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## **Explicit and Implicit Timing in Aging**

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## Abstract

Explicit and implicit measures of timing were compared between young and older participants. In both tasks, participants were initially familiarized with a reference interval by responding to the second of two beeps separated by a fixed interval. During the subsequent testing phase, this inter-stimulus interval was variable. In the explicit task, participants were instructed to judge interval duration, whereas in the implicit task they were told to respond as quickly as possible to the second beep. Cognitive abilities were assessed with neuropsychological tests. Results showed that in both explicit and implicit timing tasks, temporal performance peaked around the reference interval and did not differ between young and older participants. This indicates an accurate representation of duration that did not decline with normal aging. However, some age-related differences were observed in performance depending on the task used. In the explicit timing task, the variability of duration judgments was greater in older than young participants, though this was directly related to older participants' lower attentional capacity. In the implicit timing task, young participants' reaction times (RTs) were slower to targets appearing either earlier or later than the trained interval. Conversely, while older participants RTs were also slowed by early targets, their RTs to late targets were as fast as those to targets appearing at the trained interval. We hypothesize that with age, and irrespective of cognitive ability, there is increasing reliance on temporal information conveyed by the probability of target appearance as a function of elapsing time ("hazard function") than that conveyed by the statistical likelihood of previously experienced temporal associations.

**Key words: Time; Aging; Temporal generalization; Temporal prediction; Hazard function**

## 1. Introduction

Many of us have the sense that time is passing us by, all the more so as we get older. But is this feeling of time speeding up just a “subjective phenomenon”, or does it represent a real decline in our ability to accurately estimate time as we get older? In fact, experimental studies of the subjective perception of the passage of time have found little evidence that older people perceive time as passing more quickly. Questionnaires of hundreds of participants, from adolescents to those in their 80’s or 90’s, showed that passage of time judgements in the range of weeks to a few years were no different across age groups (Droit-Volet and Wearden, 2015; Wittmann and Lehnhoff, 2005; Friedman and Janssen, 2010; Janssen et al, 2013). It was only when participants were questioned on how quickly the past *decade* seemed to have passed that this feeling increased as a function of age. Even so, this age effect was largely accounted for by the emotional state of the participants regardless of their age (Wittmann et al, 2015). Emotional state is indeed a better predictor of how quickly shorter periods of time seem to be passing, with time appearing to go more quickly for happier people (Droit-Volet, 2016a; Droit-Volet and Wearden, 2015, 2016).

The perception of the passage of time over weeks or years is not the same as the perception of duration in the range of seconds (Droit-Volet and Wearden, 2016; Droit-Volet et al, 2017). There is now a wealth of evidence (Xu and Church, 2017) that older people have more difficulty reliably estimating an interval of a few seconds (Block et al, 1998) or hundreds of milliseconds (Wearden et al, 1997). However, it has been suggested that timing impairments in the elderly could be due to a distorted representation of the reference duration held in memory, rather than difficulty in estimating the duration of a currently elapsing interval (McCormack et al, 2002; Rakitin et al, 2005). Alternatively, poor timing could reflect the reduced attentional capacity of older adults (Bherer et al, 2007; Craik & Salthouse, 2000), consistent with findings that older adults’ timing performance is impaired under dual-task or attentional sharing conditions (Craik and Hay, 1999; Lustig and Meck, 2001; Gooch et al, 2009; Krampe et al, 2010). Most convincingly, a number of recent studies have revealed that age-related difficulties in either perceptual (Lamotte and Droit-Volet, 2017) or motor (Baudouin et al, 2006) timing tasks can be attributed to concurrent age-related attention and working memory deficits, as assessed by neuropsychological tests (Bartholomew et al, 2015; Turgeon et al, 2016).

Our hypothesis is that timing is a fundamental primitive ability that is preserved across the life span, i.e. unaffected by normal aging. Poor temporal judgements in the elderly might not reflect age-related differences in timing per se, but instead age-related differences in the cognitive processes required for making judgment in general. Indeed, the decline in cognitive abilities (attention, working memory, processing speed) after 60-65 years is well documented (Craick & Salthouse, 2000; Salthouse, 2010, 2011, 2012). Consistent with this hypothesis, Rammsayer et al (1993) showed that older people are just as good as younger ones at timing very short (50ms) intervals, which depends less upon working memory than timing of longer durations. Similarly, when duration estimates are embedded within a sequence of rhythmic taps, older adults (up to the age of around 75) perform just as well as younger ones (Vanneste et al, 2001; McAuley et al, 2006; Turgeon and Wing, 2012). In addition, very old participants, those in their 80's or 90's, were just as good as younger adults in detecting temporal deviants in a rhythmic sequence of tones (Turgeon et al, 2011). However, they show significantly higher temporal variability in the rhythmic tapping task, indicating a certain degree of fragility in their internal representation of time (McAuley et al, 2006; Turgeon and Wing, 2012). This dissociation led Turgeon et al (2016) to conclude that although the explicit timing mechanisms needed to produce precisely timed intervals are compromised in very old age, the temporal prediction mechanisms needed to detect deviants in a rhythmic sequence are preserved. This idea is supported by the finding that temporal cues improve both speed and accuracy of responding to temporally predictable targets just as much in older adults as they do in younger ones (Chauvin et al, 2016). This preserved ability to orient attention to predictable moments in time is analogous to older adults' preserved ability to orient attention to predictable locations in space (Nissen and Corkin, 1985; Folk and Hoyer, 1992).

In the current study, we compared performance of a temporal prediction task that measures the representation of time implicitly to that of a duration judgment task that measures participants' representation of time explicitly, in young and older adults. The structure of the two tasks was closely matched so as to enable meaningful comparisons. Based on previous findings using duration judgment (Bartholomew et al, 2015; Xu and Church, 2017) or temporal prediction (Turgeon et al, 2016; Chauvin et al, 2016) tasks, we hypothesized that older adults would be impaired in explicit timing, and that this impairment would be related to age-related decline in cognitive capacities (attention and working memory). By contrast, we hypothesized that there would be no difference between old and younger adults in implicit timing. To test our hypotheses, we used a paradigm based on one previously designed for young adults (Piras and Coull, 2011) and that we have already tested

in children (Droit-Volet and Coull, 2016). In this paradigm, participants are first familiarized with a reference interval by performing a reaction time task in which the interval between the cue and the target (the “foreperiod”) is fixed. The temporal information provided during the training phase is therefore temporally regular. One group of participants are instructed to make use of these temporal regularities to learn the duration of the interval and then, as in a classic temporal generalization task, to explicitly judge whether probe intervals are of the same duration or not as the learned reference (explicit timing task). Another group of participants receive no instructions concerning duration during the training phase and then, during the test phase, simply perform a reaction time task in which the target is presented after variable probe intervals (implicit timing task). During the test phase, the target is much more likely to appear after the reference interval than any of the probe intervals, thereby implicitly building up an expectation for the reference interval. Our paradigm therefore manipulated the explicit/implicit nature of the timing process in two ways. During the training phase, temporal information could be learned either explicitly through instruction or implicitly via temporal regularities in the cue-target interval. During the test phase, timing performance could be measured either explicitly via duration judgments, or implicitly via effects of temporal predictability on response speed. It is important to note that in the explicit timing task, the task goal is overtly temporal: participants are asked to provide a judgment about interval duration. On the other hand, in the implicit timing task, the goal is non-temporal: participants are asked simply to perform a reaction time task. Nevertheless, their performance in this task can be influenced by temporal regularities in task structure.

Results in young adults confirmed that the reaction times (RT) were faster for targets appearing after the implicitly expected reference interval, indicating an accurate representation of the trained interval (Piras and Coull, 2011; Droit-Volet and Coull, 2016). In addition, a quadratic profile of performance was found, with reaction times getting progressively slower as temporal distance from the reference interval increased. This profile is analogous to that observed in the Peak Interval procedure (Catania, 1970; Rakitin et al, 1998), temporal generalization tasks (Wearden, 1992), or rhythmic entrainment paradigms (Barnes and Jones, 2000), in which performance follows a Gaussian distribution, peaking at the expected (trained) time. As for these classic paradigms, both temporal accuracy (the location of the peak of the distribution) and temporal variability (the width of the distribution) can be measured in the implicit timing task. Temporal accuracy was found to be as good in the implicit timing task as it was in the explicit (temporal generalization) task (Piras and Coull, 2011; Droit-Volet and Coull, 2016). Moreover, temporal variability increased as a

function of reference duration in both tasks (Piras and Coull, 2011), indicating that performance in the implicit timing task displays the same psychophysical scalar properties as that in more traditional explicit timing tasks.

