

A multimodal analysis of sustained attention in younger and older adults

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Abstract

Age-related cognitive decline has been attributed to processing speed differences, as well as differences in executive control and response inhibition. However, recent research has shown that healthy older adults have intact, if not superior, sustained attention abilities compared to younger adults. The present study used a combination of reaction time, thought probes, and pupillometry to measure sustained attention in samples of younger and older adults. The reaction time data revealed that, while slightly slower overall, older adults sustained their attention to the task better than younger adults, and did not show a vigilance decrement. Older adults also reported fewer instances of task-unrelated thoughts and reported feeling more motivated and alert than younger adults, despite finding the task more demanding. Additionally, older adults showed larger, albeit later-peaking, task-evoked pupillary responses, corroborating the behavioral and self-report data. Finally, older adults did not show a shallowing of task-evoked pupillary responses across time, corroborating the finding that their reaction times also did not change across time. The present findings are interpreted in light of processing speed theory, resource-depletion theories of vigilance, and recent neurological theories of cognitive aging.

Keywords: aging; sustained attention; vigilance; mind wandering; pupillometry

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Considerable research has shown that aging is associated with declines in many cognitive processes, including processing speed, inhibition, and working memory (Salthouse, 2010). Processing-speed theory posits that age-related decline in processing speed interferes with the speed and efficiency with which many cognitive operations can be carried out (Salthouse, 1996). Slowing of processing speed means that certain cognitive operations may not be effectively completed in the available amount of time and limits the amount of simultaneously available information needed for higher order cognition. Thus, age-related decline in processing speed can explain findings of slower overall processing and age-related decline in higher-order cognition (e.g., Fozard, Vercruyssen, Reynolds, Hancock, & Quilter, 1994; Salthouse, 1996, 2013, 2019; Salthouse & Ferrer-Caja, 2003; Vallesi, Tronelli, Lomi, & Pezzetta, 2021; Verhaeghen & Salthouse, 1997).

However, age deficits are still found on many cognitive tasks even after controlling for processing speed, suggesting that other factors may contribute to performance. For example, the inhibitory deficit theory posits that aging is associated with declines in inhibitory mechanisms needed to prevent access of task-irrelevant information into the focus of cognition (Hasher, Lustig, & Zacks, 2007; Hasher & Zacks, 1988). Inhibitory declines in the ability to restrain from prepotent (but incorrect) responding also occur. The dual mechanisms of control framework posits that these errors may occur due to the inability for older adults to proactively maintain task-relevant goals in working memory and/or failures of reactive control processes following stimulus onset (e.g., Braver, 2012; Braver et al., 2001; Bugg, 2014a, 2014b; Paxton, Barch, Storandt, & Braver, 2006). Thus, declines in the ability to maintain task goals and inhibit task-irrelevant information may underlie age-related decrements in higher order cognitive tasks.

Given that aging is associated with declines in attention and inhibitory control, one would expect older adults to mind-wander more than younger adults. Mind-wandering,

especially during an externally directed task (e.g., reading, having a conversation, driving a car), is often considered a failure of executive control, allowing for internally-directed thoughts to usurp the focus of attention from ongoing task goals (McVay & Kane, 2010). However, the aging literature has revealed a robust and somewhat paradoxical pattern indicating that older adults report *less* mind-wandering than younger adults (Frank, Nara, Zavagnin, Touron, & Kane, 2015; Giambra, 1989, 2000; Jackson & Balota, 2012; Jackson, Weinstein, & Balota, 2013; Krawietz, Tamplin, & Radvansky, 2012; Moran et al., 2021; Shake, Shulley, & Soto-Freita, 2016; Staub et al., 2014b; Zavagnin, Borella, & De Beni, 2014). This seems to contradict the frequent observation that people with relatively poor executive-attention abilities (e.g., working memory capacity, attentional control) tend to report *more* instances of mind-wandering, especially in cognitively-demanding situations (Kane et al., 2007, 2016; McVay & Kane, 2009a, 2012b, 2012a; Mrazek et al., 2012; Robison, Gath, & Unsworth, 2017; M. K. Robison et al., 2020; Robison & Unsworth, 2015; Rummel & Boywitt, 2014; Unsworth & McMillan, 2013, 2014; Unsworth, McMillan, Brewer, & Spillers, 2012; Unsworth et al., 2020).

Several hypotheses have been proposed to explain this perplexing relationship between aging and mind-wandering propensity. One possibility put forth by Smallwood and Schooler (2006) is that mind-wandering is a resource-demanding process. Therefore, compared to younger adults, it may be more taxing for older adults to engage in mind-wandering due to their “limited cognitive capacity” (Craik & Byrd, 1982). However, McVay, Meier, Touron, and Kane (2013) compared younger and older adults’ sustained attention performance preceding various off-task thought reports and found that younger and older adults produced similar performance decrements during periods of mind-wandering. If age differences in mind-wandering were driven by cognitive capacity, and cognitive capacity decreases with age, then one would expect older adults to show greater performance decrements during periods of mind-wandering than younger adults. A second hypothesis which has attempted to explain age differences in mind-wandering posits

that older adults either lack the meta-awareness or are more reluctant to report mind-wandering (Einstein & McDaniel, 1997; Zavagnin et al., 2014). However, the findings of several experiments have challenged this hypothesis: Frank et al. (2015) found that older adults' thought reports were just as veridical as younger adults' in relation to objective mind-wandering-related eye-movement patterns, and results from Giambra (1973) indicate that older adults actually report a more positive view of mind-wandering than younger adults. Finally, the highly cited control failure \times current concerns hypothesis suggests that the negative relationship between age and mind-wandering is driven by age differences in how the testing context may cue personally relevant TUTs (McVay & Kane, 2010). For older adults, the university laboratory contains few reminders of their current concerns whereas, for younger adults, it is more directly tied to their current concerns. However, this hypothesis is contradicted by evidence showing that older adults still report fewer mind-wandering episodes than younger adults even when tested outside the laboratory context (Diede et al., under review; Jackson et al., 2013).

Another finding that is at odds with an executive control/inhibition account of aging is the fact that older adults sometimes show better performance on measures of sustained attention compared to younger adults, although these findings are mixed. The *vigilance decrement* is a worsening of performance with time on task, and it is observed across many different tasks, including perceptual discrimination tasks (Jerison & Pickett, 1964; Parasuraman, 1979; Parasuraman & Mouloua, 1987), the Psychomotor Vigilance Task (PVT; Unsworth & Robison, 2016, 2020; Massar, Lim, Sasmita, & Chee, 2016; Massar et al., 2019b; Robison, Unsworth, & Brewer, 2021), *n*-back tasks (Hopstaken et al., 2015a, 2015b; Hopstaken, Linden, Bakker, Kompier, & Leung, 2016), and the Sustained Attention to Response Task (SART; McVay & Kane, 2009b, 2012a). Some studies have specifically examined vigilance decrements and how they differ as a function of age. For example, in a stimulus-discrimination task, Parasuraman, Nestor, and Greenwood (1989) showed that older adults had lower discrimination ability overall, compared to younger adults, but did

not show steeper vigilance decrements. Deaton and Parasuraman (1993) also showed overall lower discrimination ability among older adults, despite no differences in the vigilance decrement. However, opposite patterns have been observed. For example, Tomporowski and Tinsley (1996) observed significantly better discrimination and a shallower vigilance decrement among older adults compared to younger adults in a similar stimulus-discrimination task. In a go/no-go task, Staub et al. (2014c) observed that younger adults showed a vigilance decrement across time, but older adults did not, and that older adults also reported being more motivated and reported fewer TUTs than younger adults (see also Brache, Scialfa, & Hudson, 2010; Staub et al., 2014a; Staub, Doignon-Camus, Marques-Carneiro, Bacon, & Bonnefond, 2015). In fact, a recent meta-analysis of SART performance concluded that, although older adults show slower RTs on “go” trials, they exhibit fewer false alarms on “no-go” trials and show greater post-error slowing compared to younger adults (Vallesi et al., 2021). Staub et al. (2014a, 2014c, 2015) suggest that traditionally vigilance tasks, which require responses on a rare subset of trials, differ substantially from tasks like the SART, which require responses to be withheld on a rare subset of trials, and this produces the discrepancies between such tasks and SART-like tasks.

As a potential explanation for these two paradoxical effects (i.e., lower mind-wandering and better inhibitory control in older adults), it has been hypothesized that age-group differences in dispositional factors such as conscientiousness, task interest, and motivation may underlie age differences in mind-wandering and sustained attention. Indeed, evidence is accumulating to support this hypothesis. For example, Jackson and Balota (2012) proposed that older adults’ increased conscientiousness, task interest, and perceived task difficulty may lead them to be less likely to engage in mind-wandering than younger adults. Indeed, Krawietz et al. (2012) found that including interest as a covariate eliminated the age difference in mind-wandering reported during a reading comprehension task, Frank et al. (2015) and Seli et al. (2020a) reported that participants’ self-reported

motivation partially mediated the relationship between age and mind-wandering, and Nicosia and Balota (2021) found that a dispositional composite score comprised of self-reported conscientiousness, interest, and motivation fully mediated the relationship between age and mind-wandering. Thus, it is possible that dispositional factors may explain age differences in mind-wandering although the physiological mechanisms through which this is achieved remain unclear.

In the present study, we elected to use the PVT because this task has been extensively used with younger adults. The behavioral and physiological correlates of performance are well-understood and thus offer a clear comparison against which older adults can be evaluated. The PVT is often employed to study the behavioral and physiological correlates of the vigilance decrement in younger adults. It is a simple reaction time task with an unpredictable stimulus onset time, and thus requires consistent attention both within and across trials. Because the PVT is a simple reaction time task, it does not require stimulus discrimination, it does not carry speed-accuracy tradeoffs, and it does not require inhibition of prepotent responses, like traditional vigilance tasks or the SART. Therefore, we can dissociate speed and sustained attention without an overriding influence of inhibitory control. Younger adults show a robust vigilance decrement in the PVT as a slowing of RTs across trials (Massar et al., 2019a, 2016; Robison et al., 2021; Unsworth & Robison, 2016, 2020), and it is of interest whether there are age-related differences in this vigilance decrement. In present study, we examined both age-group differences in *overall* reaction times and *changes* in reaction time across time. Processing speed theory would predict slower reaction times for older adults overall. An open question in the present design is whether older adults will show larger, smaller, or roughly equal vigilance decrements compared to younger adults. Another reason we used the PVT is because young adults report a large amount of TUT during the PVT, with participants reporting being in an off-task attentional state on about 50% of thought probes (Robison et al., 2021; Unsworth & Robison, 2016). Therefore, we believed it would be a good candidate task to

compare younger and older adults in their TUT tendencies to test various hypotheses regarding the age-TUT paradox.

