Early age-related decline in the effective number of trajectories tracked in adult human vision

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Human performance in many visual and cognitive tasks declines with age, the rate of decline being task dependent. Here, we used a multiple-object tracking (MOT) task to provide a clear demonstration of a steep cognitive decline that begins relatively early in adult life. Stimuli consisted of 8 dots that moved along linear trajectories from left to right. At the midpoint of their trajectories, a certain number of dots, *D* (1, 2 or 3), deviated either clockwise or counter-clockwise by a certain magnitude (57°, 38° or 19°); the task for observers was to identify the direction of deviation. Percent correct responses were measured for 22 observers aged 18–62 years and were converted to *effective numbers of tracked trajectories* (*E*) (S. P. Tripathy, S. Narasimhan, & B. T. Barrett, 2007). In 5 of the 7 conditions tested, there was a significant negative correlation between age and *E,* indicating an age-related decline in tracking ability. This decline was found to be equivalent to a mean performance drop of 16% per decade over the four decades of adulthood tested. Further analysis suggests that performance in this task starts to decline at around 30 years of age and falls off at the rate of approximately 20% every subsequent decade.

Keywords: multiple-object tracking, aging, tracking, attention, memory, working memory, psychophysics

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Introduction

It is well known that humans show an age-related decline in a number of basic visual capabilities, including visual acuity, spatial and temporal contrast sensitivity, and various aspects of motion perception (for reviews see Faubert, 2002; Spear, 1993). There is also evidence that various higher-level cognitive abilities suffer from a reduction with age. These include working memory (e.g. Jenkins, Myerson, Joerding, & Hale, 2000; Rypma & D'Esposito, 2000) and certain types of attention (e.g. Madden, 2007). In a society in which the aging population has been steadily increasing, such findings are potentially very important, as they highlight difficulties that may be experienced by older adults when performing many day-to-day tasks.

One perceptual task involving higher-level cognitive functions is that of multiple object tracking (MOT, Pylyshyn & Storm, 1988), in which several moving targets have to be tracked simultaneously. This paradigm is of particular interest, as it resembles various everyday tasks in which multiple objects must be tracked, such as playing, refereeing or watching various team sports, driving in heavy traffic, or crossing a busy street. Since the original findings of Pylyshyn and Storm (1988), several models have been proposed to account for the results of MOT studies, all of which invoke attentional mechanisms (for a review see Alvarez & Franconeri, 2007; Cavanagh & Alvarez, 2005). Also, more recently, it has been suggested that working memory may play a role in MOT (Allen, McGeorge, Pearson, & Milne, 2006). Given that both attention and working memory may be affected by age it is reasonable to expect performance in MOT tasks to also show an age-related decline.

This issue has been addressed to some extent by Trick, Perl, and Sethi (2005), who showed that in an MOT task young observers (mean age = 19 years) were able to track a greater number of objects than those in an older age group (mean = 73 years). Recently, this finding has been confirmed by Sekuler, McLaughlin, and Yotsumoto (2008). However, this still leaves important questions unanswered regarding the nature of the relationship

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between age and performance in MOT tasks. For example, is there a continual reduction in ability with increasing age, or does performance remain stable until a certain age and then drop in later adulthood? If the decline is continuous then at what rate does performance reduce? If performance is not affected in early adulthood, what is the critical age at which degradation in performance starts? This critical age may have important consequences for some jobs such as air-traffic controllers and pilots. The aim of this study was to address these issues directly by measuring performance in an MOT task in adults of varying ages.

The MOT task in the current study is the same as the deviation detection task used in Tripathy et al. (2007) and is different from the traditional MOT paradigm of Pylyshyn and Storm (1988). The choice of paradigm was influenced by the following considerations:

i. The paradigm used by Tripathy et al. (2007) is useful whether the number of trajectories tracked is small, or large. Observers' performance can be measured and compared even when as many as 10 or 12 trajectories have to be tracked.
ii. The theoretical basis underlying performance in the Tripathy et al. (2007) paradigm has been carefully elaborated in Narasimhan, Tripathy, and Barrett (2009), whereas the explanations proposed for the Pylyshyn paradigm are closer to descriptions of the data.

To anticipate, we found that the effective number of tracked trajectories (*E*) dropped very sharply with age over much of the age-range tested, showing that tracking performance in adults starts to deteriorate early in adulthood.

Methods

Observers

A total of 22 observers took part in these experiments (12 males and 10 females). The age range was 18 to 62 years (mean = 35.3 years; standard deviation = 13.0 years). All observers had normal or corrected-to-normal visual acuity of 6/6 or better in each eye and had no known existing or past visual abnormalities and no previous experience of participating in MOT experiments. Spectacle and contact lens wearers used their habitual distance correction. A majority of the observers were students or staff at the University of Bradford. All observers were naïve to the purposes of the experiment and all consented voluntarily to their participation, after the experimental procedure was explained to them.