Importantly, this paradigm allowed us to show that even though 5 year olds' performance was more variable than that of older children on the explicit (duration judgement) version of the task (Droit-Volet and Coull, 2016), confirming many previous studies (for a review see Droit-Volet, 2013, 2016b), their performance on the implicit version of the task was just as good as older children. Therefore, it's not the case that the 5 year olds can't reliably estimate time. Rather, they find it difficult to construct a conscious representation of duration and translate their implicit temporal knowledge into an explicit *judgement* of time. Correlations between neuropsychological test scores and timing performance reinforced this hypothesis: while performance on the explicit timing task was tightly linked to attention and working memory capacities (see also Droit-Volet, Wearden and Zélanti, 2015; Zélanti and Droit-Volet, 2011; Hallez and Droit-Volet, 2017), performance on the implicit timing task was independent of cognitive ability. These data indicate that the implicit version of the task can provide a useful measure of timing ability, "unconfounded" by any concurrent memory or attentional problems. In our study, we therefore measured performance on both explicit and implicit versions of the temporal task used in Droit-Volet and Coull (2016), but in young and older adults. Based on previous findings in the aging literature (Lamotte and Droit-Volet, 2017; Baudouin et al, 2006; Bartholomew et al, 2015; Turgeon et al, 2016), we hypothesized that older adults would be impaired on the explicit timing task and that age-related impairments in explicit timing would be related to individual differences in memory and attentional function. On the other hand, we hypothesized that even if older adults had cognitive difficulties, implicit timing performance would be unimpaired since it is unrelated to neuropsychological test scores (Droit-Volet and Coull, 2016).

## 2. Experiment 1

### 2.1. Method

#### 2.1.1. Participants

The sample was composed of 80 participants: 40 young adults (Mean age = 21.05;  $SD = 3.78$ ) and 40 older adults (Mean age = 71.28;  $SD = 6.17$ ) (Table 1). Participants were recruited by advertisement in the Psychology department and amongst relatives of Psychology students. Participants were tested at home in a quiet room with clocks and watches removed. The participants signed written informed consent to participate in the study in accordance with the principles of the Helsinki declaration. This study was approved by the Sud-Est VI statutory Ethics committee (CPP). The Mini Mental State Examination (MMSE, Folstein, Folstein & McHugh, 1975) was administered to ensure participants were not suffering from dementia (Mean score = 28.35,  $SD = 2.33$ ). The validated and shortened form of the Wechsler Adult Intelligence Scale (WAIS-III: Gregoire & Wierzbicki, 2009) confirmed that verbal IQ did not differ significantly between the young ( $M = 52.95$ ,  $SD = 10.99$ ) and older participants ( $M = 50.75$ ,  $SD = 16.50$ ,  $F(1, 78) = 0.49$ ,  $p = .485$ , although performance IQ was lower for the older ( $M = 41.80$ ,  $SD = 12.96$ ) than for the young participants ( $M = 66.50$ ,  $SD = 12.07$ ),  $F(1, 78) = 42.60$ ,  $p < .001$ ,  $\eta^2_p = 0.50$ . The level of education was also higher for the young than for the older participants (11.85 vs. 9.22,  $F(1, 78) = 33.75$ ,  $p < .001$ ,  $\eta^2_p = 0.30$ ) in both the explicit,  $F(1, 38) = 9.12$ ,  $p = .005$ ,  $\eta^2_p = 0.20$ , and the implicit condition,  $F(1, 38) = 33.74$ ,  $p < .001$ ,  $\eta^2_p = 0.47$  (Table 1).

#### 2.1.2. Material

Participants were seated in a quiet room in front a computer that produced and recorded all experimental events via E-prime (Psychology Software tools). Participants responded with the dominant hand by pressing the “1” or “2” keys of the computer keypad. A 200-ms auditory stimulus was used at the onset and offset of the temporal interval. The experimenter verified that all participants could hear the auditory sounds.



### **2.1.3. Procedure**

20 young (12 women) and 20 older (13 women) participants were randomly assigned to the explicit task, and 20 young (17 women) and 20 older (13 women) participants were assigned to the implicit temporal task (Table 1). The procedure was very similar for both tasks, apart from task-specific instructions (for the same procedure see Droit-Volet and Coull, 2016). For both tasks, participants performed two successive sessions: a training phase (25 trials) and a testing phase (27 trials), which resulted in 50 training trials and 54 testing trials for each task. On each trial, two beeps were delivered, separated by an inter-stimulus interval. The duration of this interval was 600ms (reference duration) during the training phase, and 240, 360, 480, 600, 720, 840 or 960ms (probe durations) during the testing phase. In each testing phase (27 trials), the reference duration was presented 9 times, and the 6 probe durations were presented 3 times each. The inter-trial interval was totally random, i.e. randomly chosen between 500 and 1000ms, but participants initiated each trial after the word “prêt” (“ready”) appeared on the screen by pressing the spacebar of the computer keyboard. The auditory stimuli were delivered 200-ms after the trial had been initiated.

#### ***Explicit timing task***

In the explicit timing task, the participants were explicitly instructed that they had to learn the duration of the inter-stimulus interval. In the training phase, they had to press a button as quickly as possible after the second beep to reinforce learning of this reference duration. Just before the testing phase, they were told that there would be several different interval durations, i.e., the learned reference duration as well as shorter and longer durations. Their task was to judge whether the duration of the inter-stimulus interval was the same (“yes”) or not (“no”) as the learned reference duration by pressing the corresponding key (the “1” and “2” keys of the keypad, which were covered with “yes” or “no” stickers). The association between the keys and the “yes” or “no” response was counterbalanced across participants.

#### ***Implicit timing task***

The procedure was similar for the implicit timing task as for the explicit task, except that the participants did not receive any temporal instructions in the training phase. They were

only told that their task was to press as quickly as possible (on the “1” key) after the second beep. For the testing phase, they were simply told that they had successfully learned how to press quickly after the second beep and they should continue doing so.

### *Neuropsychological tests*

After the temporal task and a 15-min break, participants performed three different neuropsychological tests. To assess short-term and working memory capacity, we used the digit span memory subtests of the WAIS-III (Wechsler, 2000). In these subtests, participants had to immediately recall the correct sequence of a given number of digits (between 2 to 9), either in the forward or backward order. There were two trials and the raw score could be between 0 and 16. Forward digit recall was used to index short-term memory (memory span) and backward digit recall to index working memory. To assess attention, we used the sustained/concentration attention scores of the D2 assessment test (Brinckenkamp, Liepman & Schmidt, 1988). In the D2 test, participants have to cross-out each letter “d” that has 2 dashes above and/or below it, from amongst a series of “d” and “p” stimuli with 1 to 4 dashes above and/or below them. The test is composed of 14 series of stimuli, with 20 s to perform each series. The score used was the GZ-F, which is the number of letters processed minus the number of errors (omission and confusion).

## **2.2. Results**

### **2.2.1. Explicit timing**

#### **Temporal performance**

Figure 1 shows the proportion of “yes” responses -  $p(\text{yes})$  - plotted against interval duration for the young and older participants. An ANOVA was conducted on  $p(\text{yes})$  with age as a between-subjects factor and interval duration as a within-subjects factor. The main effect of interval duration was significant,  $F(6, 228) = 53.60, p < .001, \eta^2_p = 0.59$ . However, there was both a significant interval duration x age interaction,  $F(6, 228) = 2.17, p = 0.047, \eta^2_p = 0.05$ , and a significant main effect of age,  $F(1, 38) = 24.33, p < .0001, \eta^2_p = 0.39$ . These results suggest that the distribution was flatter for the older participants (Figure 1).

To further examine age-related differences in the shape of the performance distribution, we calculated the peak time and the width of the curve at half of its maximum height (Full Width at Half Maximum, FWHM) for each individual participant (Figure 2). These two measures were obtained by fitting the Gaussian function from the GraphPrism program to individual profiles of performance. The curve fits were good for all participants, both for older adults (mean  $R^2 = .86$ ,  $SD = 0.10$ ) and for younger ones (mean  $R^2 = .93$ ,  $SD = 0.08$ ). The peak time is the interval duration corresponding to the highest proportion of “yes” responses (i.e. the vertex of the fitted curve) and is a measure of temporal accuracy. The FWHM measures the frequency of “yes” responses across the distribution (i.e. the spread of the fitted curve), and is a measure of temporal variability. Since these two measures preserve the shape of performance distributions within individual participants they are a more representative measure of timing performance than group-averaged means.

The ANOVA performed on peak time showed no effect of age,  $F(1, 38) = 0.658$ ,  $p = 0.42$ . This indicates that the representation of the reference duration was as accurate in older participants as in younger ones. However, the effect of age was significant for FWHM,  $F(1, 38) = 20.92$ ,  $p < 0.001$ ,  $\eta^2_p = 0.36$ , confirming that curve was flatter in older adults. Therefore, like the young adults, older adults responded “yes” more often to the reference duration than to probe durations, but they were nevertheless more variable in their temporal judgments. Age-related differences in explicit timing therefore lie in the variability of time judgments, not in their accuracy.

#### Correlation between temporal performance and neuropsychological scores

Initial statistical analyses revealed that cognitive abilities were systematically lower in the older than the younger participants (Table 1): short-term memory,  $F(1, 38) = 20.51$ , working memory,  $F(1, 38) = 7.20$ , attention,  $F(1, 38) = 30.29$ , all  $p < .05$ . Nevertheless, the matrix of correlations (Table 2) between neuropsychological scores, age and temporal performance (Peak time and FWHM) suggested that peak time was not related to any cognitive ability (all  $p > .05$ ) (even the Performance IQ,  $p > .05$ ). In contrast, FWHM was significantly correlated to both age and a number of cognitive abilities. To try to extract the factor that was the best predictor of individual differences in this index of temporal variability, we performed an initial hierarchical regression analysis on FWHM with age, memory, and attention scores successively entered into the equation (Table 3, first analysis) (adding the performance IQ did not change the results). This analysis revealed that age was a

significant predictor of individual differences in FWHM values when short-term (Model 2) and working memory (Model 3) scores were included in the regression analyses. However, age was no longer a significant predictor ( $p > .05$ ) of individual differences in FWHM values when attention scores were entered into the equation (Model 4). Indeed, attention scores appeared to be the best predictor of temporal variability of explicit timing ( $R = 0.44$ ,  $p < .05$ ). Entering the attention factor before or after the age factor did not change the significance of the attention factor (all  $p < .05$ ) (Table 3, second and third analyses). In sum, our results suggest that differences in attentional ability accounted for the majority of age-related differences in explicit timing.

