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Sustained Attention, Attentional Selectivity and Attentional Capacity across the Lifespan

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Abstract

Changes in sustained attention, attentional selectivity and attentional capacity were examined in a sample of 113 participants aged between 12 and 75. To measure sustained attention, we employed the Sustained Attention to Response Task (Robertson et al., 1997), a short continuous performance test designed to capture fluctuations in sustained attention. To measure attentional selectivity and capacity, we employed a paradigm based upon the Theory of Visual Attention (Bundesen, 1990), which enabled the estimation of parameters relating to attentional selection, perceptual threshold, visual short-term memory capacity and processing capacity. There was evidence of age-related decline in each of the measured variables but the declines varied markedly in terms of magnitude and lifespan trajectory. Variables relating to attentional capacity showed declines of very large effect size while variables relating to attentional selectivity and sustained attention showed declines of medium-large effect size, suggesting that attentional control is relatively preserved in older adults. Variables relating to sustained attention followed a U-shaped, curvilinear, trend and variables relating to attentional selectivity and capacity showed a linear decline from early adulthood, providing further support for the differentiation of attentional functions.

Key words: Attention, Aging, Sustained Attention, Theory of Visual Attention

Sustained Attention, Attentional Selectivity and Attentional Capacity across the Lifespan

The study of cognitive aging has revealed that cognitive functions follow different trajectories across the lifespan. For example, crystallized intelligence or knowledge representations remain largely stable across the lifespan while fluid intelligence or cognitive processes, such as processing speed, working memory and long-term memory show a substantial decline across the lifespan, beginning in early adulthood and following a systematic, linear decline over the decades (Park, 2000). Atrophy of the brain (Raz, 2004; Raz & Rodrigue, 2006) is one factor that may underpin decline in cognitive processing with age but the relationship between brain atrophy and cognitive decline is still not well-understood (Cabeza, Nyberg & Park, 2005). One exception is the clear concordance between frontal lobe atrophy and the marked decline of executive functioning displayed by older adults (Park, 2000; Park, Polk, Mikels, Taylor, & Marshuetz, 2001; West, 1996). The frontal lobe hypothesis (West, 1996) proposed that cognitive processes supported by the prefrontal cortex would manifest decline at an earlier age and in greater magnitude than cognitive processes supported by non-frontal regions. This hypothesis subsumed earlier explanations of cognitive aging, which drew upon specific executive functions, such as attentional capacity (Craik & Byrd, 1982) or inhibition (Dempster, 1992; Zacks & Hasher, 1997), in order to account for the decline in cognitive function due to age. Alternative accounts of cognitive aging have suggested that more general or global mechanisms, such as slowed processing speed (Salthouse,

1996) or a general deterioration of neuronal integrity (Baltes & Lindenberger, 1997), mediate cognitive decline.

Attention is at the heart of this discussion of cognitive aging. As an executive control process that is supported in large part by the frontal lobes, it is a potential casualty of the aging process. As a fundamental cognitive process that influences other aspects of cognition, it may also act as a mediator of decline in other cognitive abilities, such as memory and reasoning (Craik, 2006). However, attention is a complex cognitive process and studies examining the effect of aging on various aspects of attention have yielded different conclusions.

Attention has been defined as a set of processes that enable “the maintenance of goal-directed behaviour in the face of multiple, competing distractions” (Parasuraman, 2000). Attentional ability has been characterised as having three main aspects, labelled as ‘executive attention’, ‘selectivity’ and ‘intensity’ (Parasuraman, 2000; Raz & Buhle, 2006; Sturm, 1996; vanZomeren & Brouwer, 1994). Studies investigating the effects of aging on executive attention, using tasks like dual task (Pashler, 1994) or task-switching paradigms (Rogers & Monsell, 1995) have shown that older adults have greater difficulty on these tasks compared to younger adults (Kramer, Scialfa, Peterson, & Irwin, 2001; Reimers & Maylor, 2005; Verhaeghen & Cerella, 2002). Investigations into the effects of age on the intensity aspects of attention have largely focused on sustained attention measured by vigilance tasks. These studies have produced inconsistent results, possibly due to the complexity of the vigilance tasks themselves (Davies & Parasuraman, 1982;

Rogers, 2000). One very large-scale study involving over 500 participants aged from 18-91, found little evidence of any age-related decrement in sustained attention ability, as measured by the Mackworth Clock Test, a 62-minute sensory vigilance task (Giambra & Quilter, 1988). Studies of the selectivity aspect of attention have employed visual search tasks (Treisman & Gelade, 1980) and visuospatial orienting tasks (Posner, 1980). Studies of visual search have revealed intact feature search but significantly slowed conjunction search in older adults (Trick & Enns, 1998). Studies of visuospatial orienting have suggested that the ability to covertly orient to visual stimuli remains intact in older adults following both endogenous and exogenous cues (Greenwood, Parasuraman & Haxby, 1993).

The purpose of the current study was to document changes in central aspects of attention, namely sustained attention, attentional selectivity and capacity, across the lifespan. Sustained attention, the ability to maintain alertness and focus over time, was measured using the Sustained Attention to Response Task (SART; Robertson, Manly, Andrade, Baddeley, & Yiend, 1997). The SART is a well-validated measure of sustained attention that has been found to be significantly correlated with self-reported everyday attentional slips in normal populations (Smilek, Carriere, & Cheyne, 2010), has proved useful in the detection of sustained attention deficits in clinical populations, such as people with head injury (McAvinue, O'Keeffe, McMackin, & Robertson, 2005) and ADHD (Johnson et al., 2007a) and has been related to activation of right hemisphere frontal-parietal regions thought to underlie sustained attention (Manly et al., 2003).

Visual selective attention is the ability to focus processing on relevant features and objects while ignoring irrelevant features and objects within the context of a limited attentional or processing capacity. To assess attentional selectivity and capacity, we employed a paradigm based upon the Theory of Visual Attention (TVA, Bundesen, 1990). The TVA was first proposed by Bundesen (1990) as a computational theory that provided quantitative accounts for a wide range of attentional effects reported in the psychological literature. At the heart of TVA were two equations and Bundesen, Habekost, and Kyllingsbæk (2005, NTVA) provided a neurophysiological interpretation of these equations. In NTVA, one of the two basic mechanisms of selective attention, *filtering* (selection of *objects*), changes the number of cortical neurons in which an object is represented so that this number increases with the behavioral importance of the object. Another mechanism of selection, *pigeonholing* (selection of *features*), scales the level of activation in neurons coding for a particular feature. By these mechanisms, behaviorally important objects and features are likely to win the *biased competition* (Desimone & Duncan, 1995) to become encoded into visual short-term memory (VSTM). The VSTM system is conceived as a feedback mechanism that sustains activity in the neurons that have won the attentional competition. NTVA accounts both for a wide range of attentional effects in human performance (error rates and reaction times) and a wide range of effects observed in single cells (firing rates) in the primate visual system (for an overview see Bundesen & Habekost, 2008; Kyllingsbæk, 2006).