The PVT also produces stereotypical patterns of pupillary data in young adults. Pupil dilation is often used as a physiological index of mental effort and attentional outlay (Beatty, 1982b; Beatty & Lucero-Wagoner, 2000). In the PVT, the pupil dilates in response to stimulus onset, reaches maximal dilation between 700 and 800 ms after the stimulus, then quickly returns to baseline. The magnitude of this response tends to decline across time (Robison, 2018; Unsworth & Robison, 2016), mirroring the worsening of performance across trials, is larger when participants self-report being on-task versus off-task (Unsworth & Robison, 2017b), and correlates with individual differences in performance on the task (Unsworth & Robison, 2017b), with individuals who show larger pupillary responses emitting faster reaction times. Thus, we can compare the magnitude of pupillary responses, the change in magnitude across trials, and differences in magnitude across self-reported attentional states between younger and older adults. Novel to the present study, and rather exploratory in nature, was the question of whether the *latency* of pupillary responses would differ across age groups. It is possible that this physiological response may not differ in *magnitude* across younger and older adults, but would differ in the time course at which it occurs. Latency differences, but not necessarily magnitude differences, would be predicted by processing speed and neural response theories of aging (Bartzokis, 2004, 2011; Lu et al., 2011, 2013). However to our knowledge, no study has specifically examined the latency of pupillary response as they relate to age-related changes in processing speed.

An additional reason to include pupillometry in the present study, is that it provides an indirect index of locus coeruleus-norepinephrine system (LC-NE) functioning (Joshi, Li, Kalwani, & Gold, 2016; Rajkowski, 1993; Varazzani, San-Galli, Gilardeau, & Bouret, 2015). Recently, it has been theorized that the relative integrity of the LC-NE system may be a crucial factor underlying age-related changes in cognition (Mather & Harley, 2016;

Robertson, 2013). Evidence for such a connection comes from both *in vivo* and postmortem measurements of LC integrity in association with cognitive aging and risk for Alzheimer's disease (AD). For example, Clewett et al. (2016) used a neuromelanin-sensitive magnetic resonance imaging (MRI) contrast to assess LC neuron density in younger and older adults. Using signal intensity from the neuromelanin contrast as a measure of LC density, Clewett et al. (2016) examined associations between LC density and a composite "cognitive reserve" score formed by scores on the Wechsler Test of Adult Reading (Wechsler, 2001), occupational attainment, and level of education. Among older adults, there was a positive association between LC density and the composite cognitive reserve score. In postmortem examinations of 165 brains from participants in the Rush Memory and Aging Project, Wilson et al. (2013) measured neuronal density in the substantia nigra, ventral tegmental area, dorsal raphe nucleus, and the LC. Over the course of their participation in the project (about six years, on average), participants' cognitive functioning was measured annually with 19 tests of episodic memory, working memory, semantic memory, perceptual speed, and visuospatial ability. Wilson et al. modeled change in cognitive functioning with a composite of all of the cognitive tests. Then, they examined which neuronal densities and other neuronal pathologies (Lewy bodies and brainstem tangles) were associated with both overall cognitive functioning and cognitive decline. When entered into a model to predict cognitive functioning, LC neuron density had a significant protective effect on cognitive decline, even after accounting for neuronal density in the other brain regions of interest. Collectively, these data suggest that LC integrity may be a protective factor in cognitive aging, and may prevent Alzheimer's-related symptoms. Thus, by including pupillometry within the design, we may be able to gain insight into relative LC-NE functioning in younger and older adults, albeit with a sample of healthy older adults.

Overall, our goal was to produce a multimodal dataset comprising objective measures of speed and sustained attention via reaction time, subjective measures of motivation, alertness, and perceptions of task demand, and physiological measures of task-based effort

and relative speed of neural processes. From these data, we hoped to answer several questions: First, how do younger and older adults compare in processing speed in a simple reaction time task? Our prediction, based on processing speed theory, is that older adults would have slower reaction times than younger adults, on average. Figure 1A shows what a processing speed difference would look like in the present study. Second, how does the vigilance decrement differ between younger and older adults? Prior research is mixed on this point, with some studies showing worse sustained attention among older adults (e.g., Parasuraman et al., 1989), and some showing better sustained attention among older adults (Brache et al., 2010; Staub et al., 2014a, 2014c, 2015; Tomporowski & Tinsley, 1996). Figures 1B and 1C visually illustrate what these patterns could look like in the present data. It is also possible that we observe no differences in reaction times across age groups. Third, what subjective factors might account for age-related differences in both sustained attention and subjective task engagement (i.e., mind-wandering)? Based on prior work (Jackson & Balota, 2012; Krawietz et al., 2012; Nicosia & Balota, 2021; Seli et al., 2020a), we predict that either motivation, alertness, perceptions of task-demand, or their combination will mediate the association between age and TUT. Finally, will physiological indices of effort corroborate the behavioral and subjective differences between younger and older adults? These analyses were largely exploratory. But processing speed theory predicts that older adults will have significant delays in cognitive processing, and this could be captured by the latency of stimulus-evoked pupillary responses.

Method

Participants and procedure

The sample included 60 younger adults and 62 older adults. Younger adults were recruited from the undergraduate human subject pool at Washington University in St. Louis and were compensated with partial course credit. Older adults were recruited from the St. Louis metropolitan area and compensated with cash (\$10/hour). The

laboratory sessions lasted about two hours. In order, participants completed the following tasks: Psychomotor Vigilance Task (PVT), Raven Advanced Progressive Matrices (Raven, Raven, & Court, 1962), number series (Thurstone, 1938), letter sets (Ekstrom, Dermen, & Harman, 1976), a general knowledge quiz, a synonym quiz, and an antonym quiz (Hambrick, Salthouse, & Meinz, 1999), the color-word Stroop task (Stroop, 1935), the Simon task (Simon, 1990), and the consonant or vowel/odd or even (CVOE) task (Minear & Shah, 2008). The final nine tasks were collected as part of a larger study assessing age-related differences in attention, fluid intelligence, and crystallized intelligence. The present examination focuses on the data from the PVT. The data from the other tasks will be analyzed and reported in a separate manuscript examining age-related differences in attentional control, fluid intelligence, and crystallized intelligence. Eye-tracking data were only collected before, during, and immediately after the PVT. Prior to beginning the session, all participants gave written informed consent and completed a demographic questionnaire. The questionnaire asked participants to report their gender, age, handedness, highest level of education, racial/ethnic background, employment status, their occupation/college area of study, domestic arrangement (living alone or with others), self-rated current health, any medical treatment for heart disease, high blood pressure, anxiety, stroke, or depression, as well as an open-ended “other” response option, any prescription medications they believed might affect their memory, any previous brain injuries, and whether they were wearing corrective lenses.

Task

The PVT is a simple reaction time task. Each trial began with a row of black fixation crosses centered on a gray background. This fixation screen appeared for 2 seconds. Then, a row of blue zeros (00.000) appeared at the center of the screen. After a random time interval sampled from a uniform distribution ranging from 2-10 s, the zeros began counting forward like a stopwatch. The participants’ task was to press the spacebar as soon as they

noticed this change occurring. After the participant pressed the spacebar, the numbers turned red and paused for 1 second, revealing the reaction time for that trial (e.g., 00.378). Then, after a 1-second blank intertrial interval, the next trial began. There were 160 trials in total. Thought probes appeared on 30 randomly-sampled trials. For statistical analyses, the trials were divided into 5 blocks of 32 trials. But this division was not apparent to participants, and there was no division between blocks present in the procedure. Participants completed the tasks individually in a well-lit room.

Thought probes

The thought probe screens asked participants to “Please characterize your current conscious experience.” There were 5 response options: 1) I am totally focused on the current task, 2) I am thinking about my performance on the task or how long it is taking, 3) I am distracted by sights/sounds/temperature or by physical sensations (hungry/thirsty), 4) I am daydreaming/my mind is wandering about things unrelated to the task, and 5) I am not very alert/my mind is blank or I’m drowsy. Participants pressed the key corresponding to the response that best matched their immediately preceding thoughts. Response 1 was scored as on-task, response 2 as task-related interference, response 3 as external distraction, response 4 as mind-wandering, and response 5 as mind-blanking (Unsworth & Robison, 2016).

Self-report questionnaires

After the PVT, participants were asked to rate, on a scale from 1-9, how motivated they felt to perform well on the task (1 = completely unmotivated, 9 = completely motivated). They were also asked to rate, on a scale from 1-9, how drowsy they felt (1 = very alert, 9 = very drowsy). Participants then completed the NASA-Task Load Index (TLX), a measure of workload (Hart & Staveland, 1988). Participants were asked to make ratings regarding mental demand, physical demand, temporal demand (i.e., task pacing),

perceptions of performance, effort level, and frustration level on the PVT. These ratings were made on a scale from -10 to 10 in 0.5-unit increments.

Pupillometry

Pupil data were collected via an SR Systems EyeLink eye-tracker at 1000 Hz. Prior to beginning the task, participants' left eyes were manually calibrated to the eye-tracker using the built-in calibration procedure for pupil size and gaze position. The EyeLink reports pupil size in arbitrary units. Data were normalized within participants in several ways. First, the data from the fixation screen were extracted for each trial. Average pupil size across the 2-second window was computed and then standardized within individuals. Then, the data were epoched to include the window from 100 ms before stimulus onset to 1,200 ms after stimulus onset. Data were normalized within this window, then averaged into 50-ms-wide windows. All values were then subtracted from the average of the 100-ms prestimulus window to compute a task-evoked pupillary response (TEPR) on each trial for each participant.

Data analysis

The data were analyzed in R using the *tidyverse* (Wickham, 2017), *lmerTest* (Kuznetsova, Brockhoff, & Christensen, 2017), *cowplot* (Wilke, 2020), *psych* (Revelle, 2018), and *lavaan* (Rosseel, 2012) packages. Data were screened for outliers by eliminating any data point outside +/- 3 SDs of each group mean. All data and analysis scripts can be found on the Open Science Framework at the following URL: <https://osf.io/63wcj/>

Results

Descriptive statistics for all measures are listed in Table 1.

Behavioral results

For most analyses of both the behavioral and pupillary data, we used linear mixed effects models to examine age-group differences, time-on-task effects, and their interactions. Unless otherwise noted, the linear mixed effect models set participant as a random effect with both the intercept and the slope (e.g., the effect of block) to vary across participants. Block was centered at zero [-2, -1, 0, 1, 2]. Age group was treated as a categorical variable with sum-to-zero coding (younger adults = -1, older adults = 1).