Apparatus

Stimuli were generated on a Viglen Contender C300A personal computer and presented on a Gateway 2000 Vivitron 1776 monitor. The frame refresh rate of the monitor was 56.43 Hz (frame duration = 17.72 ms). The spatial resolution of the monitor was 800 × 600 pixels, with 798 × 574 pixels being used for stimulus display. The background luminance was 4.1 cd m^{-2}. Chin and forehead rests were used to minimize head movements and maintain a viewing distance of 127 cm. At this distance, individual pixels subtended 1′ × 1′. Normal room illumination was used to ensure that the persistence of trajectories on the screen could not be used as a cue to the task.

Stimuli

The stimuli were a subset of those described in Tripathy et al. (2007) and Tripathy and Levi (2008). In each presentation, 8 dots moved on linear trajectories across the monitor screen from left to right at a speed of 3.76 deg s^{-1}. Each dot subtended 5′ × 5′ and had a luminance of 61.9 cd m^{-2}. The choice of dot speed and dot size ensured that the motion of the dots was perceived to be smooth at the frame rate used. At the vertical midline of the screen, indicated by two markers, the trajectories of a certain number of dots, *D* (1, 2 or 3), deviated either clockwise (CW) or counter-clockwise (CCW) by a certain magnitude (57°, 38° or 19°). The *D* = 3 condition was only tested for deviations of 19°. Tripathy et al. (2007; Figure 9) found that when the angle of deviation and the number of deviating trajectories (*D*) were both large, the average orientation of the trajectories in the two halves of the screen could provide cues to the direction of deviation. In addition, for these conditions, performance can approach 100% correct; this ceiling is not ideal when one is interested in measuring changes. For these reasons the *D* = 3 condition was not tested when the deviation was 57° or 38°. The magnitudes of deviation used in this study are all substantially suprathreshold, i.e. much larger than the threshold for detecting a deviation in a single trajectory (Tripathy & Barrett, 2004). When *D* dots deviated, the trajectories of the remaining (8 − *D*) dots did not deviate. In any trial, all deviations were in the same direction and had the same magnitude and, in any block, 50% of the trials showed CW deviations. Stimuli were presented for 51 frames (904 ms). All trajectories reached the midline of the screen at the same time (i.e. on frame 26). A typical stimulus presentation is depicted schematically in Figure 1, showing 2 out of 8 trajectories deviating CCW by 38°.

Each trajectory was initially oriented randomly within ±80° of horizontal, thereby reducing the chance that two or more trajectories would run parallel to one another. The starting point for each trajectory was chosen so that at the

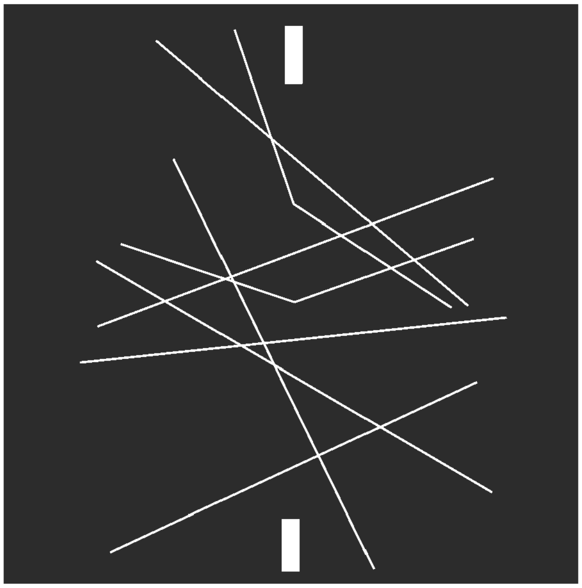

Figure 1. Schematic of typical stimulus presentation. Each white line represents the trajectory of a moving stimulus dot. Dots moved from left to right at a speed of 3.76 deg s^{-1} and there were a total of 8 trajectories. At the midpoint of their trajectories (white vertical markers) a certain number of dots, *D* (here 2), deviated either clockwise (CW) or counter-clockwise (CCW) by a certain magnitude (here CCW by 38°).

midline of the screen, where deviations occurred, all dots were vertically aligned. Additionally, while trajectories were allowed to intersect, the mean vertical distance between dots at the midline of the screen was 40′ (±5′), ensuring that trajectory-intersections did not occur too close to the points of deviation.

The number of deviating trajectories (*D*) and magnitude of deviation were fixed within a block of trials, but varied between blocks. Observers were aware that deviations would occur only at the screen midline and their task was to indicate whether the deviations were CW or CCW. Viewing was binocular. Observers were not directed to fixate any particular point on the screen but were encouraged to adopt an eye-movement strategy that they felt might help them best perform the task. Feedback was given as to the correctness of each response in the form of one of two audible tones. Each block of data collection involved 100 trials. For each combination of deviation magnitude and *D,* observers carried out a practice block. The seven practice blocks were followed by 21 further blocks of data collection. The data presented were obtained in three cycles of 7 blocks each, with each of the seven conditions tested in pseudo-random order within each cycle. The data collection was self-paced, with each cycle of seven blocks typically lasting slightly over an hour, but observers were permitted more time if needed. Results were expressed in terms of the percentage of trials on which deviation direction was correctly reported.