TVA has laid the foundation for TVA based assessment of attentional functions, which has many advantages compared with conventional clinical tests of visual attention:

Performance is analyzed into separate functional components (*specificity*), the method can reveal deficits that go undetected by conventional clinical testing (*sensitivity*), the measurement error can be quantified and in most cases shown to be minor (*reliability*), and the measures that are obtained are not bound to the tasks used, but grounded in a general theory of visual attention (*validity*). In the pioneering study, Duncan, Bundesen, Olson, Humphreys, Chavda, and Shibuya (1999) showed how analysis of partial and whole report performance in terms of parameters defined by TVA enables a very specific measurement of attention deficits in visual neglect patients (see also Bublak et al., 2005; Finke, Bublak, Krummenacher, Kyllingsbæk, Müller, & Schneider, 2005). TVA based assessment has now been used in studies of simultanagnosia (Duncan et al., 2003), integrative agnosia (Gerlach, Marstrand, Habekost, & Gade, 2005), developmental dyslexia (Dubois et al., 2010), alexia (Habekost & Starrfelt, 2006; Starrfelt, Habekost, & Leff, 2009; Starrfelt, Habekost, & Gerlach, 2010), Huntington's disease (Finke et al., 2007), Alzheimer's disease (Bublak, Redel, & Finke, 2006; Bublak et al., 2009; Redel et al., 2010), and effects of stroke in particular parts of the brain (Habekost & Bundesen, 2003; Habekost & Rostrup, 2006, 2007; Peers et al., 2005; see Habekost & Starrfelt, 2009, for a review). TVA-based assessment enables the estimation of parameters related to span of VSTM (storage capacity of K objects), the rate of encoding into VSTM (processing capacity of C objects/s), the perceptual threshold (minimum effective exposure duration of t_0 ms), and the efficiency of selecting targets rather than distractors (selectivity α, defined as the attentional weight of a distractor divided by the attentional weight of a target).

Using a cross-sectional design involving participants from the age of 12 to 75 we employed the SART and TVA-based assessment to measure age-related changes in sustained attention and attentional selectivity and capacity. Specifically, we examined whether significant age-related decline was evident for each variable and if so, the magnitude and lifespan trajectory of such decline.

Method

Participants

113 volunteers, including 49 males and 64 females, ranging in age from 12 to 75, participated in this study. Table 1 presents a breakdown of the sample by age-group in terms of age, gender and education level. All participants were recruited and tested by the first author in the Institute of Neuroscience, Trinity College Dublin. All participants were living within (or nearby) the Dublin area. The 12-year-old children and the teenagers (15 – 17 year olds) were recruited from two neighbouring primary and secondary schools which were known to the first author and which were located in a near-suburb of Dublin city. In each case, a school representative (i.e. the principal in the case of the primary school and a teacher in the case of the secondary school) facilitated recruitment by providing parents and students with information leaflets. Children and teenagers (who were all under the age of 18) gave informed assent and their parents provided informed consent. Adult participants (age 20+) were largely recruited through the Psychology Department Participant Panel. This panel consisted of members of the

general public who had expressed an interest in participating in psychological research. Prior to joining the Panel, volunteers were asked to complete a detailed questionnaire including a variety of questions covering demographic variables and medical and psychiatric history. A random selection of panel members within each of the desired age brackets was made and members were invited to participate by way of letter and accompanying information leaflet, which were followed by a phone call by the lead author. A small number of young adults (largely in the 20s age group) responded to poster advertisements placed around Trinity College. These posters invited willing volunteers to participate in a study on ‘Attention across the Lifespan’. They were subsequently given the same information leaflet that was posted to members of the Participant Panel. Exclusion criteria included a history of psychiatric disorder or neurological insult. Prior to testing, participants’ near and colour vision were screened using the Revised Sheridan Gardiner Test (Sheridan, 1970) and the Ishihara Test for Colour-Blindness (Ishihara, 1960). This study was granted ethical approval by the Department of Psychology Ethics Committee and all adult participants gave informed consent prior to participation.

(Insert Table 1 about here.)

Materials

Combi-TVA Task.

The Combi-TVA Task (Vangkilde, Coull, & Bundesen, 2011) involved a brief flash of red and blue letters on computer screen with the participant's task being to report all red letters (targets) but to ignore blue (distractors). The test took approximately 40 minutes for each participant and included 324 trials arranged into 9 blocks. Each trial consisted of the presentation of a red fixation cross (1000 ms), the stimulus display and a post-display mask (500ms). The participant was instructed to fixate on the red cross and to verbally report the red letters he/she saw when the screen went blank, following the mask presentation (see figure 1). The researcher typed the letters as the participant reported them. There were three stimulus display types: whole report of 6 targets, whole report of 2 targets, partial report of 2 targets and 4 distractors. The 6-target whole report trials were presented for 10, 20, 50, 80, 140 and 200ms. The 2-target whole report trials and the partial report trials were presented for 80ms. TVA modelling procedures (Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011; Kyllingsbaek, 2006) were applied to estimate the following parameters for each participant:

t_0: *Perceptual threshold*

The minimum exposure duration (milliseconds) at which letter identification is better than chance.

K: *Visual short-term memory capacity*

The maximum number of letters the participant can report.

C: *Visual Processing Capacity*

The rate of encoding into VSTM, expressed in terms of letters per second.

α *(Alpha):* *Efficiency of top-down selection*

A value reflecting the participant's ability to focus on the target letters and ignore distractors (calculated by dividing the estimated attentional weight of a distractor by the attentional weight of a target). A value of 0 indicates perfect selectivity with higher values indicating poorer selectivity. A value of 1 or higher indicates complete non-selectivity on the part of the participant.

(Insert Figure 1 about here.)

Sustained Attention Tasks.

The SART (Robertson et al., 1997) measured fluctuations in sustained attention by measuring the ability to inhibit a response to an infrequent target stimulus in the context of maintaining an ongoing, monotonous action. Numbers between 1 and 9 were presented on screen and participants were required to press a button for every number that appeared but to withhold their response to number 3 (see Figure 2). In the Fixed version of the task, numbers appeared in the fixed sequence, 1 to 9, and in the Random version, numbers appeared in a pseudo-random order. The numbers appeared in white against a black background and remained for 313ms. Each digit was followed by a mask, a cross within a circle, which lasted for 1126ms. Embedded within the mask period was a response cue (63ms), a thicker cross within a circle. The mask period consisted of the following sequence of images: mask (125ms), response cue (63ms), mask (375ms), fixation (a cross; 563ms). Participants were asked to respond on appearance of the response cue in order to minimise differences in inter and intra-individual response speeds (see Johnson et al., 2007a, 2007b). There were 225 digits in all, including 25 no-go targets (no. 3) and 200 go trials (all other numbers). Each SART lasted 5.4 minutes. The three measures of sustained attention were errors of commission (i.e. number of times a participant pressed for no. 3), errors of omission (i.e. number of times a participant did not press for a go-trial number) and variability of reaction time expressed as the Coefficient of Variation (i.e., standard deviation / mean reaction time).