Reaction times (RTs). Average RTs are plotted as a function of block in Figure 2A. The model on RTs indicated a significant main effect of block, such that RTs increased across blocks ($b = 9.00$, $SE = 1.29$, $p < .001$), but a non-significant main effect of age group ($b = 23.89$, $SE = 14.73$, $p = 0.11$). Older adults' RTs were slightly but not significantly slower overall. The main effects were qualified by a significant block x age group interaction, such that older adults exhibited significantly *shallower* vigilance decrements than younger adults ($b = -5.86$, $SE = 1.29$, $p < .001$). Examining the RT data for each age group individually revealed that, while younger adults showed significant slowing of RTs across time ($b = 14.86$, $SE = 1.78$, $p < .001$), older adults did not ($b = 3.10$, $SE = 1.88$, $p = 0.10$).

To further examine how younger and older adults differed in RTs, we analyzed group differences in two additional measures: intraindividual variability in RTs and RTs by speed quintile. Previously, it has been shown that intraindividual variability in RT increases across time in the PVT (Unsworth & Robison, 2016). We wanted to see if the current data would replicate that general pattern, and to see whether younger and older adults differed in these estimates both on average and across time. Previous research has shown that intraindividual variability in RT also increases in aging (Hultsch, MacDonald, & Dixon, 2002; Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000; McAuley, Yap, Christ, & White, 2006; Spieler, Balota, & Faust, 1996; Tse, Balota, Yap, Duchek, &

McCabe, 2010; West, Murphy, Armilio, Craik, & Stuss, 2002). To analyze intraindividual RT variability, we computed each participant's coefficient of variation (standard deviation/mean; CoV) of RTs in each block and analyzed these estimates across blocks and age groups. The model revealed a significant main effect of block, such that intraindividual variability in RTs increased across time ($b = 0.007$, $SE = 0.003$, $p = 0.02$), replicating the pattern observed by Unsworth and Robison (2016) in this task. There was also a significant group difference in RT variability ($b = 0.03$, $SE = 0.007$, $p < .001$), such that older adults showed more intraindividual variability in RT than younger adults. The block x age group interaction was not significant ($b = -0.005$, $SE = 0.003$, $p = 0.10$). These data are plotted in Figure 2B.

To examine RTs by speed quintile, we first rank-ordered individuals' RTs from fastest to slowest. Then, we binned RTs into five quintiles by speed (fastest 20% to slowest 20% of trials). On one hand, if age group differences are simply a matter of gross speed differences, we should observe roughly equal group differences at each quintile. On the other hand, age group differences may mostly manifest in a specific segment of the distribution. A model with fixed effects of quintile and age and a random effect of participant indicated a significant quintile x age interaction ($b = 6.94$, $SE = 0.48$, $p < .001$), such that larger group differences were observed at the longer RT quintiles. This suggests that when younger and older adults are at their fastest, they are roughly equivalent. But, in the instances when younger and older adults responded slowly, the older adults tended to respond particularly slowly. These data are plotted in Figure 2C.

As a final analysis on RTs, we examined how distributions of RTs shifted across blocks for each age group. Specifically, why were younger adults' RTs changing across blocks? Were only their slow RTs getting longer, or were all quintiles getting longer about equally. To analyze this, we submitted RTs to a model with fixed effects of block, quintile, age group, and their interactions. There was a significant 3-way interaction among block,

quintile, and age ($b = -1.82$, $SE = 0.35$, $p < .001$). This pattern is plotted in Figure 3. Older adults' RT distribution did not shift, on average. But younger adults slowest RTs tended to increase in duration across the task. In other words, the vigilance decrement was present primarily in the slow end of the distribution.

Thought probe responses. Thought probe response proportions are plotted in Figure 4. We specified a linear mixed model with the same specifications as the models on RTs for the each thought probe response. The model on on-task responses indicated a significant effect of block, such that on-task reports decreased across blocks ($b = -0.07$, $SE = 0.007$, $p < .001$) and a significant main effect of age, such that older adults reported more on-task thoughts than younger adults ($b = 0.12$, $SE = 0.02$, $p < .001$). The block x age group interaction was not significant ($b = 0.004$, $SE = 0.007$, $p = 0.60$). There was no significant age group difference in reports of task-related interference ($b = 0.02$, $SE = 0.02$, $p = 0.28$), and these reports did not significantly change across blocks ($b = -0.009$, $SE = 0.008$, $p = 0.24$). The block x age group interaction was modest in size but did not reach significance ($b = 0.01$, $SE = 0.008$, $p = 0.07$). Reports of external distraction were rare, and there was no difference between age groups ($b = -0.02$, $SE = 0.010$, $p = 0.12$), but they did significantly increase across time ($b = 0.01$, $SE = 0.004$, $p = 0.003$). There was no block x age group interaction ($b = 0.00004$, $SE = 0.004$, $p = 0.99$). Mind-wandering significantly increased across blocks ($b = 0.02$, $SE = 0.005$, $p < .001$), and older adults reported significantly less mind-wandering than younger adults ($b = -0.05$, $SE = 0.01$, $p < .001$). However there was not a significant block x age group interaction on mind-wandering ($b = 0.001$, $SE = 0.005$, $p = 0.84$). Finally, the model on mind-blanking reports indicated a significant main effect of block ($b = 0.05$, $SE = 0.005$, $p < .001$), such that mind-blanking increased across time, a significant main effect of age, such that older adults reported significantly less mind-blanking than younger adults ($b = -0.06$, $SE = 0.01$, $p < .001$), and also a significant block x age group interaction, such that younger adults showed a steeper increase in mind-blanking across time than older adults ($b = -0.02$, $SE = 0.005$, $p < .001$).

Reaction times preceding probe responses. We next examined RTs preceding each thought probe response by age group. Average RTs by response and age group are shown in Figure 5. To examine these effects, we submitted RTs immediately preceding thought probes to a linear mixed model with a categorical fixed effect of probe response with “on-task” as the reference level, age group as a fixed effect, and participant as a random effect. The model indicated that all other probe responses were accompanied by significantly slower RTs compared to “on-task” responses (task-related interference: ($b = 52.59$, $SE = 13.00$, $p < .001$); external distraction: ($b = 80.22$, $SE = 15.31$, $p < .001$), mind-wandering: ($b = 78.77$, $SE = 14.81$, $p < .001$); mind-blanking: ($b = 70.10$, $SE = 18.88$, $p < .001$)). However none of these effects interacted with age (task-related interference: ($b = -2.68$, $SE = 18.42$, $p = 0.88$); external distraction: ($b = -8.15$, $SE = 20.80$, $p = 0.70$), mind-wandering: ($b = -12.00$, $SE = 19.78$, $p = 0.54$); mind-blanking: ($b = 28.12$, $SE = 23.54$, $p = 0.23$)). Thus younger and older adults exhibited similar effects on their RTs when their attentional state was anything other than on-task.

Post-task self-report scales. The average self-report ratings are plotted by age group in Figure 6. Older adults reported being significantly more motivated than younger adults ($t(120) = 4.11$, $p < .001$) and significantly less drowsy ($t(120) = -6.39$, $p < .001$). Overall, older adults rated the PVT as more demanding ($t(120) = 4.40$, $p < .001$). On the subscales, older adults rated the PVT as more mentally demanding ($t(120) = 4.31$, $p < .001$), more physically demanding ($t(120) = 3.93$, $p < .001$), more temporally demanding ($t(120) = 2.43$, $p = 0.02$), and requiring more effort ($t(120) = 3.74$, $p < .001$). younger and older adults did not differ on how frustrating they found the task ($t(120) = -0.50$, $p = 0.62$), nor on how well they felt they performed on the task ($t(120) = 0.59$, $p = 0.56$).

Mediation of age-related differences in sustained attention. Older adults showed no vigilance decrement in the current study, which is also rather paradoxical given age-related differences in attention and cognitive control. To examine whether this was due to differences in motivation, drowsiness, and perceptions of task demand, we estimated

individual-level vigilance decrements using a linear mixed effect model. Then, we used these estimates in a model where age was set to have indirect effects on the vigilance decrement via self-reports of motivation, drowsiness, and task demand. In this case, there were no significant indirect effects (motivation: $b = 0.002$, $p = 0.96$, 95% CI = [-0.07, 0.08]; drowsiness: $b = 0.12$, $p = 0.19$, 95% CI = [-0.06, 0.30]; demand: $b = -0.005$, $p = 0.87$, 95% CI = [-0.07, 0.06]). After accounting for these three subjective measures, there was still a significant direct effect of age group on the vigilance decrement ($b = -0.24$, $p = 0.02$, 95% CI = [-0.45, -0.04]). Thus, the subjective reports could not fully explain why older adults did not show a vigilance decrement.

The present study also replicated a common, yet somewhat paradoxical finding. Older adults report less mind-wandering (and other task-unrelated thoughts) and show better sustained attention. Why? One reason that has been proposed is that older adults are more motivated to complete laboratory tasks than younger adults. Indeed, older adults did report higher motivation than younger adults in the present study. But older adults also reported feeling more alert, and they reported finding the task significantly more demanding than younger adults. To examine whether these subjective factors account for the age-TUT relation, we specified a model in which age had a direct effect on TUTs and indirect effects through drowsiness, motivation, and demand. The resulting model is depicted in Figure 7. Although both demand (indirect effect: $b = -0.07$, $p = 0.03$, 95% CI = [-0.13, -0.008]) and drowsiness (indirect effect: $b = -0.21$, $p < .001$, 95% CI = [-0.30, -0.12]) significantly mediated the effect of age on TUT, there was still a significant direct path between age and TUT ($b = -0.19$, $p = 0.03$, 95% CI = [-0.36, -0.02]). The mediating effect of motivation was not quite significant (indirect effect: $b = -0.06$, $p = 0.08$, 95% CI = [-0.12, 0.007]). Therefore, drowsiness, demand, and motivation only partially mediated the relation between age and TUT.

Pupillary results

There were two sets of pupillary measures. The first was pretrial pupil diameter, which was measured as the average pupil diameter over the 2-second fixation screen preceding each trial, and the second was TEPRs, which were computed as a change in pupil diameter in response to stimulus onset on each trial.