### 2.2.2. Implicit timing

#### Temporal performance

Figure 3a shows reaction times (RT) produced by the old and young participants plotted against interval duration. An ANOVA with age as a between-subjects factor and interval duration as a within-subjects factor was performed on RT. This ANOVA showed significant main effects of age,  $F(1, 38) = 9.55$ ,  $p = 0.004$ ,  $\eta^2_p = 0.20$ , and interval duration,  $F(6, 228) = 8.74$ ,  $p < 0.001$ ,  $\eta^2_p = 0.19$ , and a significant interaction between age and interval duration,  $F(6, 228) = 5.77$ ,  $p < 0.001$ ,  $\eta^2_p = 0.13$ . The shape of the distribution thus differed between the two age groups, over and above the fact that RT was slower overall in the older participants ( $M = 374.71$ ,  $SE = 26.32$ ) compared to young ones ( $M = 259.67$ ,  $SE = 26.32$ ). As shown in Figure 3a, young adults' RTs got faster as the probe duration approached the reference duration then got increasingly slower again, thereby forming a U-shaped curve. In contrast, for the older participants, RT also got faster as the probe duration approached the reference, but then did not slow down again beyond the reference duration.

To further examine the difference in the shape of the distribution between the two age groups, we tried to fit distributions with a quadratic function using the GraphPad prism software. Although the quadratic function fit most of young adults' data reasonably well (mean  $R^2 = 0.702$ ,  $SD = 0.14$ ), the same function had a poor fit to most of the older adults' data (mean  $R^2 = 0.565$ ,  $SD = 0.23$ ). Therefore, instead of calculating peak times from the fit of the quadratic function (as for the explicit timing task), we calculated the peak time for each participant as the probe duration that had the fastest average RT (i.e. the vertex of each participant's RT distribution). The ANOVA of peak time did not show any effect of age (old

adults,  $M = 558$ ,  $SE = 36.29$ ; young adults,  $M = 534$ ,  $SE = 36.28$ ,  $F(1, 38) = 0.22$ ,  $p = 0.64$ . The peak time was thus close to the 600ms reference duration (a little shorter) in both young and older participants (Figure 4), suggesting implicit processing of interval duration in all participants. This confirms that the representation of duration did not change with normal aging in the context of an implicit timing task.

In addition, we measured the shape of the distribution by calculating the absolute (non-signed) slope on either side of the peak time. The peak time lay between the 480ms and 600ms probe duration for both young and old participants. Therefore, the slope for early targets was calculated using RTs for the 3 shortest probe durations (240, 360, 480ms) while the slope for late targets was calculated using RTs for the 4 longest durations (600, 720, 840 or 960ms). Calculating slopes had the added advantage of correcting for age-related differences in RT generally. We conducted an ANOVA of these absolute slope values, with age as a between-subjects factor and early/late targets as a within-subjects factor. Significant main effects of age,  $F(1, 38) = 14.13$ ,  $p = 0.001$ ,  $\eta^2_p = 0.27$ , and early/late target,  $F(1, 38) = 28.33$ ,  $p < 0.001$ ,  $\eta^2_p = 0.42$ , were qualified by an age x early/late interaction,  $F(1, 38) = 12.48$ ,  $p = 0.001$ ,  $\eta^2_p = 0.24$ . This interaction confirmed that the shape of the distribution was significantly different between age groups (Figure 4). For young participants, the absolute slope values for early targets ( $M = 0.30$ ,  $SE = 0.08$ ) and late targets ( $M = 0.18$ ,  $SE = 0.04$ ) were not significantly different,  $t(19) = 1.47$ ,  $p = 0.16$ , confirming the symmetrical nature of the U-shaped curve. For older participants, by contrast, the slope for early targets ( $M = 0.77$ ,  $SE = 0.08$ ) was significantly steeper than the slope for late targets ( $M = 0.18$ ,  $SE = 0.04$ ),  $t(19) = 5.58$ ,  $p = 0.0001$ , indicating an asymmetrical distribution.

### **Correlation between temporal performance and neuropsychological scores**

ANOVAs showed that neuropsychological test scores were lower for old than young participants: short-term memory,  $F(1, 38) = 4.50$ , working memory,  $F(1, 38) = 4.55$ , attention,  $F(1, 38) = 12.75$ , all  $p < .05$  (Table 1). To identify factors that might predict individual differences in implicit timing performance, we examined correlations between these neuropsychological scores, age, peak time and the difference in absolute slope on either side of the vertex (early target slope minus late target slope). The matrix of correlations (Table 4) showed no significant correlations between peak time, age and neuropsychological test scores (all  $p > .05$ ). Although there was a significant correlation between age and early/late slope difference ( $r = .48$ ,  $p = 0.002$ ), there was no significant correlation between

early/late slope difference and neuropsychological scores. No significant correlation was also found with the performance IQ for both the peak and early/late slope difference ( $r = -.13$  and  $-.27$ , respectively, both  $p > .05$ ).

### **2.3. Discussion**

Our results showed no difference between young and older participants in the peak time of temporal distributions in either explicit or implicit tasks. This demonstrates that an accurate representation of time is preserved with normal aging. However, we predicted that although older adults would be more variable than younger ones on an explicit timing task, their performance on an implicit timing task would be unimpaired. Our results did not allow us to draw this straightforward conclusion. Older adults were indeed significantly more variable (wider distribution spread) than younger adults on the explicit timing task. Unexpectedly, however, their performance also differed significantly from younger ones on the implicit timing task. In this task, young adults showed a U-shaped profile of performance. Their RTs were fastest for targets appearing at intervals close to the (highly probable and trained) reference duration and were increasingly slower as the distance between the reference interval and the probe interval increased. Moreover, this U-shaped profile was symmetrical, indicating that early and late targets slowed performance to the same degree and were, therefore, equally unexpected. By contrast, older adults showed an asymmetrical profile of performance. Their RTs were slower for targets appearing earlier than the reference duration but not for those appearing later. Therefore, early (premature) targets perturbed performance more than late (delayed) ones. This asymmetry is reminiscent of the effects of the hazard function on RT. The “hazard function” is the increasing conditional probability over time that an event will occur, given that it hasn’t already occurred. This increasing probability induces an increasing sense of expectation as time elapses, rendering delayed targets less unexpected than premature ones. This translates empirically into faster RTs for targets appearing after longer intervals (Woodrow, 1914; Niemi and Naataanen, 1981). In our implicit timing task, it is thus likely that once the reference duration has been bypassed, older adults rely more on the hazard function to guide performance than an entrained representation of reference duration.

However, although our older participants responded very quickly to late targets, they also responded particularly slowly to early targets. Since older adults had slower RTs than younger ones, reflecting general motor slowing, it’s possible that they did not have enough time to sufficiently prepare for the very early targets (Botwinick et al, 1957; Brinley and

Botwinick, 1959; Botwinick and Brinley, 1962). The shortest interval at which a target could appear was 250ms, which was considerably less than the average RT of the older participants (375ms). Therefore, the asymmetric profile of performance for early versus late targets in the older adults might reflect slow responses to the very early targets rather than (or as well as) fast responses to the late ones. To test this hypothesis, we measured performance on an implicit timing task with longer probe durations. In this second experiment, the interval-stimulus interval ranged from 480ms to 1920ms. The shortest probe duration was therefore longer than the average RT of the older participants, allowing them enough time to prepare their response. If the results of Experiment 1 were simply due to older participants' motor slowing, then giving them more time to prepare their response should ameliorate the very slow RTs at short probe durations, leading to a U-shaped RT curve similar to that seen in young adults. On the other hand, if the results of Experiment 1 were due to older adults' increased reliance on the hazard function, we would predict the same profile of performance in both experiments: slow RTs for early targets but fast RTs for late targets.

### **3. Experiment 2**

#### **3.1. Method**

##### **3.1.1. Participants**

The sample was composed of 40 new participants: 20 young adults (19 women; mean age = 19.90,  $SD = 0.72$ ) and 20 older adults (10 women, mean age = 72.40,  $SD = 7.27$ ). Recruitment methods were the same as for Experiment 1. The participants signed written informed consent for their participation in this study, which was carried out according to the principles of the Helsinki declaration, and was approved by the Sud-Est VI statutory Ethics committee (CPP). None of the older participants suffered from dementia as indicated by their MMSE scores ( $M = 29.15$ ,  $SD = 1.23$ ). The verbal IQ score assessed by the shortened form of the WAIS (Gregoire & Wierzbicki, 2009) was lower in the young participants ( $M = 52.5$ ,  $SD = 6.98$ ) than the older ones ( $M = 59$ ,  $SD = 11.77$ ),  $F(1, 38) = 4.23$ ,  $p = .046$ ,  $\eta^2_p = 0.10$ , while the performance IQ score was higher for the young ( $M = 66$ ,  $SD = 13.66$ ) compared to the older participants ( $M = 51.20$ ,  $SD = 13.23$ ),  $F(1, 38) = 12.12$ ,  $p = .001$ ,  $\eta^2_p = 0.24$  (Table 1).