(Insert Figure 2 about here.)

Procedure

Participants attended a single testing session during which they performed the Combi-TVA task, the $SART_{fixed}$ and the $SART_{random}$, in that order. Prior to completing these tasks, participants' near and colour vision were screened using the Revised Sheridan Gardiner Test (Sheridan, 1970) and the Ishihara Test for Colour-Blindness (Ishihara, 1960). Analysis of results proceeded in two steps. First, the trajectory of lifespan changes was examined by dividing the sample into 8 age brackets (12 year olds, teens, 20s, 30s, 40s, 50s, 60s, 70s) and plotting the mean values for each age group on each variable. The trajectory was further examined by conducting a regression of each variable upon age in order to examine whether a linear or curvilinear function best characterised the trajectory of each variable. The existence and magnitude of decline on each variable was then examined by comparing younger (20s/30s) and older (60s/70s) adults in independent samples *t*-tests. Effect sizes corresponding to selectivity, capacity and sustained attention, derived from the younger – older adult comparison and the regression analyses, were then compared in order to determine whether the magnitude of age-related change was significantly different for these attentional functions.

Results

Trajectory of Age-Related Change

Figures 3 and 4 describe the trajectory of the sustained attention and attentional selectivity and capacity variables across the lifespan by plotting the mean values for each age group (12-year-olds, teens, 20s, 30s, 40s, 50s, 60s, 70s) on each variable. An examination of the plots by eye suggested that the TVA parameters tended to show improvement from age 12 to the teens, a peak in the teenage years (or 20s in the case of alpha), followed by a more or less linear decline thereafter. In contrast, sustained attention variables seemed to follow U-shaped trajectories, with poor performance in childhood and teenage years, a plateau across young and middle adulthood and performance deteriorating again in older adulthood.

(Insert Figures 3 and 4 about here.)

These observations were confirmed using regression analyses. Note that data for the 12-year-olds were not included in the regression analyses as inclusion of these data would require more complex models (e.g. cubic) which would pertain to both age-related development and age-related decline. Figures 5 and 6 present scatterplots, which display the relationship between age and each of the sustained attention, attentional selectivity and attentional capacity variables. Lowess lines were fitted to the scatterplots in order to help visualise the relationship between age and each of the variables. Lowess lines represent the relationship between two variables by tracing the trend of the data and make no assumptions about the form of the underlying relationship (Cohen, Cohen, West & Aiken, 2003). The lowess line appeared as a straight line (suggesting a linear relationship) for each of the attentional selectivity and capacity variables but as a curved, U-shaped line (suggesting a curvilinear relationship) for each of the sustained attention variables.

(Insert Figures 5 and 6 about here.)

Both linear and quadratic regression equations were fitted and values of R^2, ANOVAs and Coefficient *t*-tests were examined to determine whether each relationship was best described by a linear or quadratic equation (Cohen et al., 2003). Table 2 presents the results of the regression analyses for each variable. The relationship between each TVA parameter and age was best represented by a linear regression function while the relationship between each sustained attention variable and age was best represented by a quadratic function.

(Insert Table 2 about here.)

Magnitude of Age-Related Change

One-tailed independent samples *t*-tests were used to examine whether there was a significant decline from young adulthood (20/30s age groups) to older adulthood (60s/70s age groups) on each variable. Where the Levene's Test for Equality of Variances was statistically significant, the *t*-value corresponding to an analysis where equal variances are not assumed was adopted. Tables 3 and 4 present the means, standard deviations, *t*-test results and effect sizes for the attentional selectivity, attentional capacity and sustained attention variables. Effect sizes were calculated using Cohen's *d*, $(\text{Mean}_{\text{old}} - \text{Mean}_{\text{young}})/SD_{\text{pooled}}$ (Howell, 2008). Significant declines from younger to older adulthood were evident on every variable but declines were of markedly different effect sizes. The largest effect sizes were seen on visual processing capacity, *C* (*d*: 2.02) and VSTM capacity, *K* (*d*: 1.32). Medium-large effect sizes were observed for all sustained attention variables (*d*: .67 - .1.09). Medium effect sizes were observed for perceptual threshold, t_0 (*d*: .56), and efficiency of top-down attentional selection, α (*d*: .52). An examination of the R^2 values presented in Table 2 reveals a similar pattern in terms of the magnitude of the relationship between age and each attention variable. The highest R^2 values were obtained for *C* (43.1%) and *K* (29.5%). These were followed by the sustained attention variables, with R^2 values ranging from 11.4% to 20.8%. The lowest R^2 values were obtained for α (10.8%) and t_0 (8.2%).

(Insert Tables 3 and 4 about here.)

In order to directly compare the effect sizes (*d* & *R*) relating to attentional selectivity, capacity and sustained attention, composite effect sizes representing selectivity, capacity and sustained attention were calculated. For selectivity, the effect sizes relating to α were used. For capacity, the effect sizes relating to *K* and *C* were averaged. Although t_0 is considered to be an aspect of attentional capacity within the TVA paradigm, it was not included in the composite effect size for capacity due to the large discrepancy between the obtained effect sizes for t_0 and *K* and *C*, which raises the possibility that the measurement of t_0 was not sensitive enough to detect age-related decline in the current paradigm (see Discussion). In addition, previous research has shown that t_0 is not strongly correlated with *K* and *C*, which have a strong correlation (McAvinue et al., 2012). For sustained attention, the effect sizes relating to the sustained attention variables (RandomERC, RandomERO, RandomRTCov, FixedERC, FixedERO & FixedRTCov) were averaged. Table 5 presents the composite effect sizes for attentional selectivity, attentional capacity and sustained attention. The values for *d* were derived from the young-adult / older-adult comparison (see Tables 3 & 4) and the values for *R* were derived from the regression analyses (see Table 2).

(Insert Table 5 about here)

A visual inspection of the composite effect sizes reveals a similar pattern, with effect sizes being largest for attentional capacity (d = 1.67, R = .6), followed by sustained attention (d = .9, R = .4) and finally, attentional selectivity (d = .52, R = .33). A Test of Homogeneity was used to examine whether the variability in effect sizes was statistically significantly different from that expected by sampling error alone. *Q*-statistics were calculated using the equations presented in Cooper (2010, pp. 186 – 187) to facilitate comparisons between the three attentional effect sizes in terms of *d* and *R*. For each comparison, the *Q*-statistic was compared to critical values of the chi-square distribution, corresponding to the probability levels of .01 and .05. Pertinent values are presented in Table 6. Findings were very similar for *d* and *R*. The comparisons revealed significant variability among the three effect sizes for selectivity, capacity and sustained attention (*d*: $Q = 7.76$, $df = 2$, $p < .05$; *R*: $Q = 6.24$, $df = 2$, $p < .05$). The composite effect sizes for capacity were significantly greater than those for selectivity (*d*: $Q = 7.64$, $df = 1$, $p < .01$; *R*: $Q = 5.69$, $df = 1$, $p < .05$). There were no significant differences between the effect sizes for selectivity and sustained attention (*d*: $Q = .93$, $df = 1$, $p > .05$; *R*: $Q = .31$, $df = 1$, $p > .05$). The differences between the effect sizes for capacity and sustained attention were approaching significance (*d*: $Q = 3.35$, $df = 1$, $p > .05$; *R:* $Q = 3.37$, $df = 1$, $p > .05$).