Pretrial pupil size. First, we compared average pretrial pupil size in arbitrary units (a.u.) across age groups. Consistent with prior work, older adults had significantly smaller pupil sizes than younger adults (Figure 9A, $M_{older} = 580.53$ a.u., $M_{younger} = 893.25$ a.u., $t(102) = -9.30$, $p < .001$; Bak, Yoo, Yang, & Hwang, 2017; Birren, Casperson, & Botwinick, 1950; Winn, Whitaker, Elliott, & Phillips, 1994). We also analyzed pretrial pupil dynamics across blocks. In Unsworth and Robison (2016), pretrial pupil size dropped sharply from block 1 to block 2, then stabilized for remaining blocks. Intraindividual variability in pretrial pupil size also increased across blocks. This pattern has also been observed in other investigations of sustained attention and mental fatigue (Hopstaken et al., 2016, 2015b; Massar et al., 2019a, 2016). Here, we wanted to replicate that effect and examine whether there were any age-related differences in this pattern. Pretrial pupil size is plotted by block and age group in arbitrary units in Figure 9B and in individually-standardized units in Figure 9C. younger and older adults showed different patterns across blocks, confirmed by the presence of a block x age group interaction ($b = -0.03$, $SE = 0.01$, $p = 0.003$). Whereas older adults tended to show a small but significant monotonic decrease in pretrial pupil size across blocks ($b = -0.03$, $SE = 0.02$, $p = 0.03$), younger adults actually tended to show a small but significant increase ($b = 0.03$, $SE = 0.01$, $p = 0.04$). Although the effect in younger adults appeared curvilinear, the quadratic effect did not reach significance in the model ($b = 0.02$, $SE = 0.01$, $p = 0.06$).

Interestingly, younger and older adults also showed differential patterns of intraindividual variability dynamics. The model on variability (standard deviation of

pretrial pupil size in arbitrary units) revealed a significant main effect of block ($b = 4.06$, $SE = 0.64$, $p < .001$), such that intraindividual variability increased across time, and a significant main effect of age group, such that older adults exhibited less variability in pretrial pupil size than younger adults ($b = -27.62$, $SE = 2.78$, $p < .001$). These main effects were qualified by a significant block x age group interaction ($b = -2.66$, $SE = 0.64$, $p < .001$). Whereas younger adults showed a significant increase in variability across blocks ($b = 6.72$, $SE = 1.15$, $p < .001$), this effect was much smaller in older adults ($b = 1.40$, $SE = 0.65$, $p = 0.04$).¹ This pattern is shown in Figure 9D.

Task-evoked pupillary responses (TEPRs). We examined group-level differences in TEPRs as well as TEPR dynamics across time. The grand-averaged TEPRs for each age group are depicted in Figure 10. To statistically compare the magnitude and latency of TEPRs, we computed both the average magnitude and latency of each participant's TEPR, then compared the averages across groups. Magnitude was computed by taking the peak of the response on each trial and averaging those values within each participant. Similarly, latency was computed by taking the timepoint at which the TEPR peaked in each trial and averaging those values within each participant. Confirming what is visible in Figure 10, older adults had significantly larger TEPRs in terms of magnitude ($M_{older} = 2.04$ standardized units, $M_{younger} = 1.59$ standardized units, $t(117) = 5.59$, $p < .001$), but their TEPRs peaked significantly later than younger adults ($M_{older} = 744.71$ ms, $M_{younger} = 615.88$ ms, $t(114) = 9.73$, $p < .001$).

Our next analysis examined TEPR dynamics across blocks. Unsworth and Robison (2016) showed that TEPRs tended to significantly decrease across blocks in younger adults during the PVT, and this pattern has also been demonstrated in other investigations of mental fatigue and sustained attention (Beatty, 1982a; Hopstaken et al., 2015a). Since the older adults in this study did not show a vigilance decrement, we were interested in

¹ This pattern of results is nearly identical if using coefficient of variation rather than standard deviation as a measure of intraindividual variability.

whether they also did not show a reduction in TEPRs as a function of time-on-task. To do so we averaged the TEPRs in each block for each participant. Then, we compared the time-on-task dynamics in TEPRs (both peak and latency) by block and age group. We specified linear mixed models with peak and latency as the dependent variables, respectively, block and age group as fixed effects, and participant as a random effect. Both the intercept and slope were allowed to vary across participants. The averages are plotted by block and age group in Figure 11. Regarding TEPR magnitude, there was a significant main effect of age group ($b = 0.21$, $SE = 0.04$, $p < .001$), a significant main effect of block ($b = -0.04$, $SE = 0.01$, $p < .001$), and a significant block x age group interaction ($b = 0.21$, $SE = 0.04$, $p < .001$). Although younger adults showed a significant reduction in TEPR magnitude across blocks ($b = -0.09$, $SE = 0.02$, $p < .001$), older adults did not ($b = 0.002$, $SE = 0.01$, $p = 0.89$). This is consistent with the fact that younger adults showed significant slowing of RTs across blocks, but older adults did not. Regarding latency, the model revealed a significant main effect of age group, such that older adults' TEPRs peaked later than younger adults' ($b = 61.08$, $SE = 6.88$, $p < .001$), a significant main effect of block, such that TEPRs tended to peak later as the task progressed ($b = 4.28$, $SE = 1.59$, $p = 0.009$), but no significant block x age group interaction ($b = -0.63$, $SE = 1.59$, $p = 0.69$).

The next set of analyses examined TEPRs by speed. In the analyses of behavioral data, we examined group averages in RTs after rank-ordering participants' RTs into five quintiles from fastest to slowest. Here, we repeated that analysis but we examined how the TEPRs differed on particularly fast trials vs. particularly slow trials for younger and older adults. This was a novel analysis, and it was a bit exploratory in nature. But it analysis allowed us to assess whether there were intraindividual changes in TEPR latency and magnitude based on relative speed. That is, are faster RTs accompanied by larger and/or earlier-peaking TEPRs? Is the pattern preserved across age groups, or different? The TEPR waveforms are plotted by speed quintile in Figure 12. Younger adults' TEPRs seemed to be both shallower and later-peaking on slower trials. Older adults, although

showing longer latencies on slower trials, did not appear to have shallower TEPRs on slower trials. To examine this statistically, we repeated the analysis performed above on peak and latency by block, but with speed quintile as the independent variable rather than block. The model on TEPR magnitude revealed a small, non-significant main effect of quintile ($b = -0.01$, $SE = 0.02$, $p = 0.44$), a significant main effect of age ($b = 0.20$, $SE = 0.04$, $p < .001$), and a small and marginally significant quintile x age group interaction ($b = 0.04$, $SE = 0.02$, $p = 0.05$). Running the model separately on younger and older adults revealed that whereas older adults show a non-significant positive effect of quintile on TEPR magnitudes ($b = 0.02$, $SE = 0.03$, $p = 0.36$), younger adults showed a small and non-significant negative effect ($b = -0.05$, $SE = 0.03$, $p = 0.07$) (see Figure 12C). The model on latencies revealed a main effect of age ($b = 53.31$, $SE = 6.18$, $p < .001$) and a main effect of quintile ($b = 34.46$, $SE = 2.67$, $p < .001$), such that TEPR latencies increased for slower RTs. There was not a significant age group x quintile interaction on latency ($b = 0.70$, $SE = 2.67$, $p = 0.79$), so both younger and older adults showed roughly equal effects (see Figure 12D). To our knowledge, these results are the first to demonstrate significant changes in both TEPR magnitude and latency when comparing fast and slow trials with identical demands.

Our final set of analyses involving TEPRs separately examined TEPRs during trials preceding on-task and TUT reports (i.e., mind-wandering, external distraction, mind-blanking). The respective waveforms for younger and older adults are plotted in Figure 13. Previously Unsworth and Robison (2016) reported that participants' TEPRs were significantly shallower preceding off-task reports. To analyze this statistically, we submitted the average peak and latency of the TEPR for each participant to a linear mixed model with fixed effects for age group and report (on vs. off). There was a significant difference for on- vs. off-task reports on peaks ($b = 0.16$, $SE = 0.05$, $p < .001$), but there was no significant report x age group interaction ($b = -0.06$, $SE = 0.05$, $p = 0.22$). Thus, both age groups showed shallowed task-evoked responses on trials where they reported

being off-task, and the magnitude of this effect did not differ across age groups. There was also a significant difference between the latency of the TEPRs for on- and off-task trials ($b = -32.24$, $SE = 5.69$, $p < .001$), yet no age group x report interaction ($b = 7.06$, $SE = 5.69$, $p = 0.22$). On-task trials were accompanied by significantly earlier-peaking TEPRs in both age groups, and the magnitude of this effect did not differ across age groups. This pattern replicates prior studies showing significant differences in TEPR magnitude during on- and off-task attentional states (Unsworth & Robison, 2016, 2017b, 2018). However, to our knowledge it is the first to show significant changes in TEPR latency during off-task attentional states.

Individual differences

Because the present study was designed to examine age-related differences and not individual differences, the sample size was smaller than is typically desired for analyses of individual differences. However, we ran some exploratory analyses examining individual and age-related differences in pupil size and dynamics, sustained attention, and subjective reports. First, we examined individual differences among the full sample of participants, then each age group individually. The individual age groups had 60 and 62 participants, respectively. So the correlations and regressions within each age group should be interpreted with a degree of caution. Table 2 lists the correlations among dependent variables in the full sample of participants, Table 3 lists the correlations in the young adult sample, and Table 4 lists correlations in the older adult sample. Because many of the DVs were confounded with age, we then specified three separate regression models to examine shared and unique influences of the various subjective and pupillary measures on task performance, namely average RTs. In the first model, average RT was entered at the dependent variable with age (continuous variable), motivation, drowsiness, TUTs, average pretrial pupil size, variability (SD) in pretrial pupil size, average TEPR magnitude, and average TEPR latency as independent variables. The regression table is shown in Table 5.

Collectively, the predictors accounted for 47% of the variance in average RTs. After controlling for all variables and age, the strongest independent predictors of average RTs were TUTs, average TEPR magnitude, and average TEPR latency. Next, we separately analyzed the older and younger adult samples. These regressions were the same as those run on all participants, but they did not include age as a predictor. For the younger adults, the model accounted for 33% of the variance in average RTs, and the strongest independent predictors were average TEPR magnitude and average TEPR latency. Interestingly, the results were largely similar for the older adult sample, but the model accounted for 57% of the variance in average RTs. Again, the strongest independent predictors again were average TEPR magnitude and average TEPR latency. Therefore, the magnitude of TEPRs, which has been used in prior work to measure effort more broadly and phasic release of NE more specifically (Aston-Jones & Cohen, 2005), and the latency of TEPRs, which has received considerably less attention in the prior research, can account for the large majority of attributable variance in reaction time. We interpret these findings in the Discussion.

Discussion

The present study indicated that healthy older adults had intact, if not superior, sustained attention compared to younger adults during a simple reaction time task. This finding was present when examining RTs across time, the dynamics of TEPRs across time, and self-reports of TUTs across time.