The level of education was similar between the old and younger participants,  $F(1, 38) = 0.85$ ,  $p = .36$ .

### 3.1.2. Material and procedure

In this experiment, we used exactly the same materials and procedure as for the implicit timing task in Experiment 1, except that the inter-stimulus intervals were longer. The reference duration presented in the training phase was 1200 ms and the probe durations presented in the testing phase were 480, 720, 960, 1200, 1440, 1680 or 1920 ms.

## 3.2. Results

### Temporal performance

Figure 3b illustrates RTs produced by the young and older participants for each of the probe intervals in the 1200-ms duration range condition. It appears that the distribution obtained in this longer duration condition was very similar to those obtained in the shorter duration condition (Experiment 1). Specifically, young participants' RTs followed a relatively symmetrical U-shape distribution, while older participants' profile of performance was more asymmetric. The ANOVA of RTs showed that, by using this longer duration range, the main effect of age was no longer significant,  $F(1, 38) = 0.61$ ,  $p = 0.44$ . On average, older participants' RTs ( $M = 287.06$ ,  $SE = 27.72$ ) were as fast as the younger ones ( $M = 256.33$ ,  $SE = 27.73$ ). However, as in Experiment 1, we found a significant age x interval duration interaction,  $F(6, 228) = 4.27$ ,  $p < 0.001$ ,  $\eta^2_p = 0.10$ , which subsumed a significant main effect of interval duration,  $F(6, 228) = 12.90$ ,  $p < 0.001$ ,  $\eta^2_p = 0.25$ . Therefore, despite the fact that older participants now responded as quickly as younger ones, their profile of performance differed significantly from that of the younger participants. To explore this difference more thoroughly, we performed the same peak time and slope analyses as in Experiment 1.

As in Experiment 1, the statistical analysis on the peak time (i.e. the vertex of individual participant's RT distribution) did not show any age effect,  $F(1, 38) = 1.11$ ,  $p = 0.30$  (Figure 4). Therefore, the peak time of the distribution did not differ between the young ( $M = 1092$ ,  $ES = 72.28$ ) and older ( $M = 1200$ ,  $SE = 72.28$ ) participants, being close to the reference duration (1200 ms) in both age groups.



By contrast, the symmetry of the distribution differed significantly across age groups. Although older participants responded as quickly as younger ones,  $F(1, 38) = 0.64, p = 0.43$ , the significant interaction between age and the slopes for early versus late targets,  $F(1, 38) = 5.215, p = 0.028, \eta^2_p = 0.12$ , revealed an age-related difference in the symmetry of the RT distribution. For older participants, as in Experiment 1, the absolute slope was steeper for early targets ( $M = 0.34, SE = 0.05$ ) than for late targets ( $M = 0.06, SE = 0.23$ ),  $t(19) = 4.19, p = 0.0001$ . For younger participants, the absolute slope for early targets ( $M = 0.22, SE = 0.05$ ) was also steeper than that for late targets ( $M = 0.11, SE = 0.23$ ),  $t(19) = 2.54, p = 0.2$ . However the difference in the absolute slope value between the early and late targets was significantly smaller in the young participants ( $M = 0.11, SE = 0.055$ ) than in the older ones ( $M = 0.28, SE = 0.06$ ),  $F(1, 38) = 5.22, p = 0.02, \eta^2_p = 0.12$ . These data indicate that although there was an asymmetrical profile of performance in all participants, the asymmetry was more marked in the older than in the younger participants.

### **Correlation between temporal performance and neuropsychological scores**

ANOVAs showed that neuropsychological test scores of short-term memory,  $F(1, 38) = 5.78$  and attention,  $F(1, 38) = 42.77$ , both  $p < .05$ , were significantly lower for older participants than younger ones. Working memory only tended to differ between groups,  $F(1, 38) = 3.00, p = 0.09$  (Table 1). As in Experiment 1, there were no significant correlations (Table 4) between peak time, age and neuropsychological test scores (all  $p < .05$ ) (including performance IQ,  $r = .028, p > .05$ ). On the other hand, again replicating results of Experiment 1, there was a significant correlation between the difference in slope for early versus late targets and age ( $r = .34, p < .05$ ) (and performance IQ,  $r = -.39, p < .05$ ), but not between the slope difference and any of the neuropsychological test scores assessing specific cognitive abilities (all  $p < .05$ ).

### **3.3. Discussion**

The results of our second Experiment replicated those found in Experiment 1. There was no age-related difference in the peak time of the RT distribution, but the shape of the distribution was less symmetrical in older adults than in younger ones. Specifically, once the reference duration had been bypassed, delayed targets slowed young adults' RTs whereas older participants' RTs were unaffected by a delay in target appearance. In Experiment 2, we

deliberately lengthened the range of intervals to verify that older adults' slow RTs for early targets in Experiment 1 were not simply due to insufficient time to prepare their motor response. In Experiment 2, temporal intervals were double the length of those in Experiment 1 (1200ms trained interval) and the shortest interval was now 480ms. Despite this lengthening of intervals, the older adults' responses to targets appearing at the shortest interval were still the slowest of the entire range. Furthermore, when the 480ms interval was near the middle of the range in Experiment 1, RTs to targets appearing at this interval had been among the fastest. Therefore, slow responses to early targets in Experiment 1 were unlikely to be simply due to motor slowing in the older participants. Indeed, the asymmetric shape of their RT profile was strikingly similar across the two experiments despite the difference in duration range.

The results of Experiment 2 thus confirmed those of Experiment 1 showing that younger adults' RT profiles were significantly more symmetrical than those of older adults. Nevertheless, the distribution of young adults' responses was not entirely symmetrical in Experiment 2, with RTs leveling off at longer intervals. This pattern indicates that when we used a longer duration range, the temporal predictability conveyed by the hazard function influenced performance in young, as well as older, adults. Prior studies have already shown that, as the duration range increases, the disparity in RTs to targets presented after short versus long intervals also increases (Elliott, 1973; Steinborn et al, 2008). Although the duration range was proportional to the duration of the trained interval across our two experiments, the range was nevertheless larger in Experiment 2 (a range of 1440ms) than in Experiment 1 (720ms range). Therefore, the longer durations of Experiment 2 allowed performance to be influenced not only by the relative probability of the trained interval, but also by the increasing probability of target appearance as a function of the elapsing interval.

#### **4. General Discussion**

We compared the performance of young and older adults on both a duration judgment task, which measures timing explicitly, and a temporal prediction task, which measures timing more implicitly. In both explicit and implicit timing tasks, performance peaked around the trained duration and did not differ between age groups. This indicates that the representation of duration used in either task was equally accurate in young and older participants. Therefore, an accurate representation of duration does not decline with normal aging. Moreover, although older adults' duration judgments were more variable (i.e. wider

spread of responses) than those of younger participants in the explicit timing task, this age-related difference in temporal precision was directly related to neuropsychological scores of attentional function. This is consistent with results of several previous studies of explicit temporal judgments that also assessed cognitive capacity in older participants (Baudouin et al, 2006; Bartholomew et al, 2015; Lamotte and Droit-Volet, 2017; Turgeon et al, 2016). We surmise, therefore, that lower temporal precision of duration judgements in healthy older participants might not reflect a selective timing deficit but, instead, a side-effect of their cognitive difficulties.

In our paradigm, we manipulated the explicit/implicit nature of the timing process in two ways: by the type of instruction during the training phase (learn duration/RT) and by the type of measurement during the test phase (duration judgment/RT). Older adults' poor performance in the explicit timing task could have been due to either one, or both, of these manipulations. One way of dissociating the influence of implicit/explicit temporal learning from implicit/explicit temporal measurement would be to manipulate the explicit/implicit nature of the instructions during the training phase but ask participants to perform the same RT task during the testing phase. In fact, Chauvin et al (2016) have already shown that when participants were given explicit temporal instructions concerning a cue-target interval and were subsequently tested on a temporal prediction RT task, older participants performed the task as well as younger ones. This result suggests that the difficulties often experienced by older participants in duration judgment tasks (Bartholomew et al, 2015; Xu and Church, 2017) might not be due to explicit temporal instructions but, instead, to the requirement to make an overt judgment about duration.

Since performance on the implicit timing task depends less upon general cognitive ability than the explicit timing task (Droit-Volet and Coull, 2016), we predicted that performance on this task would be unimpaired in the elderly. Contrary to our hypothesis however, performance on this implicit measure of timing differed significantly between age groups. Nevertheless, the age-related difference was not in the accuracy of timing nor its precision. Instead, the performance profile of older adults was more asymmetric than that of younger participants. While younger adults were slowed equally by premature or delayed targets, older adults were slowed only by premature targets. Crucially, while this asymmetric RT profile correlated with age, it did not correlate with neuropsychological test scores. This suggests that it might reflect an age-related measure of timing (temporal probability processing) that influences task performance, and which is independent of any coexistent specific cognitive dysfunction.