The effective number of tracked trajectories (*E*)

Percent correct responses of observers can be converted to effective numbers of tracked trajectories (*E*) using the concept of a limited capacity hypothetical observer (LCHO). This process has been described in detail elsewhere (Tripathy et al., 2007), but the basic concept can be outlined as follows. Firstly, it is assumed that this hypothetical observer has a limited amount of tracking resources available and that these resources are distributed among the maximum number of trajectories that can be tracked perfectly (*A*). Next, since all deviations are substantially supra-threshold, it is assumed that the direction of deviation will be correctly identified if any of the deviating trajectories (*D*) are among those that are tracked. Given any total number of trajectories (*T*), the predicted performance of the LCHO (*P*) can then be described by the following equations based on simple probability:

$$P = 100 \quad \text{for} \quad (D > (T - A)), \tag{1}$$

$$P = 100 \times \left[\left\{ 1 - \binom{T-D}{A} \Big/ \binom{T}{A} \right\} + \left\{ \binom{T-D}{A} \Big/ \binom{T}{A} \right\} \Big/ 2 \right] \quad \text{for} \quad (D \leq (T - A)). \tag{2}$$

where $\binom{x}{y}$ represents the different ways of selecting *y* items from *x* available items.

Equation 1 states that performance will be perfect when $D > (T - A)$, as the *A* trajectories allocated resources will contain at least one deviating trajectory. In Equation 2, the first expression within the double braces represents the probability that the *A* tracked trajectories will contain at least one deviating trajectory, and the second expression represents the probability of correctly guessing the direction of deviation when there is no deviating trajectory among the *A* that are tracked.

Using these equations, a plot can be made that shows how predicted performance varies with *D* for various values of *A* when $T = 8$ (Figure 2). For example, if 2 trajectories can be tracked ($A = 2$) and 2 of the 8 trajectories deviate ($D = 2$) then the predicted performance would be 73%. The effective number of tracked trajectories (*E*) is defined as the number of trajectories that must be tracked perfectly by the LCHO in order to match the performance of a human observer. This can be calculated from the human observer's proportion of

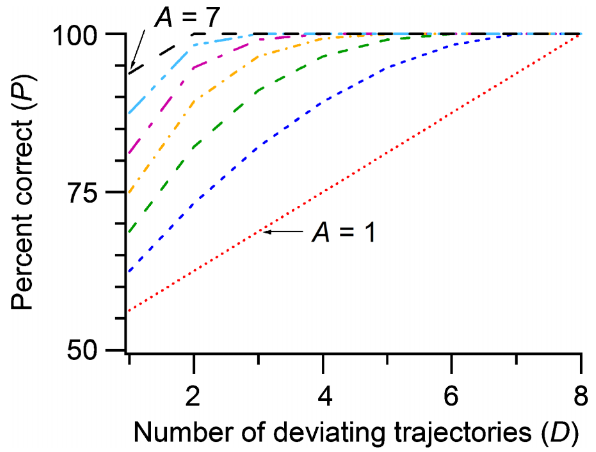

Figure 2. Predictions for a limited capacity hypothetical observer (LCHO). Equations 1 and 2 can be used to predict performance for an LCHO that accurately tracks A out of the 8 trajectories. (See text and Tripathy et al., 2007, for further details). The plot shows how predicted performance varies with the number of deviating trajectories (D) for various values of A when 8 trajectories are displayed. For example, if 2 trajectories can be tracked ($A = 2$) and 2 trajectories out of 8 deviate ($D = 2$ and $T = 8$) then the predicted performance would be 73%. Given actual percent correct performance levels, it is possible to interpolate between these curves to derive effective numbers of tracked trajectories (E) using these predicted values.

correct responses for any value of D by interpolating between the curves in Figure 2. The procedure used for interpolation has been explicitly described in Figure 5 of Tripathy et al. (2007). The advantage of this metric is that E permits comparison of performance across different conditions since it takes into account the increased probability of detecting a deviation when there are many deviating trajectories. For example, 80% correct when $D = 2$ may not be better performance than 75% correct when $D = 1$. Indeed, Tripathy et al. (2007) showed empirically that while E is an increasing function of the deviation angle, it is largely independent of D.