The processing speed account of cognitive aging predicts that older adults should be slower than younger adults in the PVT, which is essentially a simple reaction time task with an unpredictable stimulus onset time. However, older adults were only about 48 ms slower than younger adults on average. When looking at segments of the RT distributions from fastest to slowest quintiles, differences between younger and older adults were observed primarily in slower trials. So although older adults were only slightly slower than younger adults overall, when older adults responded slowly, they tended to respond

particularly slowly. These results are consistent with prior work that measures of intraindividual variability and distributional analyses are often a better differentiator of younger and older adults, and older adults with and without Alzheimer's and dementia, than mean or median RTs (Balota & Yap, 2011; Duchek et al., 2009; Hultsch et al., 2002, 2000; McAuley et al., 2006; Spieler et al., 1996; Tse et al., 2010; West et al., 2002).

Despite this finding, older adults actually showed superior sustained attention compared to younger adults. Specifically, older adults did not show a vigilance decrement in RT, a pattern of slowing across time that has been repeatedly observed in younger adults using this task (Massar et al., 2016, 2019b; Robison et al., 2021; Unsworth & Robison, 2016, 2020). The younger adults did indeed show a large vigilance decrement, as is typical. Collectively the data were most consistent with the hypothesized pattern of results in Figure 1B (*speed difference + better sustained attention*). The data were also consistent with prior work showing similar patterns in both traditional vigilance tasks (Tomprowski & Tinsley, 1996), and go/no-go tasks like the SART (Brache et al., 2010; Staub et al., 2014a, 2014c, 2015; Vallesi et al., 2021). The present results cannot resolve the discrepancies observed between go/no-go tasks and other cognitive control tasks. That is, older adults tend to show more Stroop interference and reduced proactive control in continuous performance tasks, (e.g, AX-CPT; Braver, Satpute, Rush, Racine, & Barch, 2005; Bugg, 2014a; Paxton et al., 2006; Vallesi et al., 2021), but they show fewer no-go errors in the SART (Vallesi et al., 2021). We used the PVT specifically because it does not involve resolving conflict or inhibiting a prepotent response. Thus we cannot fully explain the discrepancies noted above. However, the ability to sustain attention to a particular task for a long period of time appears to be one aspect of cognition that seems to remain intact in healthy aging.

Regarding the age/mind-wandering paradox, the present results were largely consistent with prior findings that suggest this paradox can be resolved by accounting for

subjective and dispositional factors (Jackson & Balota, 2012; Krawietz et al., 2012; Moran et al., 2021; Nicosia & Balota, 2021; Seli et al., 2020b). Older adults reported fewer instances of TUTs than younger adults, including less mind-wandering and mind-blanking. We also asked participants to self-report their motivation to perform well on the PVT and how drowsy they felt following the task. Older adults reported being significantly more motivated and alert than younger adults. However, they also reported finding the task significantly more demanding than younger adults. Mediation showed that accounting for these subjective state differences significantly mediated the relation between age and TUT. Specifically, the older adults reported fewer TUTs because they found the task more demanding and because they felt more alert. These findings are consistent with prior work suggesting the age/mind-wandering paradox can be accounted for by differences in task interest, motivation, perceptions of task difficulty, and other dispositional traits, like conscientiousness.

The pupillary results also showed several interesting differences between younger and older adults. First, older adults had significantly smaller pupil diameters than younger adults, a finding consistent with prior examinations of pupil size across age (Bak et al., 2017; Birren et al., 1950; Winn et al., 1994). Across blocks, older adults showed a rather typical pattern of a decrease in pretrial pupil diameter (Massar et al., 2016, 2019b; Unsworth & Robison, 2016), but younger adults did not. Based on the behavioral data, we would have expected younger adults to also show a decrease in arousal/pretrial pupil diameter across time, but they did not. This was one finding that was particularly perplexing, and it deserves follow-up investigation. Older adults also showed less variability in pretrial pupil size than younger adults. Previously, intraindividual variability in pretrial/tonic pupil size has been used as a measure of arousal regulation, and the degree to which arousal fluctuates within an individual often correlates with their behavioral performance and how often they report TUTs (Aminihajibashi, Hagen, Andreassen, Laeng, & Espeseth, 2020; M. K. Robison & Brewer, 2020; Robison & Unsworth, 2019; Unsworth &

Robison, 2015, 2017a, 2017b). The present results indicate that older adults had more regulated arousal than younger adults, which is consistent with the fact that they also reported fewer TUTs.

The discrepancy between intraindividual variability in RTs, which was larger among older adults, and intraindividual variability in pretrial pupil diameter, which was smaller among older adults, is interesting, as it presents a bit of a paradox. In younger adult samples, intraindividual variability arousal typically correlates with worse sustained and controlled attention performance. If intraindividual variability in RT is indicative of shifting attentional state (Unsworth & Robison, 2017b, 2017a), older adults should show *more* variability in arousal than younger adults. The discrepancy here might be that intraindividual variability in RTs indexes micro-level shifts in attentional state, lapses that occur over very brief timescales but nonetheless cause slow responding, and macro-level shifts in attentional state, longer-duration shifts of attention away from the task and to totally unrelated thought streams (i.e., TUT). The fact that older adults showed more intraindividual variability in RT and slower responding in the slow tail of the distribution, but fewer TUTs, would be consistent with this account. But further research is necessary to investigate this phenomenon.

There were also several key age differences in TEPR dynamics. First, older adults showed larger TEPRs than younger adults. TEPRs have been used as measure of cognitive effort, and can be used to track the degree of effort exerted on a task, or the degree of cognitive demand required by a task (Alnæs et al., 2014; Beatty, 1982b; Beatty & Lucero-Wagoner, 2000; Kahneman & Beatty, 1966; Kahneman & Peavler, 1969; Unsworth & Robison, 2015). The fact that older adults showed larger TEPRs is consistent with the fact that they reported greater motivation, greater alertness, and perceived the PVT as more demanding than younger adults. Second, whereas younger adults showed a shallowing of TEPRs across time, consistent with prior work using this task (Unsworth & Robison,

2016), older adults did not. The shallowing of TEPRs across time among younger adults is consistent with the fact that they also exhibited a slowing of RTs across time (i.e., a vigilance decrement). The fact that older adults did not show a shallowing of TEPRs across blocks is consistent with the fact that older adults also did not show a vigilance decrement in their RTs. It is worth noting that TEPRs mimicked changes in task performance across age groups, but pretrial pupil dynamics did not. Previously, changes in both TEPR and pretrial pupil diameter have been used as indices of sustained attention as it wanes across time (Hopstaken et al., 2015a, 2016, 2015b; Massar et al., 2019a, 2016; Unsworth & Robison, 2016). But in the present data, changes in pretrial pupil diameter did not mimic changes in performance. This is a finding that also begs replication in future work. Finally, both younger and older adults showed longer RTs and shallower TEPRs preceding reports of being off-task compared to being on-task. However, these effects did not differ across age groups.

We performed several novel analyses on the TEPRs. Although other studies have shown important TEPR latency differences in other tasks (e.g., Diede & Bugg, 2017; Paivio & Simpson, 1968; Richer & Beatty, 1987), and prior work has noted within- and between-subject differences in TEPR magnitude (Massar et al., 2016, 2019b; Unsworth & Robison, 2016, 2017a, 2017b), to our knowledge no study has given careful consideration to TEPR latency in the PVT. Indeed, the present findings revealed several informative patterns regarding latency. First, older adults' TEPRs peaked much later than younger adults' - by about 130 ms on average. Thus, it appears TEPRs can be used to characterize between-subject differences in the speed of cognitive, and perhaps neural, processes. This finding is consistent a processing speed account of cognitive aging. However, it is worth noting the 130-ms discrepancy in the TEPR peaks was actually larger than the ~48-ms average RT discrepancy. Second, both younger and older adults' TEPRs were significantly later peaking on trials with slower RTs. Thus, it appears that TEPRs can be used to measure within-person processing speed differences on a trial-by-trial basis. Finally, TEPR

latency was a significant predictor of processing speed differences in both younger and older adults (see below). Collectively, these findings highlight a novel and potentially important use of the TEPR - measuring and comparing the speed of cognitive and neural processes.

Our final set of analyses examined individual differences in task performance, subjective reports, and pupillary measures. The results of these analyses demonstrated several potentially important relations. In the younger adult sample, both TEPR magnitude and TEPR latency were significant predictors of average RT. Specifically, participants who exhibited larger and earlier-peaking TEPRs tended to have faster RTs. In the older adult sample, these same two factors were again significant predictors of RTs. However, the effect of TEPR latency was much stronger in the older adults, accounting for about 50% of the variance in mean RTs. While the within-group sample sizes are small for examining these types of relations, this is a large effect that deserves replication and extension. If it is indeed the case that the speed of cognitive processes can be strongly accounted for by the speed of a physiological response, this could provide a mechanistic explanation for processing speed differences with age.

The present results might also provide a glimpse into relative functioning of the LC-NE neuromodulatory system. If indeed we can measure LC functioning with pupil diameter, then we can potentially leverage pupillary measures to gain better insight into cognitive age- and AD-related cognitive deficits. The present sample of older adults were quite healthy, and reported their health as “excellent” (19%), “good” (55%), or “O.K.” (18), and most reported that their health limits their daily activities either “Not at all” (55%) or only “a little” (31%). Only 5% of the older adults reported their health as “Fair” and none reported their health as “Poor.” But even among this relatively healthy sample, there was a strong correlation between TEPR latency and processing speed. This opens doors for future research using pupillometry, which is low-cost, portable, non-invasive, and easy to implement, to uncover the neural mechanisms underlying processing speed changes

with age. While obviously very indirect, it is possible that age- and individual differences in TEPR latency measure an important neural mechanism, like the speed of NE delivery to from LC to cortex. It is also possible that the latency of pupillary responses may indicate differences in neural myelination, which has been hypothesized as a mechanism underlying age-related changes in processing speed (Bartzokis, 2004, 2011; Lu et al., 2011, 2013). If we can use the latency of the TEPR to measure the speed of neural processing, then we can potentially use this measure as an indicator of cognitive decline. Future research should replicate the present design in samples of healthy older adults, older adults with MCIs, and older adults with AD diagnoses. Further, it could be used in combination with more direct measures like MRI to examine whether it does indeed measure an important neural difference, or something different like degeneration of the pupil dilator muscle.

