults was selected that had the most similar mean RT. Mean error was derived from all the responses within these quartiles and then modeled. This approach collapses data across participants. Thus, to check that fitting such averaged data did not influence modeling outcomes, an additional analysis was completed in which, for each of the quartiles selected for comparison, the five adults who had the most frequent responses within that quartile were selected. These data were then modeled (data within the selected quartile only) for these adults (five older adults and five younger adults) simultaneously.

For Experiment 1, older adult quartile 1 (mean RT = 2108 ms) was compared with the younger adult quartile 3 (mean RT = 1951 ms). The best fitting model for the average data was $2\lambda\ 2\beta\ 1\delta$, with older adults showing a lower asymptote and slower processing. However, modeling the five older and five younger adults' data found the best model to be $1\lambda\ 1\beta\ 1\delta$, indicating no processing rate difference. Thus, as with the original analysis of the entire data set, it was inconclusive whether processing rate differed between older and younger adults. For Experiment 2 (older adult quartile 1 mean RT = 2391 ms, younger adult quartile 4 mean RT = 2575 ms) the best fitting model for the average data was $2\lambda\ 2\beta\ 2\delta$, with older adults showing a lower asymptote, slower processing, and a delayed take off relative to younger adults. Modeling the five older and five younger adults data found the best model to be $1\lambda\ 2\beta\ 1\delta$, matching the modeling analysis of the entire data set and crucially also showing slower processing for older adults. In Experiment 3 (older adult quartile 1 mean RT = 2637 ms, younger adult quartile 4 mean RT = 2603 ms) the best fitting model of the average data was, $2\lambda\ 2\beta\ 1\delta$, with older adults showing a lower asymptote and slower processing. Modeling the five older and five younger adults data found the best model to be 1λ 2β 1δ. Crucially, both modeling analyses showed slower processing rates for older adults. Overall then, even when controlling for RT, the modeling outcomes in respect of processing rates were the same, older adults showed slower processing in both Experiments 2 and 3.

A second issue was the extent to which eye movements may have differentially influenced performance for older and younger adults in Experiments 2 and 3. There was little evidence to suggest this was the case. In Experiment 3 both stimuli were equally relevant during stimulus presentation, so there was no reason to preferentially fixate on one. Differences in eye movements would also reflect differences in search strategy, however, as noted previously, serial search strategies are characterized by an S-shape TAF function (McElree & Carrasco, 1999) and such functions were not observed. Moreover, in both experiments eye movements could influence performance only after the 200 ms presentation duration at which point there would have been enough time to plan and execute a saccade. As can be seen, the data points for the two longest display durations do not deviate from the model predictions in which a similar process of parallel information accrual is assumed throughout the time course. To verify that the modeling outcomes were not dependent on the influence of eye movements, data were re-modeled using only the first five display durations (up to and including 200 ms). In both Experiments 2 and 3 this modeling showed that older adults had slower processing than younger adults.

Age differences in visual information processing

It has been suggested many times that age-related processing speed differences become more apparent when the number of concurrent operations increases (Salthouse, 1994, 1996). It is therefore possible that age-related visual processing speed differences manifest only in tasks in which the cognitive processing demands are more numerous, thus, increasing the number of individual operations that must be completed, and inflating the overall effect of processing speed deficits. Clearly, in comparison to Experiment 1, Experiments 2 and 3 required an increased number of basic operations. Experiment 2 required encoding of four objects, identifying the target and nontargets, and inhibiting the further processing of the nontargets. Experiment 3 required encoding of two objects, maintenance of these until the post cue, and inhibition of the noncued object. To compare the relative impact of these processes iso performance traces were

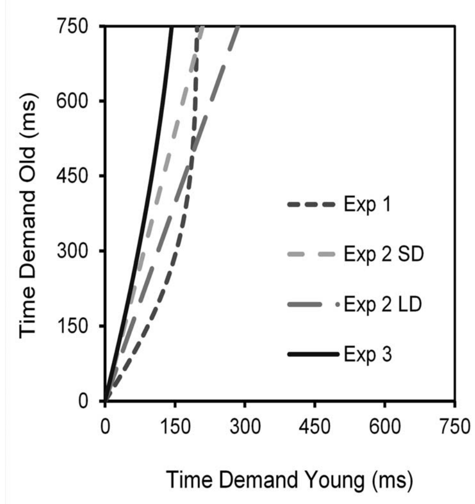

Figure 9. ISO performance traces for Experiments 1–3. NB: SD and LD refer to trials in which the target-distractor difference was small or large, respectively.