Results

Percent correct responses were measured for each observer for various combinations of deviation magnitude and D, and least-squares regression was used to fit a straight line to each data set. For each condition, values of Pearson correlation (r) were calculated and were tested for deviations from zero (Bobko, 2001, pp. 44–47). Figures 3a and 3b show the relationship between percent correct responses and age for deviations of ±57° and ±38° respectively, when 1 (red circles, dashed lines) or 2 trajectories (blue squares, dotted lines) out of 8 deviated. Percent correct responses are generally higher for $D = 2$ compared to $D = 1$, but for all conditions performance decreases systematically with age. In each case, the correlations were significantly negative (57° deviations: $r = -0.465$, $p = 0.0292$ for $D = 1$ and $r = -0.551$, $p = 0.0078$ for $D = 2$; 38° deviations: $r = -0.666$, $p = 0.0007$ for $D = 1$ and $r = -0.521$, $p = 0.0129$ for $D = 2$), with a steep decline in performance with increasing age. Figure 3c shows percent correct responses and regression lines for

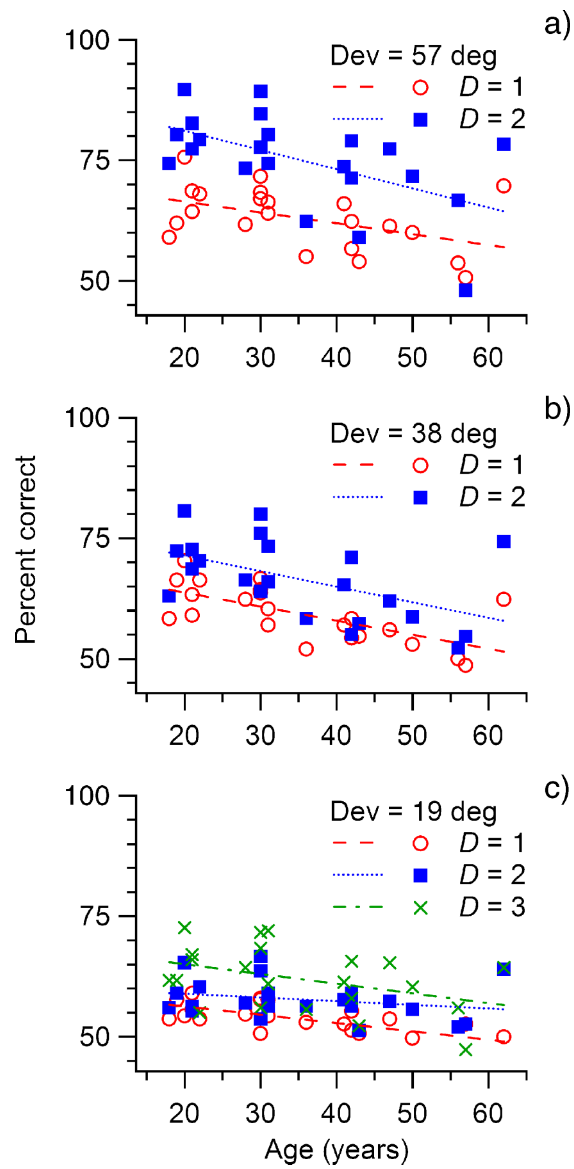

Figure 3. Percent correct responses. Panels (a), (b) and (c) show percent correct responses as a function of observer age for deviations of 57°, 38° and 19°, respectively. Data and regression lines are shown for $D = 1$ (red circles, dashed line), $D = 2$ (blue squares, dotted line) and $D = 3$ (crosses, green line, panel (c) only). For all data shown in panels (a) and (b) and for the $D = 1$ condition in panel (c), there is a significant negative correlation between percent correct and age (see text). For the $D = 2$ and $D = 3$ data in panel (c) the correlations are negative but not significantly different from zero.

deviations of 19°. Analysis shows that for D = 1 (red circles, dashed line), there is a significant negative correlation between percent correct and age (r = −0.671, p = 0.0006). However, for D = 2 (blue squares, dotted line) and D = 3 (green crosses, dash-dot line), although the correlations are negative, they are not significantly different from zero (r = −0.247, p = 0.267 for D = 2 and r = −0.406, p = 0.0608 for D = 3).

Percent correct responses were next converted to effective numbers of tracked trajectories (E) and the data were re-plotted in terms of E rather than percent correct (Figure 4). Plotting the data in this way causes a clear overlap of the data for different values of D. Values of E range from 0 to 4.18 for deviations of ±57° (Figure 4a), from 0 to 3.25 for ±38° (Figure 4b) and from 0 to 1.44 for deviations of ±19° (Figure 4c). Again, regression lines were fitted to the data and again, for deviations of 57° and 38° there is a significant negative correlation between age and E for all four combinations of D and deviation magnitude (57° deviations: r = −0.465, p = 0.0293 for D = 1 and r = −0.543, p = 0.0090 for D = 2; 38° deviations: r = −0.661, p = 0.0008 for D = 1 and r = −0.494, p = 0.0196 for D = 2). As before, for deviations of 19°, the correlations are significantly negative for D = 1 (r = −0.657, p = 0.0009) but not for D = 2 (r = −0.236, p = 0.290) or D = 3 (r = −0.388, p = 0.0745). Potential reasons for this are discussed later.