A final implication for this study is one that addresses a more general phenomenon under debate in cognitive psychology - what is the cause of vigilance decrements? Some theories argue that vigilance depletes a limited pool of mental resources, and when this pool of resources declines, performance decrements occur (Smit, Eling, & Coenen, 2004; Warm, Parasuraman, & Matthews, 2008). Other theories argue that a tradeoff occurs between the resources devoted to a task and the resources devoted to other cognitive operations, like mind-wandering, based on a perception of the costs of task completion (effort) and the rewards associated with continuing the task (Kurzban, Duckworth, Kable, & Myers, 2013; Thomson, Besner, & Smilek, 2015). In the present study, the fact that older adults did not show a vigilance decrement and did not show a shallowing of TEPRs across time indicates that, when people are sufficiently motivated and engaged with a task, the vigilance decrement is not an obligatory phenomenon. In fact, the older adults reported the task being even more demanding than younger adults. According to resource theories, more demanding tasks should deplete resources more quickly, causing steeper vigilance decrements. The opposite was true here, as older adults did not show a vigilance decrement despite finding the task more demanding. Thus, the present results also have

important implications for how we interpret the vigilance decrement and what causes it. Rather than having a physiological derivation that is a result of repeated use of a limited pool of resources, the present results indicate that the vigilance decrement is caused by other factors. However, those factors are still a bit unclear, given we were unable to mediate the association between age and the vigilance decrement with measures of motivation, alertness, and task demands.

Conclusions

The present study indicated that older adults showed superior sustained attention compared to younger adults. Specifically, older adults did not show a vigilance decrement in a 30-minute task that produces a robust decrement among younger adults. The reaction time data also indicated that processing speed differences were largely due to the slowest reaction times. When older adults reacted slowly, they tended to react particularly slowly. Older adults also reported fewer task-unrelated thoughts (mind-wandering and mind-blanking), and exhibited both larger and more stable task-evoked pupillary responses across time, despite slower-peaking pupillary responses. The pupillary data also suggested that the latency of task-evoked pupillary responses was a strong predictor of individual differences in processing speed, particularly among older adults. Finally, the fact that older adults did not show a vigilance decrement, nor a shallowing of task-evoked pupillary responses across time, casts doubt on resource theories of vigilance, and suggests the vigilance decrement is driven by other factors. In sum, the ability to sustain attention to a task over a long period of time is preserved in healthy cognitive aging.

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Table 1

Descriptive statistics for each dependent measure by age group

| Age Group | Measure | Mean | SD | Range | Skew | Kurtosis |
|----------------|--------------------------|--------|--------|--------------------|-------|----------|
| Younger adults | Age | 19.88 | 1.43 | [18.00, 25.00] | 0.68 | 0.85 |
| | Average reaction time | 364.39 | 49.41 | [274.64, 510.10] | 0.57 | 0.40 |
| | Vigilance decrement | 13.74 | 10.88 | [-7.65, 57.92] | 1.34 | 3.23 |
| | Motivation | 6.43 | 1.57 | [1.00, 9.00] | -0.85 | 1.21 |
| | Drowsiness | 6.12 | 1.76 | [1.00, 9.00] | -1.08 | 0.96 |
| | TUT proportion | 0.50 | 0.23 | [0.03, 0.93] | 0.08 | -0.97 |
| | Mean pretrial pupil size | 893.25 | 168.53 | [620.93, 1,352.16] | 0.64 | -0.29 |
| | SD pretrial pupil size | 100.91 | 29.36 | [62.05, 206.99] | 1.39 | 2.16 |
| | TEPR magnitude | 1.59 | 0.46 | [0.47, 2.52] | -0.36 | -0.16 |
| | TEPR latency | 615.88 | 57.61 | [516.67, 800.00] | 1.12 | 1.87 |
| Older adults | Age | 75.37 | 7.53 | [63.00, 92.00] | 0.30 | -1.01 |
| | Average reaction time | 384.52 | 55.00 | [286.27, 596.36] | 1.10 | 2.27 |
| | Vigilance decrement | 4.18 | 11.98 | [-45.78, 39.08] | -0.55 | 3.98 |
| | Motivation | 7.85 | 2.19 | [1.00, 9.00] | -2.33 | 4.11 |
| | Drowsiness | 3.69 | 2.37 | [1.00, 8.00] | 0.42 | -1.30 |
| | TUT proportion | 0.23 | 0.23 | [0.00, 0.87] | 0.96 | 0.09 |
| | Mean pretrial pupil size | 580.53 | 173.41 | [273.02, 1,016.71] | 0.52 | -0.54 |
| | SD pretrial pupil size | 43.18 | 22.20 | [14.53, 95.31] | 0.77 | -0.46 |
| | TEPR magnitude | 2.04 | 0.42 | [0.62, 2.98] | -0.98 | 1.31 |
| | TEPR latency | 744.71 | 82.78 | [600.00, 950.00] | 0.31 | -0.61 |

Note. SD = standard deviation, TEPR = task-evoked pupillary response.

Table 2

Correlations among dependent variables in full sample

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----------------------------|-------|-------|-------|-------|-------|-------|-------|------|---|
| 1. Mean RT | – | | | | | | | | |
| 2. Vigilance decrement | .39* | – | | | | | | | |
| 3. Motivation | .07 | -.17 | – | | | | | | |
| 4. Drowsiness | .08 | .38* | -.24* | – | | | | | |
| 5. Task-unrelated thoughts | .18* | .42* | -.38* | .55* | – | | | | |
| 6. Pretrial pupil mean | -.17 | .29* | -.35* | .40* | .37* | – | | | |
| 7. Pretrial pupil SD | -.03 | .44* | -.34* | .55* | .49* | .74* | – | | |
| 8. TEPR magnitude | -.23* | -.33* | .30* | -.48* | -.45* | -.36* | -.53* | – | |
| 9. TEPR latency | .48* | -.08 | .31* | -.31* | -.29* | -.47* | -.43* | .39* | – |

Note. N = 122, SD = standard deviation, TEPR = task-evoked pupillary response, asterisks indicate significant correlations at $p < .05$.

Table 3

Correlations among dependent variables in younger adult sample

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----------------------------|-------|------|-------|-------|-------|------|------|------|---|
| 1. Mean RT | – | | | | | | | | |
| 2. Vigilance decrement | .63* | – | | | | | | | |
| 3. Motivation | -.25 | -.08 | – | | | | | | |
| 4. Drowsiness | .15 | .29* | -.32* | – | | | | | |
| 5. Task-unrelated thoughts | .43* | .32* | -.58* | .40* | – | | | | |
| 6. Pretrial pupil mean | -.10 | -.16 | .07 | .07 | -.08 | – | | | |
| 7. Pretrial pupil SD | .13 | .21 | -.16 | .28* | .19 | .49* | – | | |
| 8. TEPR magnitude | -.45* | -.17 | .32* | -.34* | -.48* | -.10 | -.25 | – | |
| 9. TEPR latency | .13 | .20 | .01 | -.08 | -.07 | .00 | .09 | .38* | – |

Note. N = 60, SD = standard deviation, TEPR = task-evoked pupillary response, asterisks indicate significant correlations at $p < .05$.

Table 4

Correlations among dependent variables in older adult sample

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|----------------------------|-------|------|-------|-------|------|------|-------|------|---|
| 1. Mean RT | – | | | | | | | | |
| 2. Vigilance decrement | .40* | – | | | | | | | |
| 3. Motivation | .17 | .02 | – | | | | | | |
| 4. Drowsiness | .25 | .19 | .05 | – | | | | | |
| 5. Task-unrelated thoughts | .25 | .25* | .05 | .41* | – | | | | |
| 6. Pretrial pupil mean | -.04 | .17 | -.31* | .01 | .15 | – | | | |
| 7. Pretrial pupil SD | .20 | .24 | -.09 | .25 | .20 | .49* | – | | |
| 8. TEPR magnitude | -.29* | -.20 | .01 | -.31* | -.07 | -.03 | -.38* | – | |
| 9. TEPR latency | .67* | .31* | .10 | .15 | .19 | -.02 | .26 | -.06 | – |

Note. N = 62, SD = standard deviation, TEPR = task-evoked pupillary response, asterisks indicate significant correlations at $p < .05$.

Table 5

Regression predicting average reaction time among all participants

| Predictor | <i>b</i> | 95% CI | <i>t</i> (91) | <i>p</i> |
|---------------------|----------|----------------|---------------|----------|
| Intercept | 0.17 | [-0.42, 0.77] | 0.57 | .569 |
| Age | 0.00 | [-0.01, 0.01] | -0.55 | .585 |
| Motivation | 0.07 | [-0.10, 0.24] | 0.82 | .416 |
| Drowsiness | -0.06 | [-0.27, 0.16] | -0.53 | .601 |
| TUT | 0.26 | [0.05, 0.46] | 2.52 | .013 |
| Pretrial pupil mean | -0.10 | [-0.34, 0.14] | -0.82 | .416 |
| Pretrial pupil SD | -0.02 | [-0.31, 0.27] | -0.14 | .887 |
| TEPR magnitude | -0.42 | [-0.62, -0.23] | -4.32 | < .001 |
| TEPR latency | 0.73 | [0.49, 0.96] | 6.11 | < .001 |

Note. $R^2 = 0.47$, *b* = standardized regression coefficient, TUT = task-unrelated thoughts, SD = standard deviation, TEPR = task-evoked pupillary response.

Table 6

Regression predicting average reaction time among younger adults

| Predictor | <i>b</i> | 95% CI | <i>t</i> (39) | <i>p</i> |
|---------------------|----------|----------------|---------------|----------|
| Intercept | -0.02 | [-0.29, 0.25] | -0.16 | .875 |
| Motivation | 0.07 | [-0.26, 0.39] | 0.41 | .681 |
| Drowsiness | -0.13 | [-0.47, 0.21] | -0.77 | .448 |
| TUT | 0.27 | [-0.09, 0.62] | 1.53 | .133 |
| Pretrial pupil mean | -0.15 | [-0.45, 0.15] | -1.02 | .315 |
| Pretrial pupil SD | 0.09 | [-0.23, 0.41] | 0.58 | .566 |
| TEPR magnitude | -0.46 | [-0.78, -0.13] | -2.80 | .008 |
| TEPR latency | 0.30 | [0.00, 0.60] | 2.05 | .047 |

Note. $R^2 = 0.33$, *b* = standardized regression coefficient, TUT = task-unrelated thoughts, SD = standard deviation, TEPR = task-evoked pupillary response.

Table 7

Regression predicting average reaction time among older adults

| Predictor | <i>b</i> | 95% CI | <i>t</i> (45) | <i>p</i> |
|---------------------|----------|----------------|---------------|----------|
| Intercept | 0.04 | [-0.16, 0.24] | 0.40 | .694 |
| Motivation | 0.10 | [-0.12, 0.32] | 0.92 | .360 |
| Drowsiness | 0.03 | [-0.21, 0.27] | 0.26 | .798 |
| TUT | 0.14 | [-0.09, 0.37] | 1.26 | .216 |
| Pretrial pupil mean | 0.02 | [-0.23, 0.27] | 0.18 | .857 |
| Pretrial pupil SD | -0.10 | [-0.38, 0.17] | -0.76 | .451 |
| TEPR magnitude | -0.27 | [-0.49, -0.04] | -2.38 | .021 |
| TEPR latency | 0.71 | [0.49, 0.93] | 6.43 | < .001 |

Note. $R^2 = 0.57$, *b* = standardized regression coefficient, TUT = task-unrelated thoughts, SD = standard deviation, TEPR = task-evoked pupillary response.