(Insert Table 6 about here)

Discussion

The purpose of this study was to examine age-related change in central aspects of visual attention, namely sustained attention, attentional selectivity and attentional capacity. To measure sustained attention, we employed the SART, a simple continuous performance test which captured fluctuations in sustained attention during a monotonous task. To measure attentional selectivity and capacity, we employed TVA-based assessment, which enabled the estimation of basic attentional parameters relating to visual attentional capacity (perceptual threshold, VSTM capacity, processing capacity) and efficiency of top down attentional selection. There was evidence of age-related decline in each of the measured variables. However, the declines varied markedly in terms of magnitude and lifespan trajectory. The TVA parameters (attentional selectivity and capacity) displayed a linear relationship with age while the sustained attention variables were found to have a curvilinear relationship. A comparison of composite effect sizes reflecting age-related decline yielded largest effect sizes for attentional capacity, followed by sustained attention and attentional selectivity. There was a statistically significant difference between the effect sizes for capacity and selectivity, suggesting that age had a significantly greater impact on capacity than on selectivity. The difference between the effect sizes for attentional capacity and sustained attention was approaching significance.

The largest declines were seen on the variables, visual processing capacity (*C*) and VSTM capacity (*K*). In the comparison between younger (20s/30s) and older (60s/70s) adults, very large effect sizes were yielded for these two variables. Furthermore, the graphical and regression analyses suggested a linear relationship with age. Both variables had their peak in the teenage years, followed by a linear decline through the succeeding decades. These findings are in keeping with previous evidence of linear decline with age beginning in young adulthood for processing speed (Salthouse, 1996) and VSTM (Lee et al., 2012; Verhaeghen, Marcoen, & Goossens, 1993). There was also a significant increase in perceptual threshold in older compared to younger adults. However, this increase was of a medium effect size and there was only weak evidence for a linear relationship with age (R^2 = 8.2%). This finding was surprising given the marked declines observed on the other variables relating to visual attentional capacity. It is possible that perceptual threshold is simply not as vulnerable to age-related decline. However, it is also possible that the current method of estimating perceptual threshold is not sensitive enough to detect decline across the decades.

Efficiency of top-down attentional selection, α, showed a significant decline from young to older adulthood. This decline was of medium effect size and there was weak evidence for a linear increase (signifying decline) with age (R^2 = 10.8%). Again, it is possible that the current paradigm was not sensitive enough to detect greater changes across the lifespan. Alternatively, this finding raises the intriguing possibility that efficiency of top-down attentional selection is somewhat robust against the effects of age.

All sustained attention variables displayed decline from younger to older adulthood of medium to large effect size. Their lifespan trajectories were best described by a quadratic function, or U-shaped curve, with poor performance in childhood (age 12) and teenage years, a plateau during young to middle adulthood and a deterioration in performance in older adulthood. Previous studies which have used vigilance tasks to assess sustained attention have yielded inconsistent results (Davies & Parasuraman, 1982; Rogers, 2000). One very large-scale study using a vigilance task known as the Mackworth Clock Task failed to find any evidence of sustained attention deficits in older adults (Giambra & Quilter, 1988). It is possible that the increased sensitivity of the SART in comparison to vigilance tasks enabled it to detect age-related decline in this study. Vigilance tasks typically require a participant to passively observe a stream of stimuli and to respond on appearance of an infrequent target stimulus. However, the sudden appearance of the infrequent target and associated response may have an alerting effect which reduces the demands on the endogenous sustained attention system and so, reduces the sensitivity of the task in the detection of lapses in sustained attention. In the SART, these task demands are reversed and the participant is required to respond to most stimuli within a stream of stimuli and to withhold his response to an infrequent no-go target. It is argued that a task requiring inhibition of a response within the context of an ongoing monotonous action is more taxing upon the endogenous sustained attention systems and more sensitive in detecting lapses of sustained attention than traditional vigilance tasks (Robertson et al., 1997). However, one drawback of the SART in the current arena is its reliance upon a speeded motor action. The SART requires a participant to press a button for every stimulus that appears (except for number 3) within an inter-stimulus interval of 1439 ms. This requires quite a fast and co-ordinated motor response on the part of the participant and given that motor responses are typically slowed in older adults, it is difficult to conclude for certain whether the sustained attention deficits seen in the older adults in this study are the result of true lapses in sustained attention or difficulties with a speeded motor response. A future study could investigate this issue further using different versions of the SART with varying inter-stimulus intervals.

The current study was conducted to examine changes in attentional variables across the lifespan and was not designed to test any particular theory of cognitive aging. However, it is noteworthy that the findings are somewhat at odds with the Frontal Lobe Hypothesis of aging (West, 1996). This hypothesis stated that cognitive processes supported by the prefrontal cortex would manifest decline at an earlier age and in greater magnitude than cognitive processes supported by non-frontal regions. In support of this hypothesis are the findings of marked declines in executive functioning in older adults (Kramer et al., 2001; Park, 2000; Park et al., 2001; Reimers & Maylor, 2005; Verhaeghen & Cerella, 2002). In this study, however, the more rudimentary cognitive processes, VSTM capacity and visual processing capacity, showed declines at an earlier age and of greater magnitude than variables relating to the arguably more executive processes of attentional selection and sustained attention. These findings are more compatible with the ideas put forward by Madden and colleagues (Madden, 2007; Madden & Whiting, 2004; Madden, Whiting & Huettel, 2005) who suggested that top-down attentional control is preserved in older adults and indeed, that they rely more upon this attentional control in order to compensate for decline in basic sensory and perceptual function. They describe a number of studies of visual search in which older adults are particularly penalised in conditions where their sensory acuity is challenged (i.e., conditions where stimuli are degraded, targets are presented at low exposure durations or target-distractor similarity is increased) and contrast these results with the finding that older adults are able to engage in top-down attentional guidance (i.e. to take advantage of a cue in order to guide visual search). In a functional imaging study, Madden et al. (2007) showed that during visual search older adults had greater activation of frontal and parietal cortical areas, traditionally associated with attentional control, than younger adults, who showed greater activation of occipital areas, related to visual processing. Indeed, this posterior-anterior shift in aging (PASA), essentially an age-related reduction in occipito-temporal activity coupled with an age-related increase in frontal activity, has been observed for a variety of cognitive functions and is thought to reflect a compensatory action (Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008). The findings, in this study, of medium-large declines in attentional selection and sustained attention alongside very large decline in aspects of visual attentional capacity (VSTM and processing capacity) are in keeping with the notion that attentional control is relatively preserved in older adults and with the possibility that they rely upon this attentional control to compensate for decline in other functions.