In young adults, performance in the implicit timing task followed a U-shaped profile, with fastest RTs to targets appearing around the trained interval and increasingly slower RTs to targets appearing earlier or later (see also Piras and Coull, 2011; Droit-Volet and Coull, 2016). This is the mirror image of the inverted-U shaped (Gaussian) profile observed in rhythmic entrainment studies, in which discrimination accuracy for non-temporal stimulus features is highest for stimuli appearing after the rhythmically entrained interval and progressively tails off for stimuli appearing earlier or later (Jones et al, 2002). These data provide evidence that even when the time of target presentation is incidental to task requirements, a representation of the trained interval has nevertheless been memorised and used to enhance processing of targets appearing at the trained time. In the elderly, however, we did not observe this U-shaped curve. For the older participants, RTs were significantly slower for targets appearing earlier than the trained interval but were just as fast for those appearing later. This asymmetric profile of performance seems reminiscent of that commonly attributed to the “hazard function”. The hazard function reflects the increasing probability of target appearance as a function of interval duration, and results in faster RTs to targets that appear after longer intervals. It appears therefore, that performance in the elderly was guided not only by a memorized representation of the trained interval but also by the increasing likelihood over time that the target would eventually appear after the trained interval had been bypassed. Indeed, their pattern of performance is consistent with previous findings that RTs decrease more steeply with increasing interval duration in older adults than young ones (Botwinick et al, 1957; Bherer and Belleville, 2004; Zanto et al, 2011; though see Jurkowski et al, 2005 and Vallesi et al, 2009).

It might be argued that slow RTs to very early targets might simply be due to general motor slowing in the elderly, with short intervals allowing insufficient time to prepare a motor response (Botwinick et al, 1957; Botwinick and Brinley, 1962). However, in Experiment 2, the use of longer intervals made little difference to older adults’ response profile, with RTs still being far slower to early targets than to late ones. Moreover, Bherer and Belleville (2004) found that increasing the probability of an early target (using an exponential or “nonaging” distribution of intervals) speeded RTs to early targets, making their performance indistinguishable from that of young adults. Therefore, older adults slow responses to very early targets is more likely due to difficulty in processing low probability stimuli, than to general motor slowing (see also Botwinick and Brinley, 1962). Our data further suggest that for late targets, which are as equally unlikely as early targets in our paradigm, elderly adults appear to compensate for their difficulty in processing low-probability stimuli by instead

relying on the temporally predictable information conveyed by the hazard function. This speeds RTs to targets appearing after long intervals, producing an asymmetric RT curve.

Interestingly, when a longer duration range is used, the hazard function also significantly influences performance of the implicit timing task in young adults (Experiment 2) and children (Droit-Volet and Coull, 2016). Although the response profile of young adults in our study was less asymmetric than that of older adults, their RTs nevertheless flattened out once the trained interval had been bypassed. Indeed, several authors have already reported a mitigating influence of the hazard function on the inverted U-shaped profile of performance induced by rhythmic entrainment paradigms in young adults (Ellis and Jones, 2010; Sanabria et al, 2011; Jones, 2015). This functional interaction suggests that the hazard function and entrainment represent two distinct ways of manipulating temporal predictability. The temporal information provided by trained intervals, isochronous rhythms, or even symbolic cues (Coull and Nobre, 1998), is learned *a priori* and predicts that the target will appear after a particular fixed interval. By contrast, the temporal information provided by the hazard function evolves dynamically over the interval, with the probability of target appearance increasing as each critical moment is bypassed. Moreover, the neural implementation of the hazard function is distinct from that of rhythms (Jones et al, 2017) or temporal cues (Coull et al, 2016). Therefore, performance can be influenced conjointly by the temporal probability conveyed by prior training or experience and/or that conveyed by the passage of time itself. Our data add to this literature by showing that the relative influence of these two forms of temporal probability varies as a function of age and duration range.

One reason why the hazard function influences performance more in older participants than young ones could be related to age-related differences in cognitive resources. Our own data, and that of many other studies, show that older participants have lowered cognitive capacity ( Craik and Salthouse, 2000). In our explicit timing task, this low cognitive capacity was directly linked to an increase in the variability of older adults' temporal judgments (see also Bartholomew et al, 2015; Turgeon et al, 2016). By contrast, in our implicit timing task, the index of performance reflecting the asymmetry of the RT distribution, and thereby the influence of the hazard function, did not correlate with inter-individual differences in cognitive scores. In fact, this measure of asymmetry covaried significantly with age (and performance IQ in Experiment 2), but not with attentional or working memory scores, indicating that that speeding in RTs for late versus early targets provides an age-dependent measure of performance that is unconfounded by potential cognitive dysfunction. Nevertheless, the D2 test (Brinckenkamp et al, 1988) we used to

assess individual attentional function is a neuropsychological measure of selective and sustained attention that does not assess one specific component of attention, but several interconnected components. In future experiments, it will be informative to verify our results with more specific neuropsychological tests of attention, including those on inhibitory control. Since older adults have poor inhibitory control (Hasher and Zacks, 1988), we might predict that the impact of the hazard function on performance of our implicit timing task might be greater in individuals with poor inhibitory control, i.e. an inability to resist “waiting” for an improbable target once the critical (trained) interval has passed. Indeed, response inhibition is a critical component of being prepared to respond at the right time (Davranche et al, 2007; Los, 2013) and, in response conflict tasks, it has been shown that the higher the temporal probability of event occurrence, the more likely the participant is to make an inappropriate response (Correa et al, 2010; Korolczuk et al, 2018).

In summary, performance on both explicit and implicit timing tasks indicates that older participants are able to memorize a trained interval as accurately as young participants. Our data also confirm prior findings that age-related differences in performance of an explicit timing task (duration judgement) may not be a true reflection of the effects of age on timing variability but, instead, simply reflect the effects of age on attentional function. On the other hand, age-associated differences in implicit timing performance are unrelated to general cognitive ability and appear to reflect an increased reliance on the temporal probabilities conveyed by the hazard function, rather than those conveyed by a pre-learned interval.

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### Figure captions

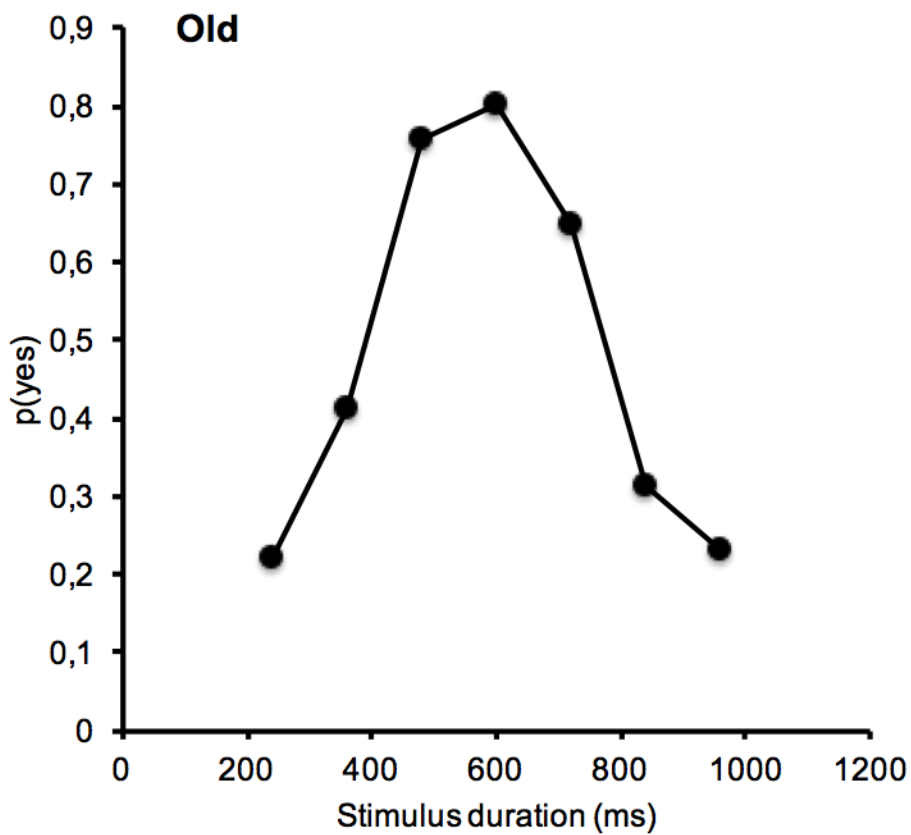
**Figure 1.** Proportion of “yes” response plotted against interval duration for young and older participants in the explicit timing task.

**Figure 2.** Peak time (a measure of temporal accuracy) and full width at half maximum (FWHM) (a measure of temporal variability) of curves fitted to young and older participant's data in the explicit timing task.