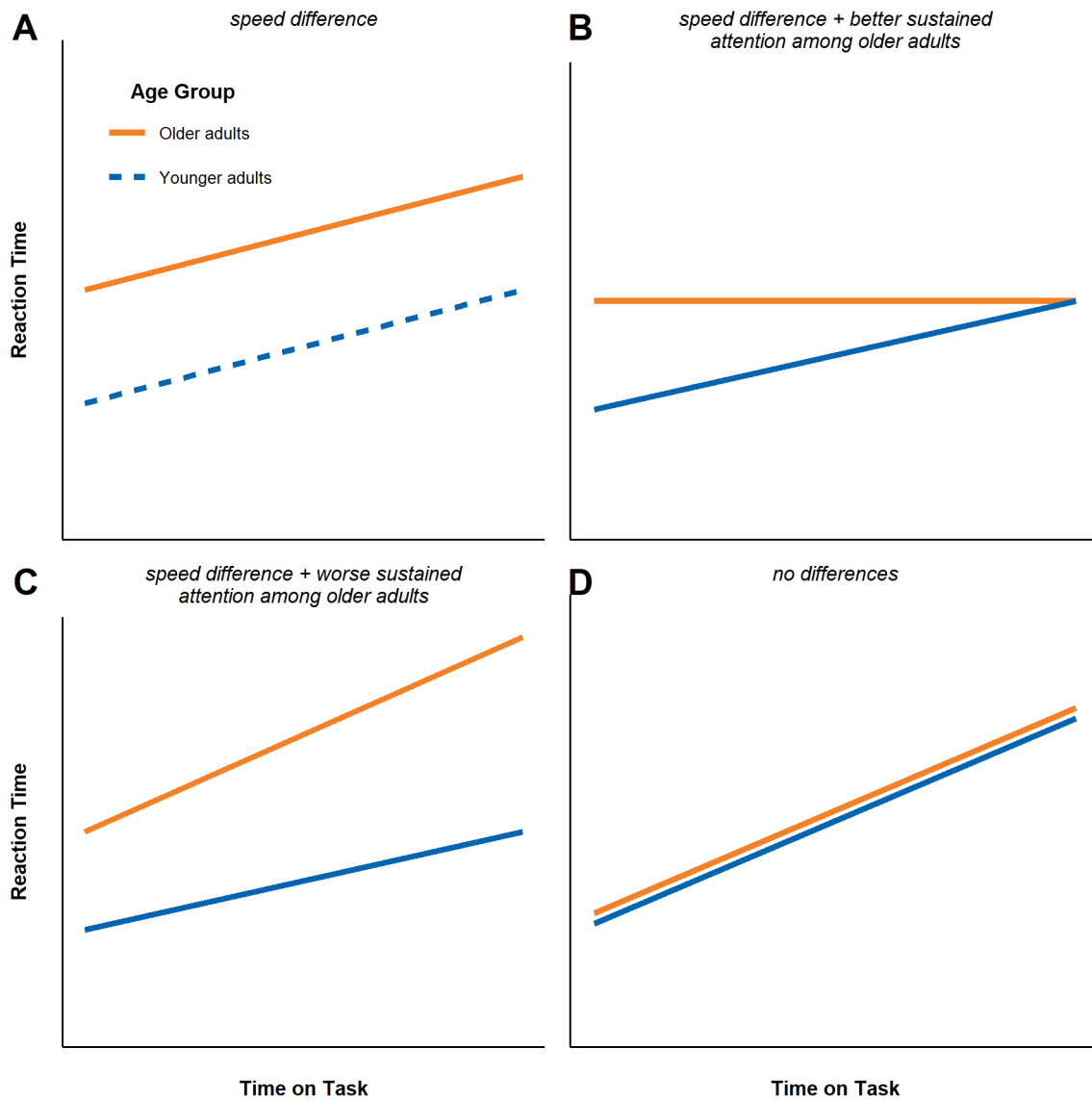


Figure 1. Potential patterns of age-related differences in task performance: A) general speed difference (slower reaction times) for older adults, B) general speed difference, but superior sustained attention among older adults, C) general speed difference and worse sustained attention among older adults, and D) no group differences in reaction times.

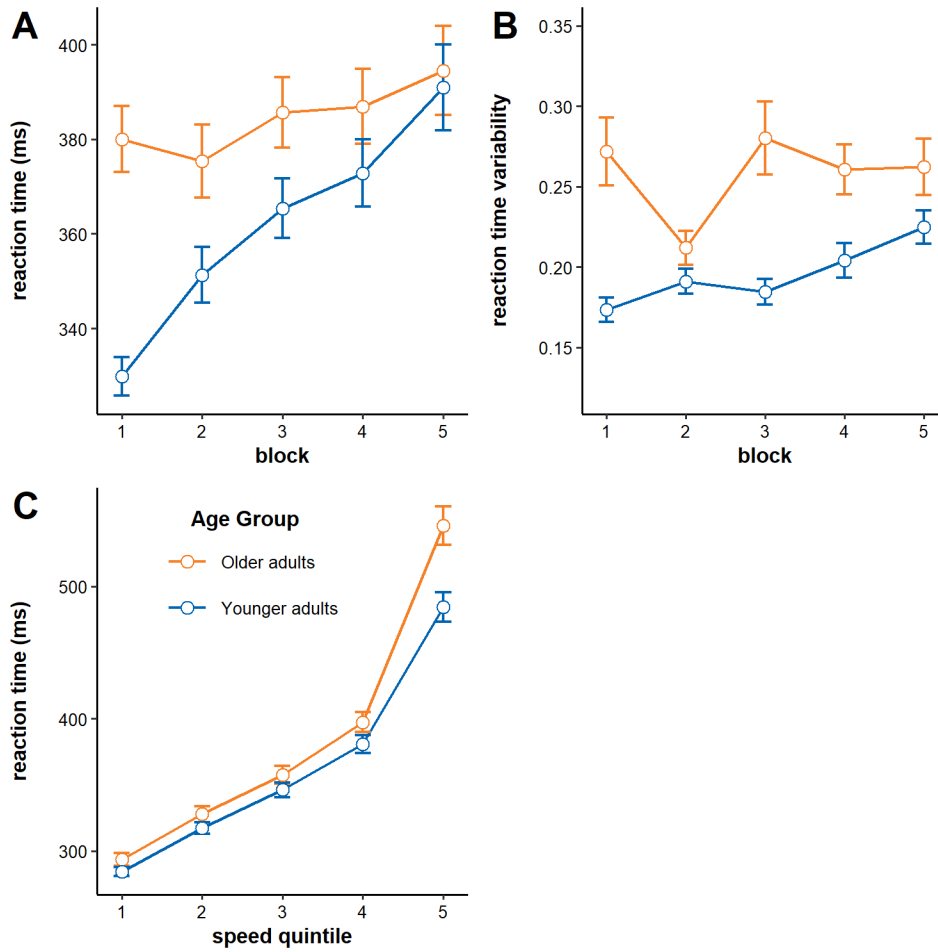


Figure 2. A) Reaction times by block and age group, and B) Reaction times by speed quintile and age group. Error bars represent \pm one standard error.

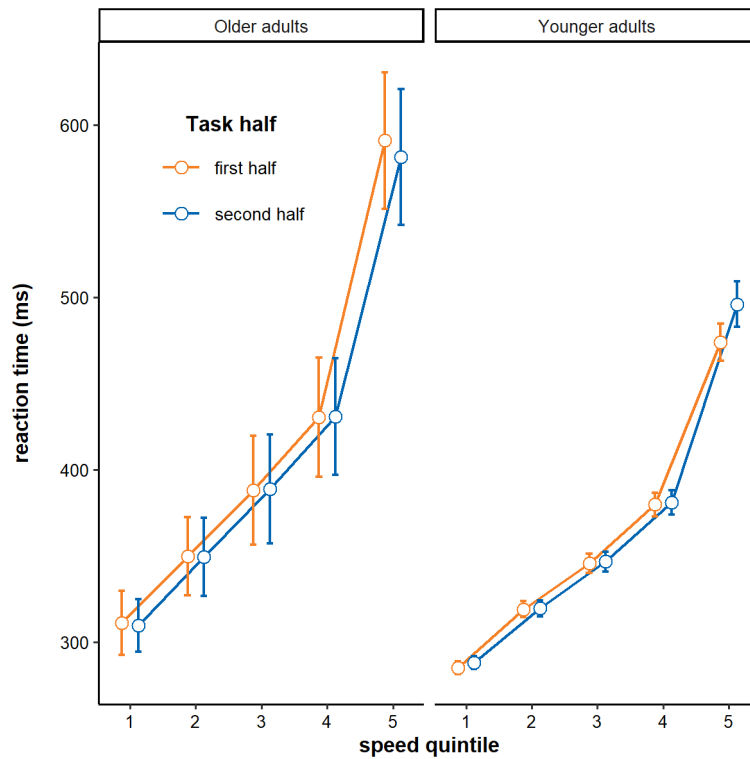


Figure 3. Reaction times by speed quintile for the first half and second half of the task by age group. Error bars represent +/- one standard error of the mean.