The study of cognitive aging has revealed that cognitive functions follow different trajectories across the lifespan. In this study, there was a clear difference in the trajectories followed by the attentional selectivity, attentional capacity and sustained attention variables. The variables relating to visual attentional capacity, t_0, K, C and efficiency of top-down attentional selection, α, all showed development from age 12 to teenage years, a peak in the teens or early 20s and a linear decline thereafter. In contrast, the sustained attention variables mostly showed a curvilinear relationship with age and were represented by a U-shaped curve with poor performance in childhood and teenage years, a plateau during young to middle adulthood and deterioration in older adulthood. Attention has been characterised as comprising of a series of subsystems serving ‘executive’, ‘intensity’ and ‘selectivity’ functions (Parasuraman, 2000). It has been argued that these aspects of attention represent independent functions relying upon separate neural systems (McAvinue et al., 2012; Posner & Petersen, 1990). These results provide further evidence for the differentiation of attentional functions, displaying a difference between attentional selectivity, attentional capacity and sustained attention in terms of magnitude and lifespan trajectory of age-related decline.

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Table 1

Number, Age, Gender and Education of Participants in each Decade

	Children	Teens	20s	30s	40s	50s	60s	70s
n	17	13	14	14	13	15	14	13
Mean Age	12	15.69	23.57	32.93	45.15	54.33	63.5	72.38
(SD)	(0)	(.75)	(3.1)	(2.6)	(3.3)	(2.9)	(2.8)	(1.9)
Age Range	12-12	15-17	20-29	30-37	40-49	50-59	60-69	70-75
Gender (m,f)[a]	10, 7	9, 4	5, 9	5, 9	6, 7	3, 12	7, 7	4, 9
Mean Education Level[b]	1	2	3.43	3.14	3.23	2.8	2.93	2.77
(SD)	(0)	(0)	(.5)	(.66)	(.73)	(.68)	(.83)	(.73)

[a]m, f = Number of Males, Females

[b]Education Level: 1 = Primary, 2 = Secondary, 3 = University Undergraduate, 4 = University Postgraduate

Table 2

Regression of each Attentional Variable upon Age

Y	Model	Equation of Y	*F* Value	*R*	R^2	I^a
t_0	Linear	.15X + 12.3	$F(1, 94) = 8.4$*	.29	8.2%	1.3%
K	Linear	-.03X + 4.28	$F(1, 94) = 39.4$**	.54	29.5%	.6%
C	Linear	-.62X + 75.63	$F(1, 94) = 71.1$**	.66	43.1%	.2%
α	Linear	.004X + .613	$F(1, 94) = 11.4$*	.33	10.8%	1.5%
Random ERC	Quadratic	$-.594X + .006X^2 + 16.66$	$F(2, 91) = 9.6$**	.42	17.4%	14.3%
Random ERO	Quadratic	$-.32X + .004X^2 + 7.02$	$F(2, 91) = 5.9$*	.34	11.4%	11.2%
Random RTCov	Quadratic	$-.008X + .00009X^2 + .37$	$F(2, 91) = 9$**	.41	16.5%	16.4%
Fixed ERC	Quadratic	$-.17X + .002X^2 + 4.52$	$F(2, 92) = 5.9$*	.34	11.4%	11.2%
Fixed ERO	Quadratic	$-.56X + .007X^2 + 11.9$	$F(2, 92) = 11.3$**	.44	19.7%	19.1%
Fixed RTCov	Quadratic	$-.02X + .000X^2 + .62$	$F(2, 92) = 12.1$**	.46	20.8%	19.8%

[a]*I* refers to the increment in R^2 when a quadratic element is added to the linear regression equation.

* $p < .01$ ** $p < .001$

Table 3

Comparison between Younger (20s/30s) and Older (60s/70s) Adults on TVA Parameters

Variables	Younger Mean (SD)	Older Mean (SD)	One-tailed *t*-test	Effect Size *d*
t_0	16.86ms (6.21)	22.91ms (13.99)	$t\ (36)^a = -2.06,\ p = .024$	.56
K	3.53 (.6)	2.46 (.99)	$t\ (43)^a = 4.86,\ p < .001$	1.32
C	58.94 (14.25)	33.76 (10.25)	$t\ (53) = 7.5,\ p < .001$	2.02
α	.73 (.25)	.87 (.28)	$t\ (53) = -1.9,\ p = .03$	.52

[a] Correction of DF for unequal variances.

Table 4

Comparison between Younger (20s/30s) and Older (60s/70s) Adults on Sustained Attention Variables

Variables	Younger Mean (SD)	Older Mean (SD)	One-tailed *t*-test	Effect Size *d*
Fixed ERC	.86 (1.01)	1.92 (1.6)	t (52) = -2.99, p = .002	.81
Fixed ERO	1.39 (2.96)	7.54 (7.55)	t (32)[a] = -3.88, p < .001	1.09
Fixed RTCov	.25 (.099)	.39 (.17)	t (39)[a] = -3.59, p < .001	1
Random ERC	2.63 (2.5)	5.19 (3.78)	t (52) = -2.93, p = .0025	.8
Random ERO	.52 (.7)	2.48 (2.53)	t (30)[a] = -3.88, p < .001	1.05
Random RTCov	.19 (.06)	.23 (.06)	t (52) = -2.63, p = .005	.67

[a] Correction of DF for unequal variances.

Table 5

Composite Effect Sizes for Attentional Selectivity, Attentional Capacity and Sustained Attention

	d	*R*
Selectivity	.52	.33
Capacity	1.67	.6
Sustained	.9	.4

Table 6

Comparison of Effect Sizes

	χ^2 Comparison Values			*d*		*R*	
Variables	*df*	$\chi^2_{.05}$	$\chi^2_{.01}$	*Q*	*p*	*Q*	*p*
Sel - Cap - Sust	2	5.99	9.21	7.76	< .05	6.24	< .05
Sel - Cap	1	3.84	6.63	7.64	< .01	5.69	< .05
Sel - Sust	1	3.84	6.63	.93	ns	.31	ns
Cap - Sust	1	3.84	6.63	3.35	ns	3.37	ns

Note. Sel = Attentional Selectivity; Cap = Attentional Capacity; Sust = Sustained Attention