constructed (see Verhaeghen, 2000). These show the time required to reach equivalent performance between older and younger participants in each experiment. This required scaling reversed error from 0–45 (45 being most accurate) to 0–1 (1 indicating highest precision). The following formula (from Verhaeghen, 2000) can be used to determine the time (t) required to reach a particular level of precision (p) based on processing rate β and the asymptotic level of performance λ.

$$t = \beta ln(\frac{\lambda}{(\lambda - p)}), \tag{4}$$

Iso performance traces for all the Experiments are shown in Figure 9. The important feature is the linear aspect of these performance traces (a line begins to curve when one group simply cannot achieve the same level of performance as the other, regardless of time, due to differing asymptotic levels of performance). As is evident the time required for similar performance between the groups was least similar for Experiment 3. Importantly, the time taken for equivalent performance is influenced both by asymptotic and processing rate differences. In terms of processing rate, older adults show slowing by a factor of 2.97 in Experiment 2 and 2.96 in Experiment 3. The relative slowing of processing was therefore similar between Experiments 2 and 3 even though there were half as many stimuli in Experiment 3, suggesting that per item, increasing the processing demand via the number of object representations to be encoded for temporary storage (Experiment 3) impacts older adults more than increasing the number of nontarget objects that need to be dismissed online (Experiment 2). In terms of the number of operations, arguably Experiment 2 has more operations than Experiment 3, because it required processing of more dimensions (spatial frequency and orientation) across more objects and then using this information to select the target and ignore the nontargets.[1] Clearly, however, it is the nature of the operations that are important, with the rate of visual processing for older adults being as severely reduced when having to process and maintain two object representations in working memory as when searching through four.

This latter interpretation is of interest in relation to the literature on change detection and aging. Change detection has been used extensively in order to assess working memory capacity and the processes that may underlie the decline in working memory observed for older adults (Chen, Hale, & Myerson, 2003; Myerson, Emery, White, & Hale, 2003). In particular, a recent focus has been on the impact of irrelevant information, either from other objects or from irrelevant dimensions. This relates to our Experiment 2 insofar as this involved selecting an object based on an otherwise irrelevant dimension and then ignoring irrelevant nontargets. Zhang, Shen, Tang, Zhao, & Gao (2013) measured the extent to which children, younger adults, and older adults were able to ignore irrelevant features of stimuli. In their visual working memory task color information needed to be encoded for 2 or 4 objects while irrelevant shape changes in the stimuli needed to be ignored. Although older adults had reduced visual working memory capacity compared to younger adults, they seemed as able as younger adults to ignore irrelevant features of stimuli. This may partly explain why, despite having to process more dimensions in Experiment 2 than in Experiment 3, the age-related deficit in processing rate was similarly severe.

Conversely, age does appear to influence how distracting objects are dealt with. Sander, Werkle-Bergner, and Lindenberger (2011) used a change detection task in which distracters were defined by one feature (shape) and participants attempted to detect changes in another feature (color) in a set of targets (analogous to our Experiment 2). The effect of distractors on performance was greater for older adults. Similarly Gazzeley and colleagues (2005, 2008), have reported age-related difficulties in ignoring irrelevant stimuli. In their experiments, photos of faces and scenes were shown sequentially, and participants had to detect whether either a face or a scene matched the previously presented faces/scenes. Results suggested that older adults found it harder to gain control of the visual input by engaging top-down modulation mechanisms during working memory encoding. However, this was the case only in the early stages of processing such that irrelevant information was initially attended, but then inhibited later in processing. They suggested that this accounts for some of the processing speed deficit observed in older adults. Similar findings have been shown in the time course of perceptual filtering, in which, during a retention interval for a memory display, older adults tend to filter our distractors later in processing compared to younger adults (Jost et al., 2011).