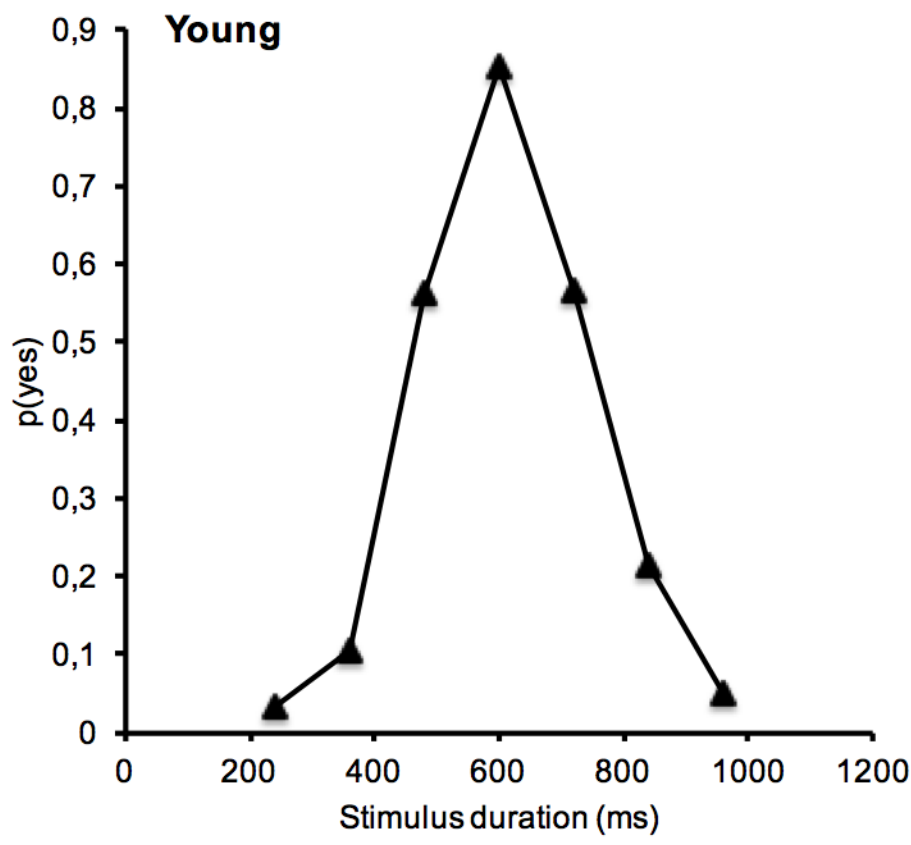
**Figure 3.** Mean reaction time (RT) plotted against interval duration for young and older participants in the implicit timing task at the short (600ms, Experiment 1) and the long (1200ms, Experiment 2) interval duration range.

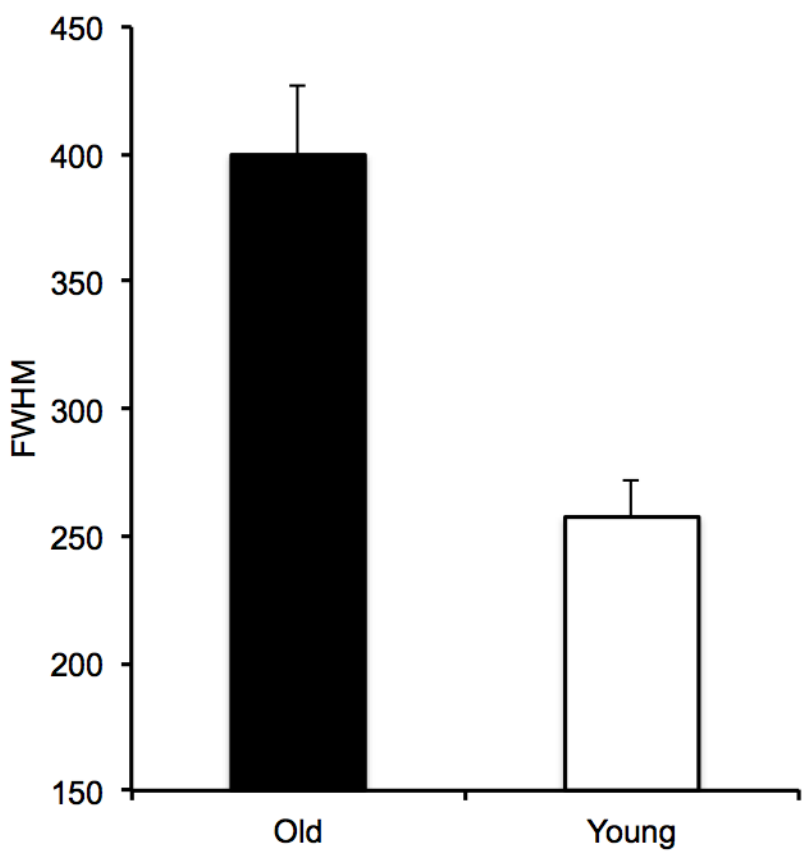
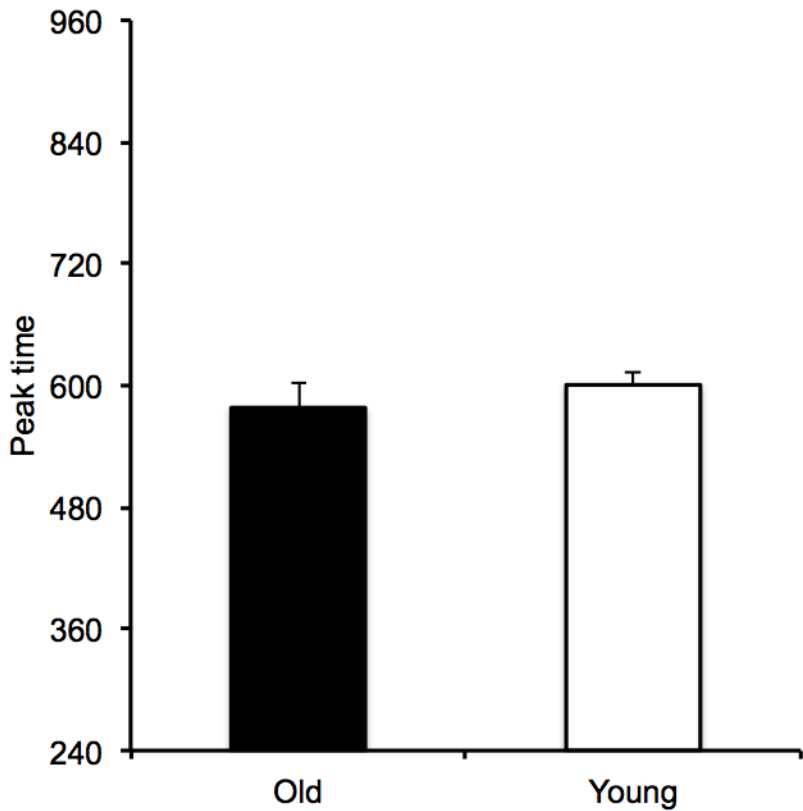
**Figure 4.** Peak time (a measure of temporal accuracy) and difference in the absolute slope for early versus late targets (a measure of RT distribution asymmetry) for young and older participants at the short (600ms, Experiment 1) and the long (1200ms, Experiment 2) interval duration range of the implicit timing task.