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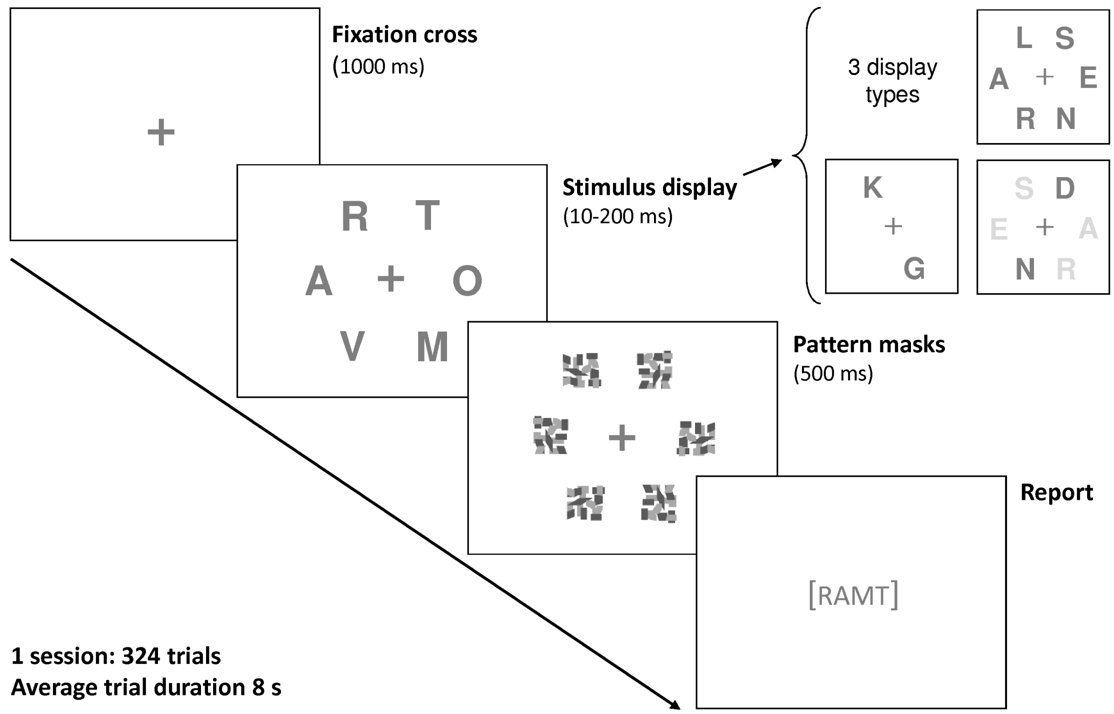
Figure 5. Scatterplots and lowess lines representing the relationship between age and each TVA parameter.

Note. Data for the 12-year-olds are not represented in the scatterplots.

Figure 6. Scatterplots and lowess lines representing the relationship between age and each sustained attention variable.

Note. Data for the 12-year-olds are not represented in the scatterplots.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Average trial duration 8 s

Figure 1.

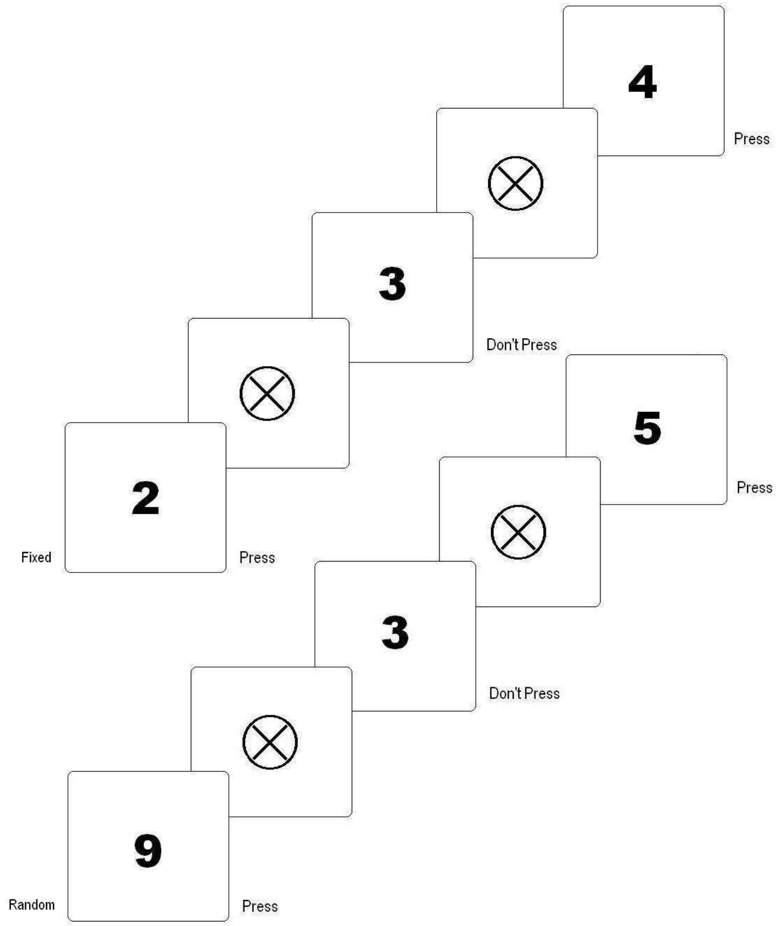
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Figure 2.