The regression slopes in Figure 4 indicate that E reduces at a rate of 0.36 (D = 1) and 0.41 (D = 2) trajectories per decade for deviations of ±57°, and 0.46 (D = 1) and 0.27 (D = 2) trajectories per decade for deviations of ±38°. Compared to mean performance levels of an 18 year old (as estimated from the regression lines), these figures are equivalent to reductions in performance of 13%, 14%, 20% and 15% per decade respectively, or an average performance drop of 16% per decade over the four decades of adult years tested.

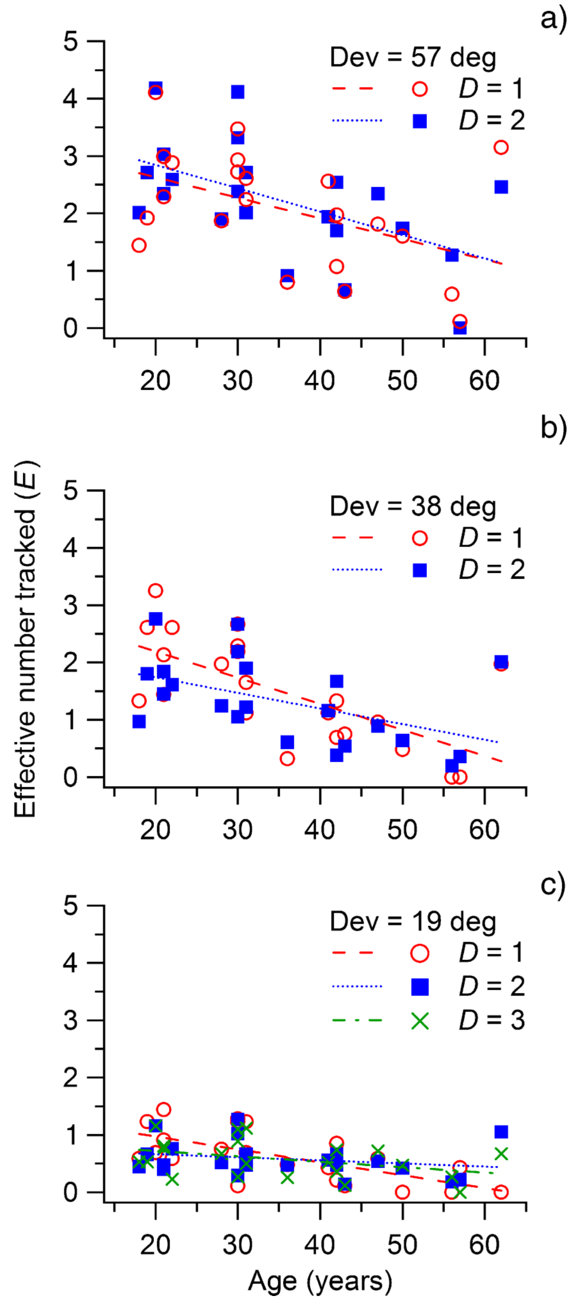

Figure 4. Relationship between age and effective number of trajectories tracked (E). The data from Figure 3 are re-plotted in terms of E rather than percent correct responses. For deviations of 57° (a) and 38° (b) there is a significant age-related decline in tracking ability for each combination of D and deviation magnitude (see text). However, for deviations of 19° (c), the age-related decline in tracking ability is statistically significant for D = 1 but not for D = 2 or D = 3.

Discussion

Rapid age-related decline in tracking

We measured performance in an MOT task over a wide range of ages and showed that, for 5 of the 7 conditions tested, there is a significant age-related decline in the number of trajectories that can be tracked (E). This age-related decline in E is, therefore, a robust, reliable effect. In the 2 conditions where the age-related correlations did not differ significantly from zero, there may have been a floor effect; performance for young observers is already poor and the performance for older observers cannot drop lower than chance, i.e. E cannot fall below 0.

Our results are in line with the previous findings of Sekuler et al. (2008) and Trick et al. (2005), which also showed younger observers to be better at tracking multiple moving objects than older adults. However, these studies compared the performance of a group of young observers with that of an older group and, therefore, they do not make clear the exact nature of the relationship between age and performance (mean ages in these two studies were

19 and 20.6 years, respectively, for young observers and 73 and 75.3 years for older observers). The most significant result of the present study is that it highlights a steady and steep decline in tracking ability, which extends over most of adulthood.

We have used linear regression to fit our data and argue that there is a steep decline in performance that is present from a young age. The linear fit helps us visualize and quantify the steepness of the drop in performance with age. However, it is plausible that the decline in performance is small during early adulthood and steep in later years. The number of observers used does not permit us to address this possibility directly, but since data were collected in several stimulus conditions, it is possible to combine the data from some of the conditions in order to systematically study the relationship between age and the drop in tracking performance.