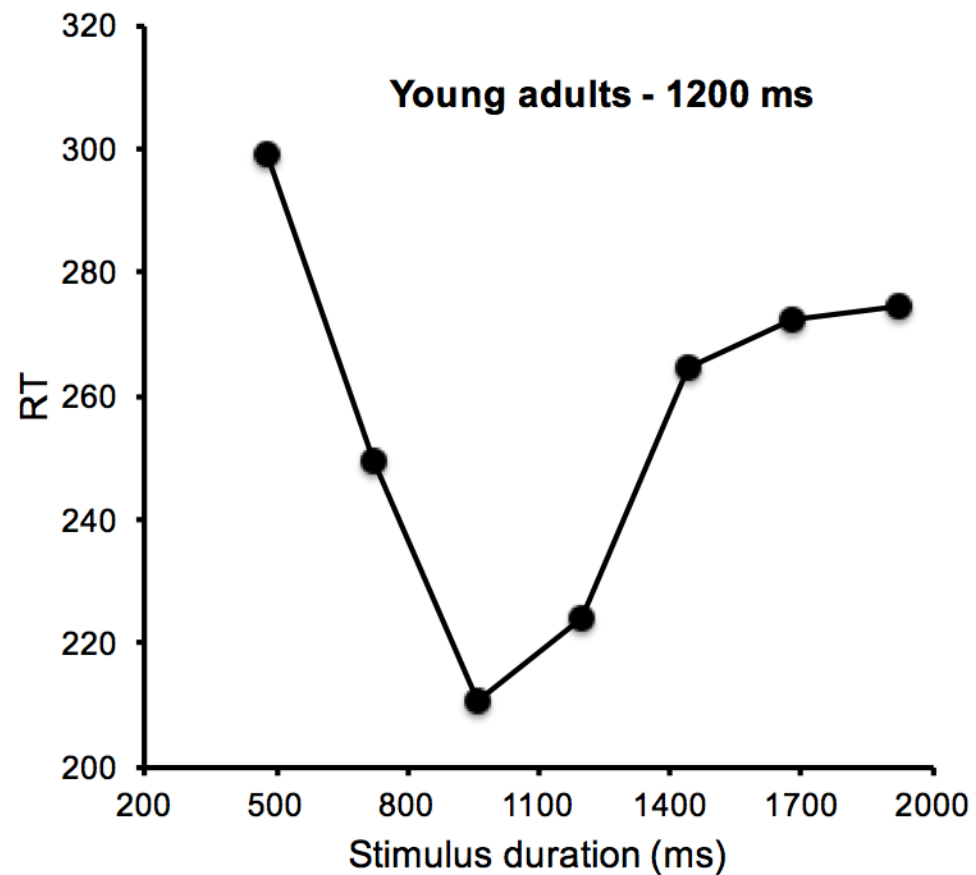
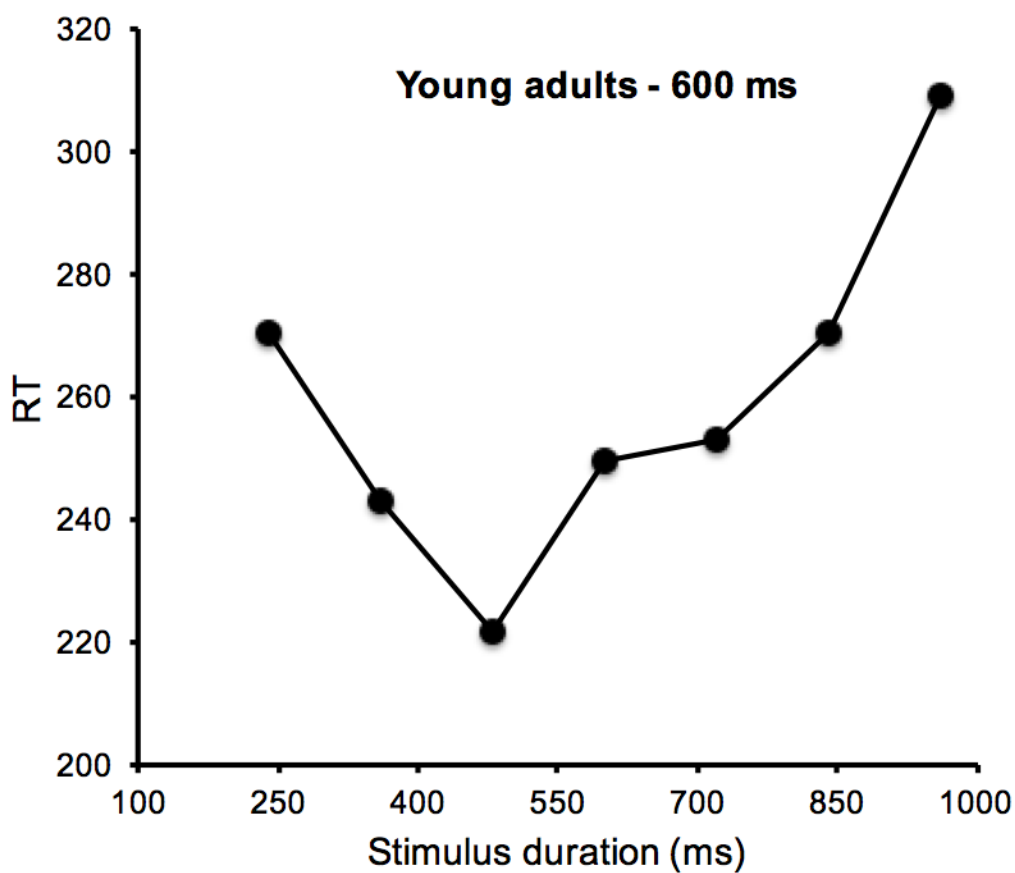
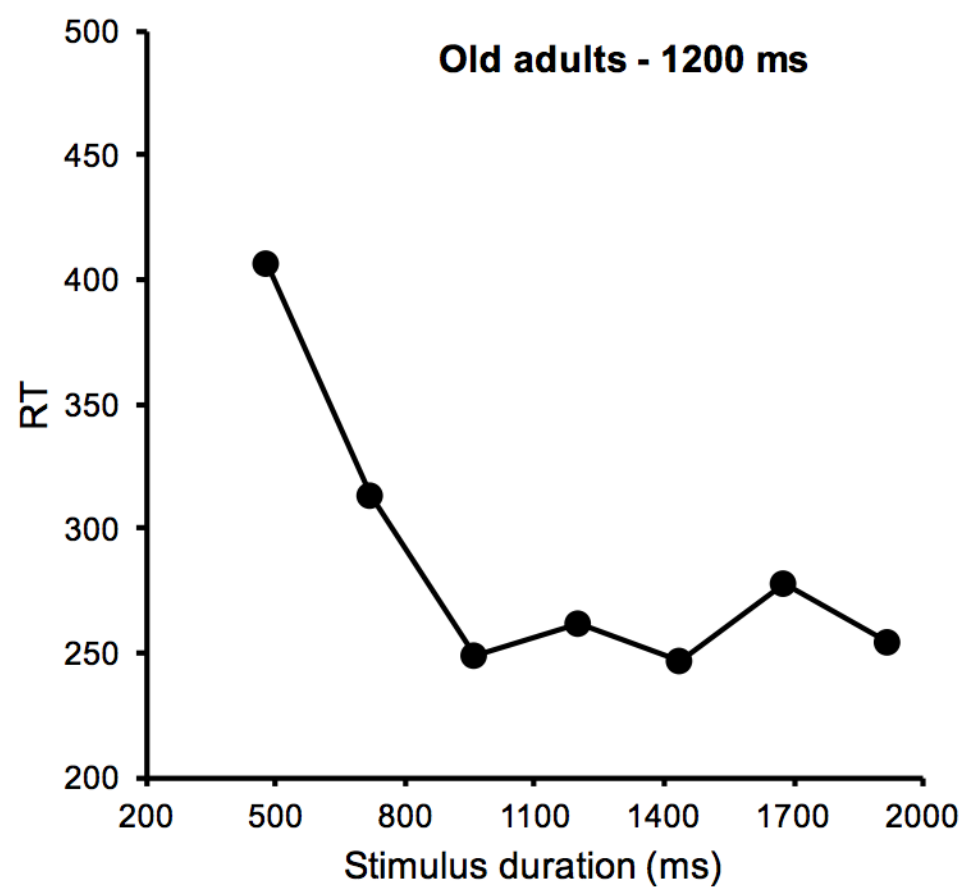
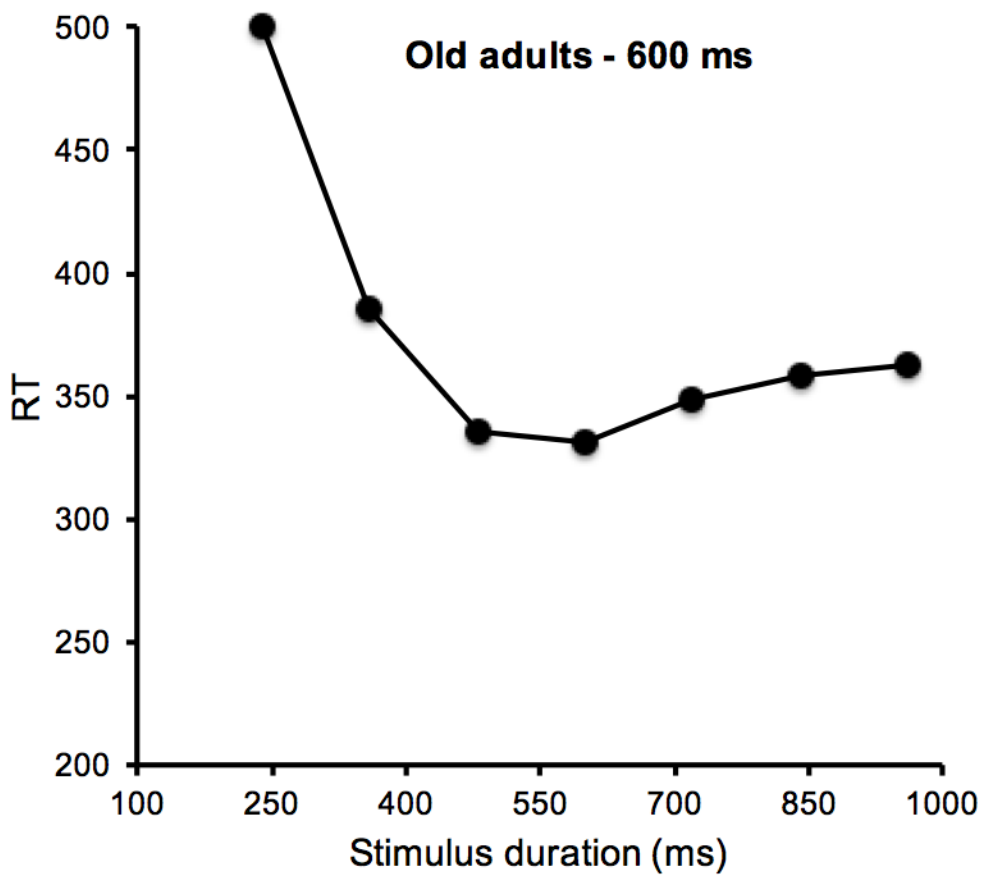
**Old**