Taken together, these findings in change detection paradigms help explain why an age-related deficit in processing speed was more readily observed in Experiment 2 compared with Experiment 1. Clearly, any delay in inhibiting nontargets for older adults would contribute to slower processing of target information. Nevertheless, our finding that the age-related deficit in processing speed is similar in Experiments 2 and 3 but that the time to reach equivalent performance is greater in Experiment 3 suggests that a reduction in the ability to suppress the processing of, or filter out, non-targets, is not the major contributor of performance differences in the literature for older adults. Adding a single additional item in Experiment 3 had a similar impact to adding three additional items in Experiment 2, suggesting that having to *process and maintain* multiple object representations in working memory has a greater effect than distractor filtering on the rate of visual information processing. One explanation for this is that older adults have reduced working memory capacity (e.g., Chen et al., 2003) and if this resource can be flexibly allocated (Bays & Husain, 2008; Bays, Gorgoraptis, Wee, Marshall, & Husain, 2011, although see Zhang & Luck, 2008) then reduced resources will lead to slower encoding into working memory. That is, slower encoding is the result of a reduction in capacity. Speaking against this is that in Experiment 3 only two objects required processing, which seems likely to be within resource limits, and the age difference in asymptotic performance was similar in Experiment 1 (one object) to Experiment 3 (two objects), suggesting memory capacity was not exceeded in either experiment. Another explanation is that the slower processing was the result of attention capacity limits. There is evidence for age differences in attention capacity in older adults (for a review, see Zanto & Gazzaley, 2014) and evidence that attention is a flexible resource (Alvarez & Franconeri, 2007; Howard & Holcombe, 2008), with reductions in the fidelity of processing even when required to attend to two objects relative to just one. Thus, older adults may presently have suffered from a greater reduction in available attentional resources per object than younger adults when the load is increased from one to two objects. Crucially, though, the age-related processing rate difference was equally severe in Experiment 2 and Experiment 3, yet Experiment 3 was arguably less attentionally demanding than Experiment 2 (i.e., fewer objects and features requiring attention). In Experiment 2, older adults therefore appear to have benefited from the ability to filter out nontargets and spatial frequency information at the encoding stage, once the target had been identified. In contrast, age-related reductions in attentional capacity become problematic when the information is required to be encoded into visual working memory. That older adults' reduced processing speed is more prevalent when demands are placed on visual working memory complements previous research showing that, out of a variety of measures, visual working memory capacity is best predicted by processing speed (Brown et al., 2012).

Conclusion

Across three experiments a possible age-related deficit in the rate of visual information processing was examined. A deficit was observed primarily when multiple objects were involved in the display, reconciling findings reported by Ratcliff and colleagues (e.g., Ratcliff et al., 2006) that showed no age-related differences in the speed of visual information processing with tasks using single stimuli, with those from Kliegl et al. (1994) that showed age-related slowing of visual information processing in a task with multiple stimuli. Importantly, the methodology utilized here allowed for fine grained measurement of individuals' representations of stimuli. Furthermore, TAF modeling enabled the independent measurement of visual processing rates, separated from influences of absolute performance and onset of processing. The simple cases of attending to a single feature, or to one or two objects in the presence or absence of nontargets, were examined. Taken together, these provided a systematic assessment of age-related differences in the rate of visual information processing across a variety of circumstances. Notably, the age-related deficit in visual information processing was influenced greatly by adding a single additional object to be encoded into visual working memory, supporting the notion that visual working memory is particularly age-sensitive (Beigneux et al., 2007; Brown et al., 2012; Jenkins et al., 2000; Johnson et al., 2010).

Interestingly, we also provided evidence for an executive component to the age-related declines observed presently, in that older adults were biased towards responding more similarly to the response in the previous trial and, thus, may suffer from an inhibition deficit (Braver & West, 2008; Hasher et al., 2007). Somewhat surprisingly, evidence for this deficit in trial-to-trial response inhibition was much greater than evidence for problems with inhibiting either previous stimulus information or information from other stimuli within the same trial (Experiment 3).

These findings have particular applied implications when the processing of multiple objects is key, particularly those requiring encoding of information into working memory. For example, research has linked age-related differences in visual perception task performance with driving performance (e.g., Owsley, 2013; Sekuler, Bennet, & Mamelak, 2000). Future work examining the relation between the present findings and more applied tasks is therefore warranted.

Keywords: information processing speed, inhibition deficit, speed-accuracy trade-off, cognitive aging, visual memory

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Footnote

[1] The difference in iso performance traces between Experiment 2 and 3 also indicates that performance in Experiment 2 reflects the ability to inhibit the processing of nontarget items while they were displayed. If this inhibition had been completed after stimulus offset, then iso performance traces similar to that in Experiment 3 would have been observed (or even steeper given the larger number of objects).

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