Visual inspection of Figures 4a and 4b suggests that performance drops rapidly over the age-range 28–62 years, but it is not obvious whether there is a drop in performance over the age-range of 18–31 years. Therefore, we decided to examine these two age ranges separately. In addition, we only selected the 57° and 38° deviation conditions, since in these conditions a reliable effect of age on performance was found. In order to be able to combine the data from the different stimulus conditions, we normalized the data, so that the mean for the effective number of tracked trajectories was 1.0. (For example, in the condition: deviation = 57°; $D = 1$, for the 12 observers in the 18–31 age range, the mean value of E was 2.62; to obtain the normalized E for this condition, each value of E was divided by 2.62.) Figure 5a shows the normalized effective number of tracked trajectories in all four conditions as a function of age for observers aged 18–31 years. Data for observers in the age-range 28–62 years were similarly normalized and plotted in Figure 5b. Regression lines were fitted to the two sets of data. For the younger set of observers the correlation with age was not significantly different from zero ($r = -0.01$; $p = 0.94$) and the slope of the regression-line was 0.006 per decade. For the older set of observers the correlation was significantly different from zero ($r = -0.473$; $p = 0.00008$) and the slope was 0.255 per decade. From the fits in Figures 5a and 5b, the normalized effective number of tracked trajectories for an 18-year-old observer is 1.004 and that for a 28-year-old observer is 1.332 (this is greater than for the 18-year-old observer because of separate normalization of the data for the two age-groups). Compared to these baselines the drop in performance is 0.6% per decade over the 18–31 year-range and 19.2% per decade for the 28–62 year-range. Our data suggest that the age-related decline in tracking performance is very small or non-existent in adults younger than 30 years, but drops off very steeply, at almost 20% per decade over the 30–60 year-range.

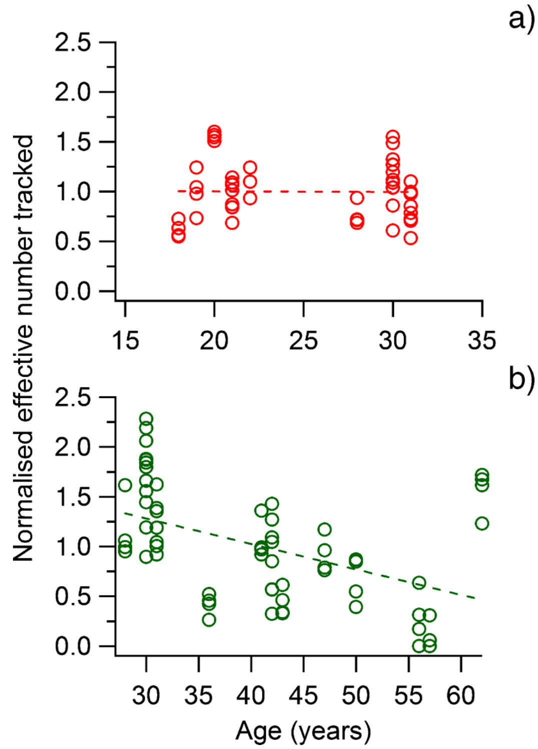

Figure 5. Effect of age in younger/older observers. Four of our data sets for effective number of trajectories tracked (E for deviation = 57°: $D = 1$ and 2, and for deviation = 38°: $D = 1$ and 2) were normalized so that each of the 4 data sets had a mean E of 1.0 (see text) and the normalized Es were plotted as a function of age, for observers aged: (a) 18–31 years, and (b) 28–62 years. In each panel a line was fitted to the combined data set. The correlations were not significantly different from zero in panel (a) but were very significantly negative in (b). Note that the data in (a) and (b) were normalized *separately.*

Tracking v change detection

One could claim that the current paradigm is not really a tracking paradigm, but rather a change detection paradigm, i.e. that the critical feature is the change occurring between frames 25 and 27, and the remaining frames of the 51 frame sequence are not relevant to the task. Age-related deficits in change detection have previously been reported (e.g. Veiel, Storandt, & Abrams, 2006), and it could be argued that the age-related deficits reported here have a similar origin. However, arguments against such a claim are:

i. Tripathy and Barrett (2004) measured deviation thresholds for single-trajectory stimuli as a function of the number of frames presented; deviation thresholds varied systematically with the number of frames in the stimulus even when the number of frames exceeded 15 (see their Experiment 1,

Figure 2a). It is likely that at least 15–20 frames are utilized when tracking a single item and many more frames when multiple items are to be tracked. (Also see Hohnsbein & Mateeff, 1998, for the minimum time that a deviation must persist in order to be detected.)

ii. Using similar stimuli, Tripathy and Barrett (2006) showed that even when the central part of the trajectories are occluded by having the deviation occur within the blind spot of the observer, observers can report the deviation of the target trajectory as well as the perceived path of the moving target dot. Reporting the perceived path of the target dot requires tracking the target dot.

iii. Kanai, Sheth, and Shimojo (2007), using stimuli undergoing linear motion, showed that transients in the stimulus occurring within the first 200 ms of motion onset were more easily detected than transients occurring after more than 300 ms following motion onset, suggesting that longer sequences were "perceived as single, indivisible gestalt integrated over space as well as time" (p. 937). The duration of our stimuli was well in excess of 200 ms.