**Young**







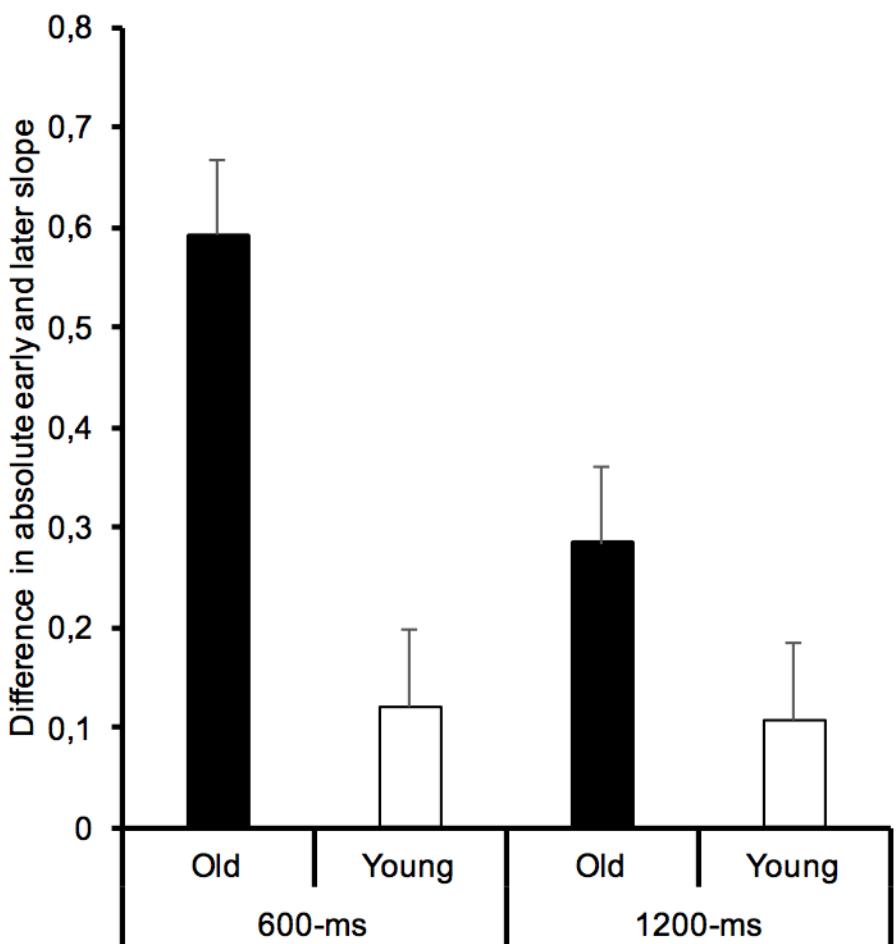
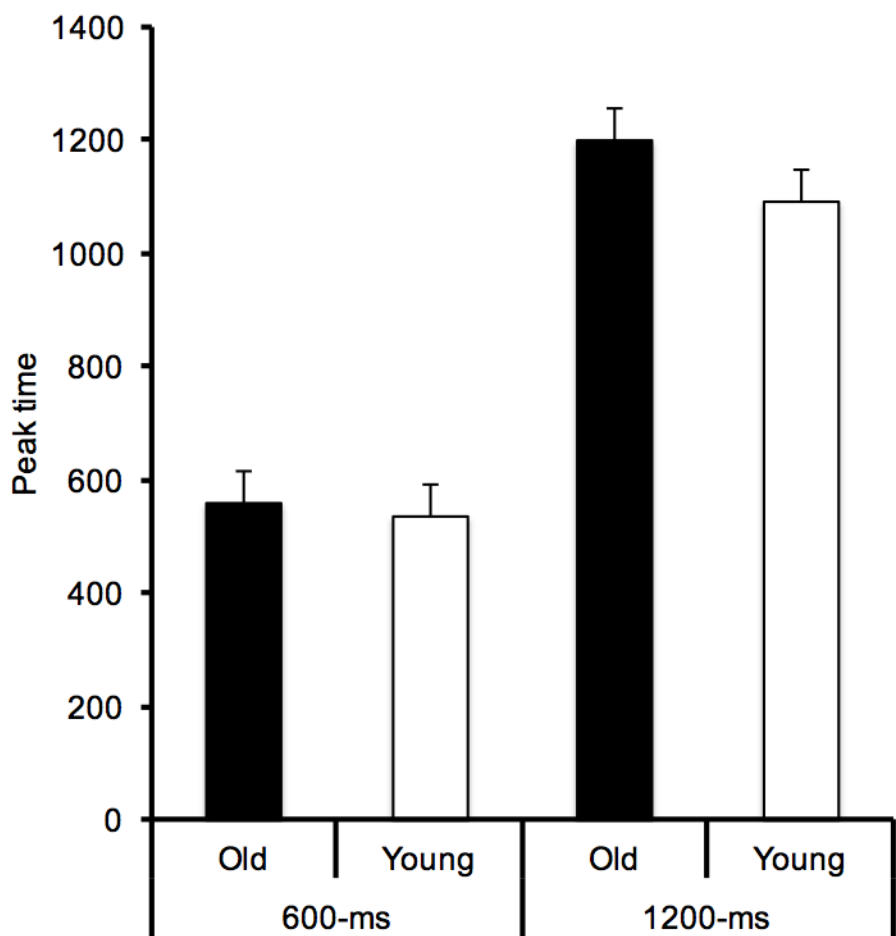




Table 1

Age, years of school education, verbal IQ, performance IQ and neuropsychological test scores for the old and young participants in the different task groups of Experiment 1 and 2.

	Experiment 1				Experiment 2	
	Explicit		Implicit		Implicit	
	M	SD	M	SD	M	SD
<b>Age (years)</b>						
<i>Old</i>	71.50	6.19	71.05	6.30	72.40	7.27
<i>Young</i>	22.65	4.66	19.45	1.50	19.90	0.72
<b>Education<sup>1</sup> (years)</b>						
<i>Old</i>	10.00	2.92	8.45	2.06	11.40	2.91
<i>Young</i>	12.10	1.07	11.60	1.27	12.00	0
<b>Verbal IQ</b>						
<i>Old</i>	50.75	18.55	50.75	14.64	59.00	11.77
<i>Young</i>	54.95	12.64	50.95	8.95	52.70	6.98
<b>Performance IQ</b>						
<i>Old</i>	42.65	13.50	40.95	12.68	51.20	13.23
<i>Young</i>	69.50	12.50	63.50	11.13	66.00	13.66
<b>Short-term memory</b>						
<i>Old</i>	7.65	1.84	8.05	2.04	7.75	1.48
<i>Young</i>	10.35	1.93	9.40	1.98	8.95	1.67
<b>Working memory</b>						
<i>Old</i>	4.95	2.11	5.00	1.81	5.60	1.82
<i>Young</i>	6.60	1.76	6.15	1.59	6.60	2.01
<b>Attention</b>						
<i>Old</i>	493.05	104.05	521.40	139.52	564.63	47.85
<i>Young</i>	630.20	39.90	635.05	28.31	640.00	52.12

1. In France, from preparatory class (CP) in primary school (6-7 years)

Table 2

Correlation between peak time (temporal accuracy) or full width at half maximum (FWHM) (temporal variability) of the explicit timing data and age or neuropsychological scores.

	Peak time	FWHM
Age	-.21	.54**
Short-term memory	-.07	-.48**
Working memory	.01	-.38*
Attention	.18	-.58**

\*  $p < .05$ , \*\*  $p < .001$

Table 3

Hierarchical regression analyses of temporal variability (FWHM) in the explicit timing task

*First analysis*

	B	SE B	$\beta$	R <sup>2</sup>
Model 1				
1. Age	2.59	0.65	0.54	0.30**
Model 2				
1. Age	1.92	0.79	0.40*	
2. Short-term memory	-12.83	8.62	-0.25	
Overall significance				0.34**
Model 3				
1. Age	1.95	0.80	0.41*	
2. Short-term memory	-8.51	11.87	-0.16	
3. Working memory	-6.16	11.51	-0.11	
Overall significance				0.34**
Model 4				
1. Age	0.35	1.03	0.07	
2. Short-term memory	-17.82	11.93	-0.34	
3. Working memory	4.61	11.85	0.80	
5. Attention	-0.51	0.22	-0.44*	
Overall significance				0.43**

*Second analysis*

	B	SE B	$\beta$	R <sup>2</sup>
Model 1				
1. Age	2.59	0.65	0.54	0.30**
Model 2				
1. Age	1.33	0.85	0.28	
2. Attention	-0.45	0.21	-0.39*	
Overall significance				0.37**

*Third analysis*

	B	SE B	$\beta$	R <sup>2</sup>
Model 1				
1. Attention	-0.67	0.15	-0.58	0.33**
Model 2				
1. Attention	-0.45	0.21	-0.39	
2. Age	1.33	0.85	0.28	
Overall significance				0.37**

\*  $p < .05$ , \*\*  $p < .001$

Table 4

Correlation between neuropsychological scores, age, peak time and difference in the absolute early/late target slope in the implicit timing task for the 600-ms (Experiment 1) and the 1200-ms interval duration range (Experiment 2).

	600-ms condition		1200-ms condition	
	Peak time	Slope difference	Peak time	Slope difference
Age	.09	.48**	.22	.34*
Short-term memory	-.10	-.14	.13	-.05
Working memory	.03	-.12	-.04	-.03
Attention	-.07	-.07	-.20	-.29

\* $p < .05$ , \*\* $p < .001$