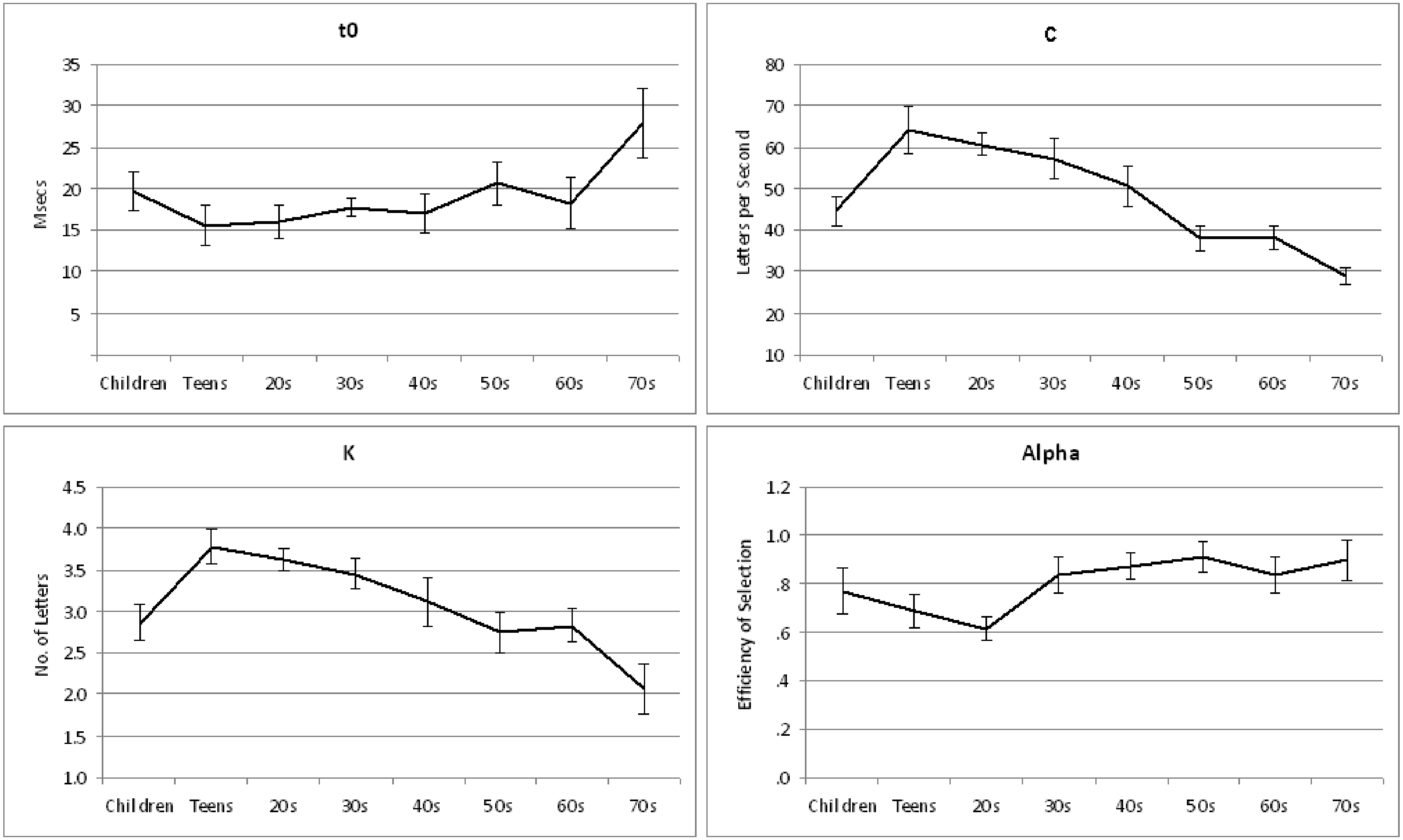
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Figure 3.

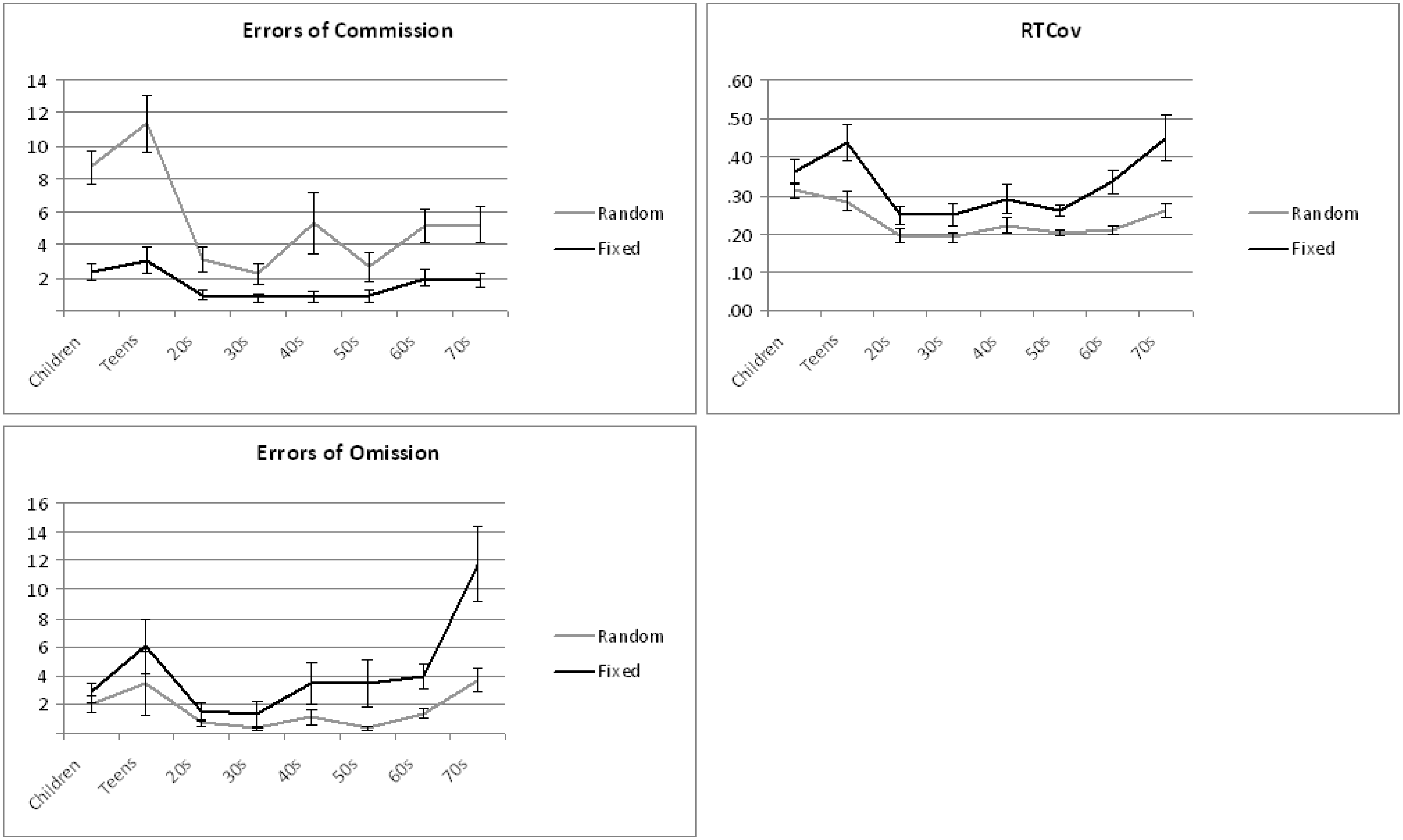
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Figure 4.