For these reasons we believe that a substantial portion of the trajectories, well beyond the few frames around the point of deviation, influence the measured thresholds. In fact, Narasimhan et al. (2009) report that the persistence of the trajectory traces in sensory memory plays a critical role in determining deviation thresholds (also see Suganuma & Yokosawa, 2006).

Capacity limits in multiple-object tracking

One topic of debate in the tracking literature has been whether the maximum number of objects that can be tracked simultaneously is fixed (e.g. Pylyshyn & Storm, 1988) or whether the resources available for tracking can be allocated in a flexible manner, depending on the difficulty of the task (e.g. Alvarez & Franconeri, 2007; Tripathy et al., 2007). Our finding that values of E generally increase with deviation angle (see Figure 4) is in agreement with the latter proposal, i.e. the more difficult the task, the fewer the number of trajectories that can be tracked.

In order to demonstrate this point more clearly, mean values of E for each observer, averaged across different values of D, were calculated for each magnitude of deviation. Regression lines were fitted to these values and are shown in Figure 6. That the lines are separated and non-overlapping highlights that the main factor affecting performance in this task is the angle of deviation. This, along with the fact that plotting the data in terms of E rather than percent correct collapses together the data for different values of D (Figure 4), indicates that, for each deviation magnitude, there is a distinct capacity limit to the number of trajectories that can be tracked, and this

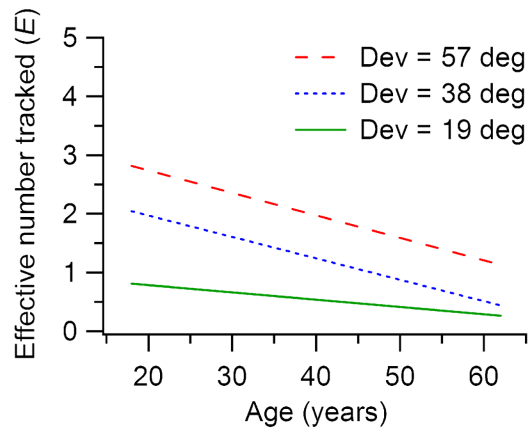

Figure 6. Mean values of *E,* collapsed across different values of *D,* for each magnitude of deviation were calculated for each observer and regression lines fitted to these values. This highlights that the number of trajectories that can be tracked simultaneously is limited by the magnitude of deviation.

limit is independent of D (Tripathy et al., 2007). Note, however, that this independence is an approximation, as can be seen from the slightly different slopes seen in the fits for the two values of D in Figure 4b.

Aging and low-level visual functions

We next consider whether our results can be explained in terms of an age-related decline in various basic visual capabilities, namely visual acuity, temporal integration, and motion direction discrimination. Visual acuity shows a characteristic reduction with age (Elliott, Yang, & Whitaker, 1995; Weymouth, 1961). Also, because no additional refractive correction was used to compensate for the working distance of 127 cm (observers wore their distance correction), presbyopic observers may have been blurred by up to 0.79 dioptres. Is it possible that reduced visibility of the stimuli in older observers could have contributed to the observed reduction in performance? This seems unlikely, for the following reasons. Firstly, all of our observers had monocular Snellen acuities ranging from 6/4 to 6/6. In an observer with 6/6 acuity, blurring the image by 0.79D should only reduce the visual acuity to approximately 6/12 (Bennett & Rabbetts, 1984, p. 97; Tunnacliffe, 1984, p. 156), which is still significantly better than that required to discriminate individual stimulus dots. Secondly, spatial vision is known to be severely compromised in amblyopia (Levi & Klein, 1985; McKee, Levi, & Movshon, 2003), yet a recent study of MOT in amblyopic observers (Tripathy & Levi, 2008, see also Levi & Tripathy, 2006) has shown values of E to be, on average, only 15% lower in amblyopic eyes (i.e. equivalent to the reduction seen each decade in normal observers in the current study) compared to non-amblyopic, even though the acuity of the amblyopic eye of some observers was as much as 800% poorer.

The ability to track moving objects relies on the integration of visual information over time, and the temporal resolution of the visual system is known to reduce with age (Tyler, 1989). However, using experiments where observers had to identify shapes on the basis of dynamic texture information, Andersen and Ni (2008) have provided clear evidence that aging deficits in visual processing are not the result of reduced temporal integration and this is unlikely to explain our main result. Andersen and Ni (2008) did find a deficit in spatial integration in their older observers who had a mean age of 74.5 years (also see Willis & Anderson, 2000). However, as discussed above, even deep amblyopes, known to show both low-level and high-level deficits in spatial vision, show only minor deficits in our current task; thus deficits that are purely spatial are unlikely to explain the steep fall off in performance seen in our older observers.