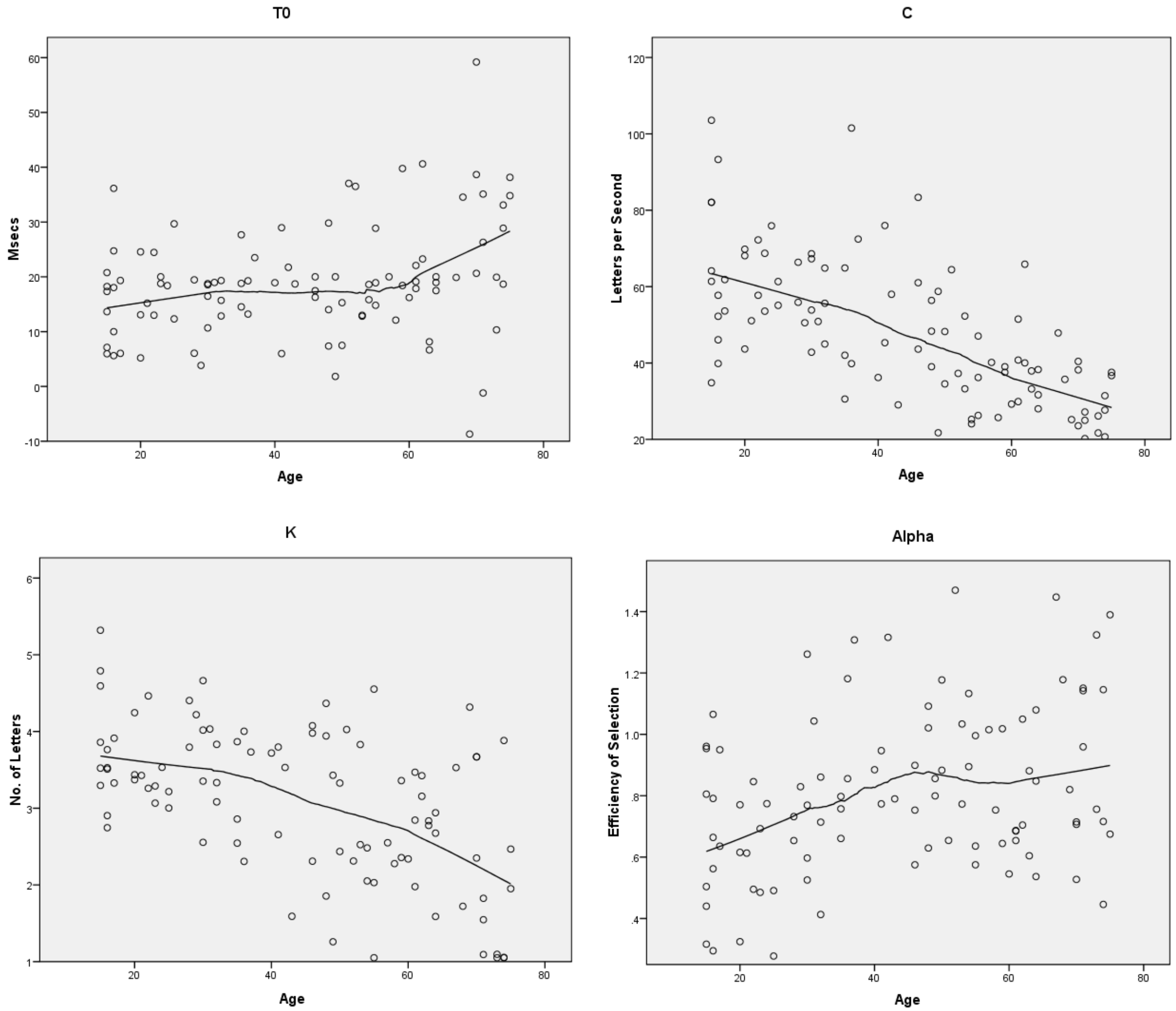
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Figure 5.

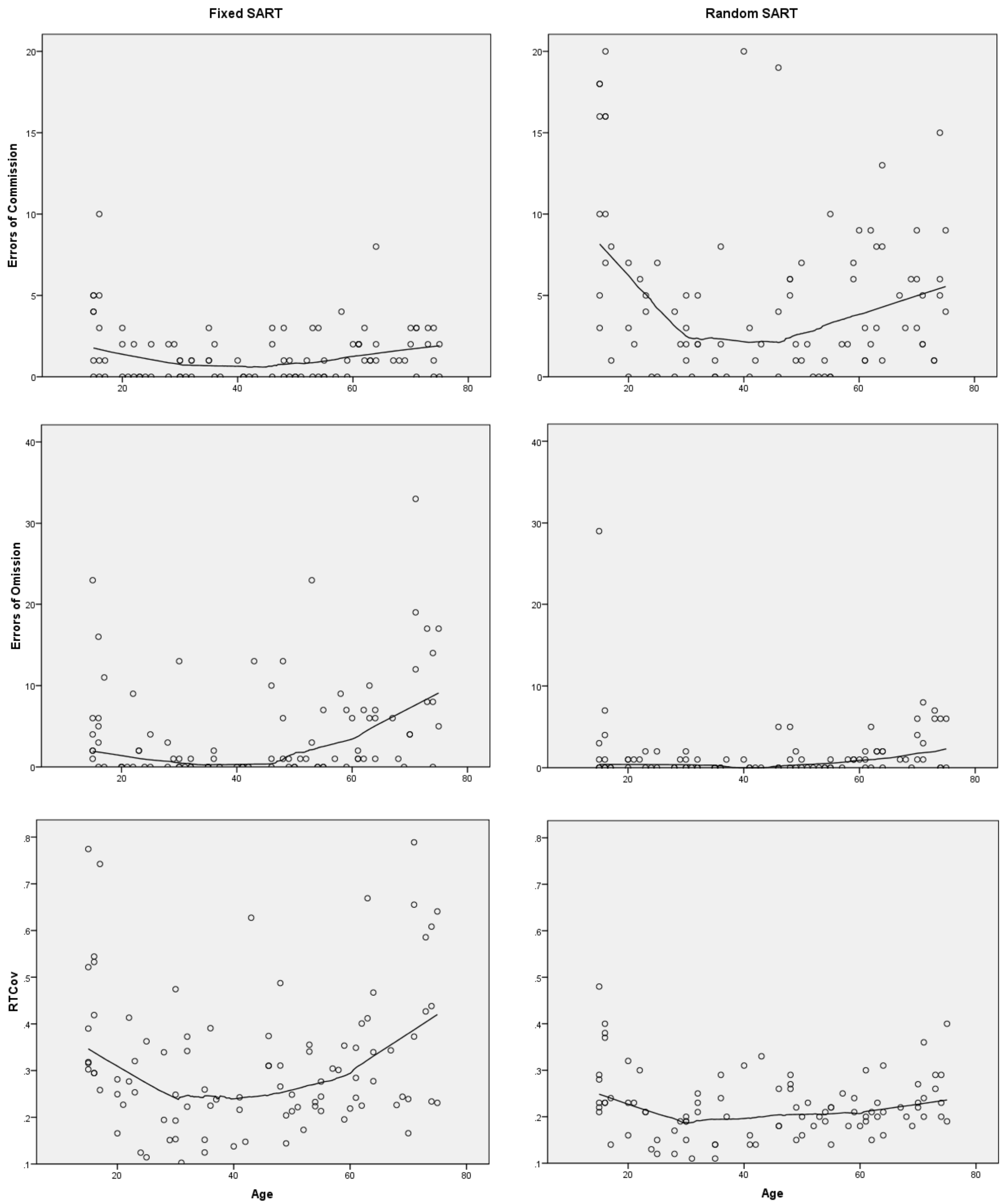
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Figure 6.