A further prerequisite for the current task is the ability to compare the pre- and post-deviation motion direction of the stimulus dots. Using dynamic random-dot patterns, Bennett, Sekuler, and Sekuler (2007) have shown that older observers are less accurate in judging motion direction than younger observers. However, they found no evidence for a progressive decline throughout adulthood; an aging effect was only apparent in their oldest group of observers (aged 70–81 years). Given that our oldest observer was aged 62 years, a loss of accuracy in judging motion direction is unlikely to have contributed to the progressive decline in tracking ability seen in our experiments. In general, we are not aware of any low-level visual function that shows as rapid a decline in performance with age as that seen in our current task. This suggests that the deterioration of performance seen here may reflect age-related deficits in the functioning of high-level processes.

Aging and high-level functions

It was discussed earlier that performance in MOT tasks may be mediated by mechanisms of visual attention (Alvarez & Franconeri, 2007; Cavanagh & Alvarez, 2005) and visual working memory (Allen et al., 2006), and that both of these may be subject to an age-related decline. Like previous studies of aging and MOT, investigations of the effects of age on attention and working memory have often compared performance between a young group and an older group (e.g. Jenkins et al., 2000; Rypma & D'Esposito, 2000), rather than measuring performance across a wide age range. The implication of the current study is that if, indeed, MOT is mediated by attention and working memory, then one, or both of these may also show a steep decline beginning early in adulthood. This could have further implications for other tasks that involve attention and memory.

Narasimhan et al. (2009) showed that in the current task it is the persistence of the trajectory-traces in sensory memory that limits the number of trajectories that can be tracked. If the traces persist for a few hundred milliseconds, then that duration limits the number of trajectories that can be processed before the traces decay to the point that they no longer provide useful information to the tracking process. According to the sensory memory explanation for MOT, the performance decline in aging described here would be a consequence of either a persistence of sensory memory declining continuously with age, or a continuous slowing down of the computational processes involved, so that fewer trajectories are processed in the time available.

It is possible that it is not the persistence of the traces that is changing so dramatically with age, but the speed at which these traces are processed; with slower processing, fewer trajectories can be processed within the duration for which the traces persist. Faubert (2002) suggests that aging affects on visual perception and working memory are more dramatic when the task performed is complex; in this review paper, simultaneous perceptual processing (a prerequisite for performing the tasks described in the current study) is viewed as an instance of complex perceptual processing. Therefore, we would infer from Faubert's paper that MOT would be severely compromised with age. Faubert's reasoning is as follows: simple tasks involve simple neural machinery, which, if compromised by age, can be compensated for by alternate neural networks; complex tasks involve complex neural machinery, which, if compromised by age, cannot be compensated for by alternate neural machinery (also see Habak & Faubert, 2000). Applied to the current study, tracking deteriorates with age because the complex neural machinery involved is degraded, possibly resulting in the recruitment of slower, or less accurate, alternate neural machinery. Degradation of cortical machinery with age, resulting in reduced orientation and direction selectivity, and in increased neural latency, have been reported in V1 and V2 of monkeys and area 17 of cats (Hua et al., 2006; Wang, Zhou, Ma, & Leventhal, 2005; Yu, Wang, Li, Zhou, & Leventhal, 2006). This reduction in processing speed, or accuracy, could reduce the effective number of trajectories processed before the trajectory traces decay in sensory memory (Narasimhan et al., 2009).

Relation to brain imaging studies

Functional magnetic resonance imaging (fMRI) studies of cortical activity during MOT have reported strong activation of parietal and frontal areas, with parietal areas in particular showing a linear increase in activity with increasing number of targets to be tracked (Culham et al., 1998; Culham, Cavanagh, & Kanwisher, 2001; Jovicich et al., 2001). Other imaging studies report that older subjects show greater activity in frontal and parietal areas of cortex which could compensate for the reduced visual sensory input that occurs as a result of functional and structural decline in occipital brain regions (Madden, 2007; Madden et al., 2007). These studies also report potential disconnections of cortical areas as a result of decreased white matter with age. The age-related performance decline in the current task suggests that any potential increase in activity in frontal and parietal areas does not adequately compensate for the cognitive and functional decline with age.

Effects of expertise on tracking

One other factor that should be considered is the influence of expertise. It has been shown that video game playing leads to improved visual attention (Green & Bavelier, 2003; Riesenhuber, 2004). Additionally, Allen, McGeorge, Pearson, and Milne (2004) found that professional radar operators were better able to track multiple moving objects than were undergraduate students. It would be reasonable to assume that there are many other activities, professional and recreational, in which expertise may lead to improved tracking abilities, e.g. driving, participation in certain team sports, etc. In short, it is difficult to assemble a group of observers in which expertise in every task that might potentially influence tracking abilities is controlled for. It is plausible, therefore, that the decline in performance with age seen in our study at least partly reflects differences in the range of activities undertaken by adults of different age groups.

In summary, our results cannot be explained in terms of well known age-related declines in various low-level visual functions. Instead, we suggest that our findings may indicate a steep decline in higher-level cognitive functions involved in the tracking of multiple objects that begins around the age of 30.

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