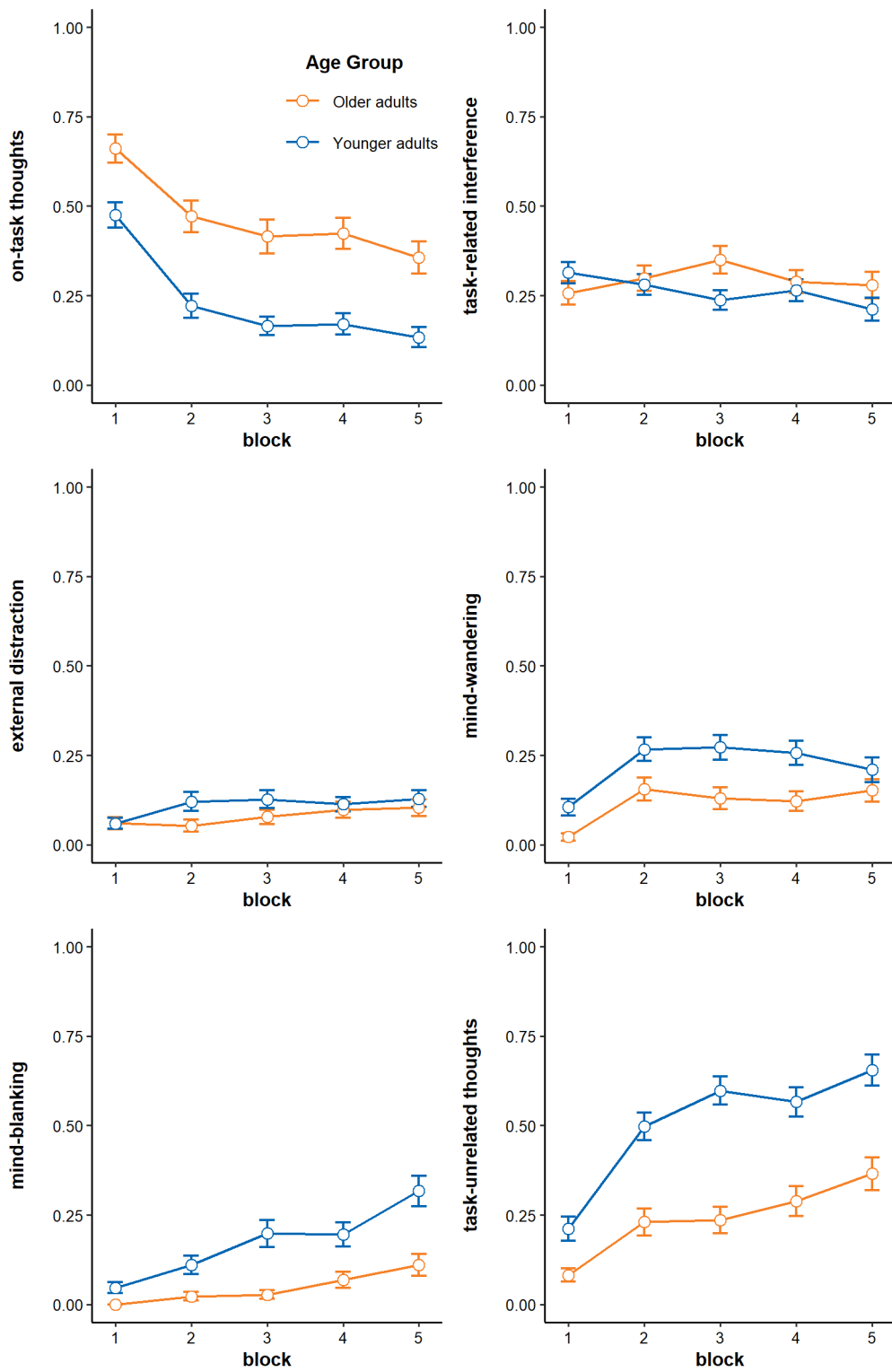


Figure 4. Thought probe response proportions by block and age group. Error bars represent +/- one standard error.

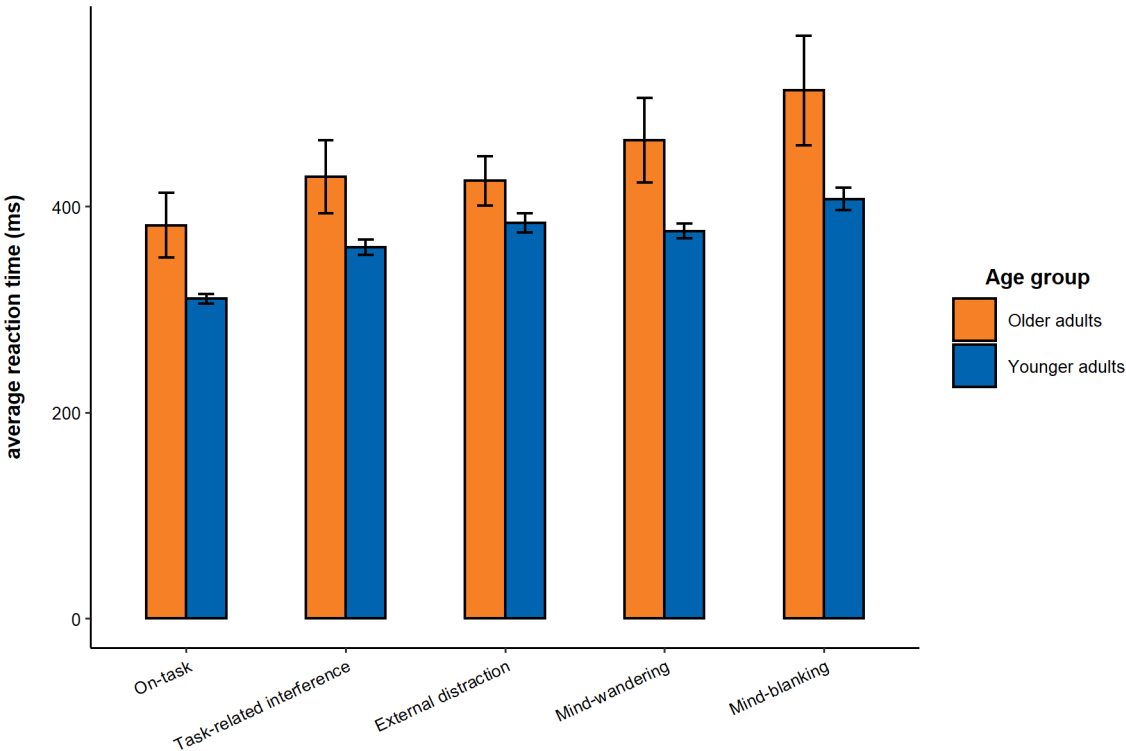


Figure 5. Reaction times preceding each probe response by age group. Error bars represent +/- one standard error.

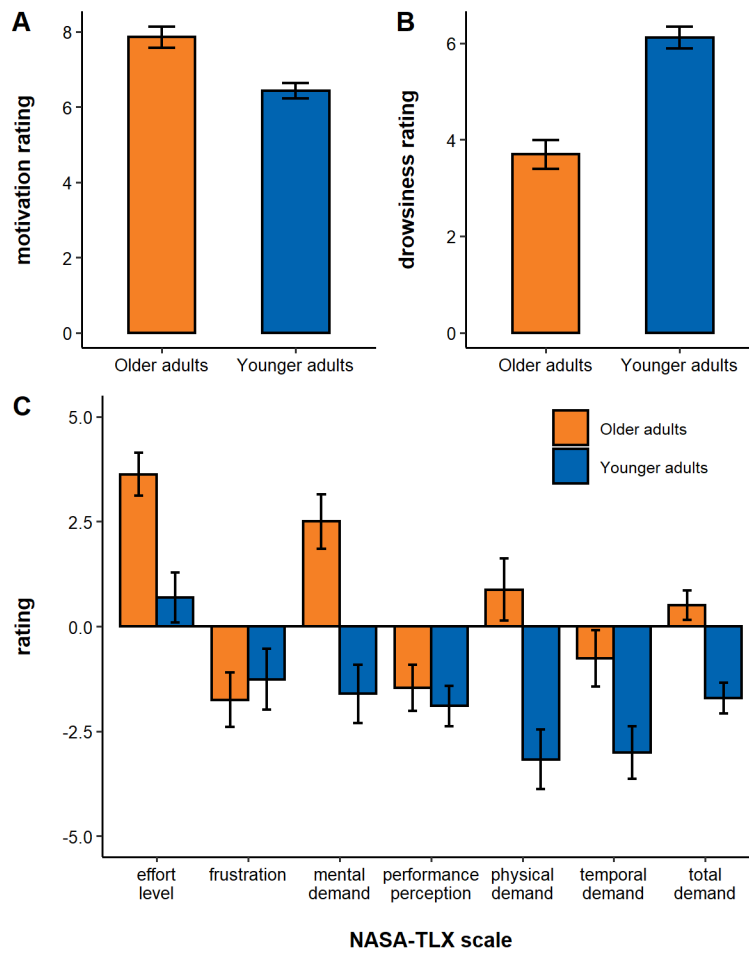


Figure 6. A) Motivation ratings, B) Drowsiness ratings, and C) NASA-TLX workload ratings by age group. Error bars represent +/- one standard error.

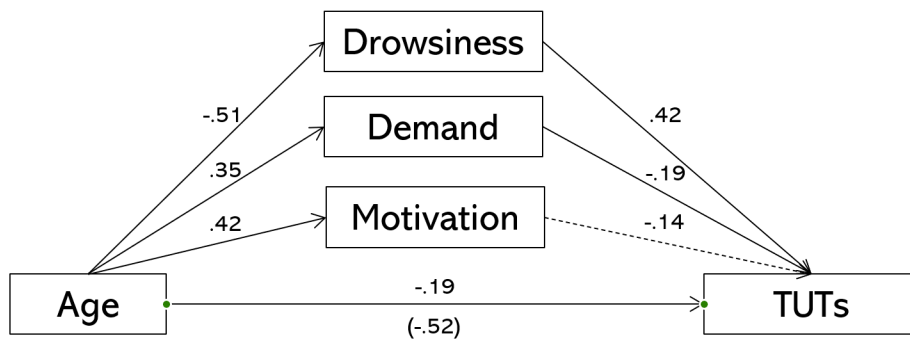


Figure 7. Mediation model in which age was allowed to have a direct and indirect effects on task-unrelated thoughts (TUTs) via motivation, drowsiness, and perceptions of task demand. Solid lines indicate significant paths at $p^* < .05$, dashed lines represent non-significant paths.

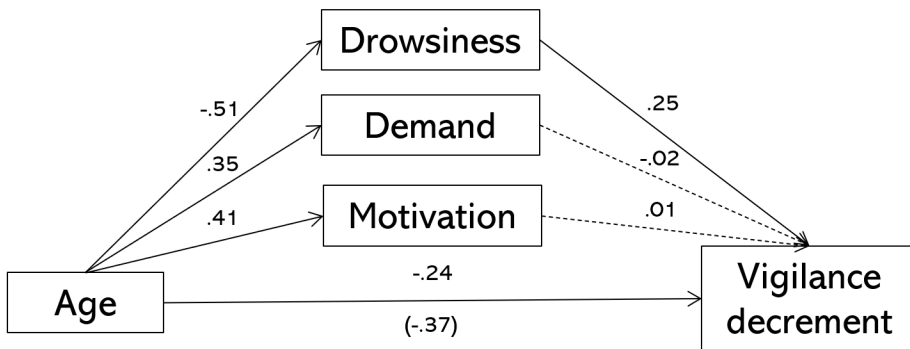


Figure 8. Mediation model in which age was allowed to have a direct and indirect effects on the vigilance decrement via motivation, drowsiness, and perceptions of task demand. Standardized parameter estimates are shown. Solid lines indicate significant paths at $p^* < .05$, dashed lines represent non-significant paths.

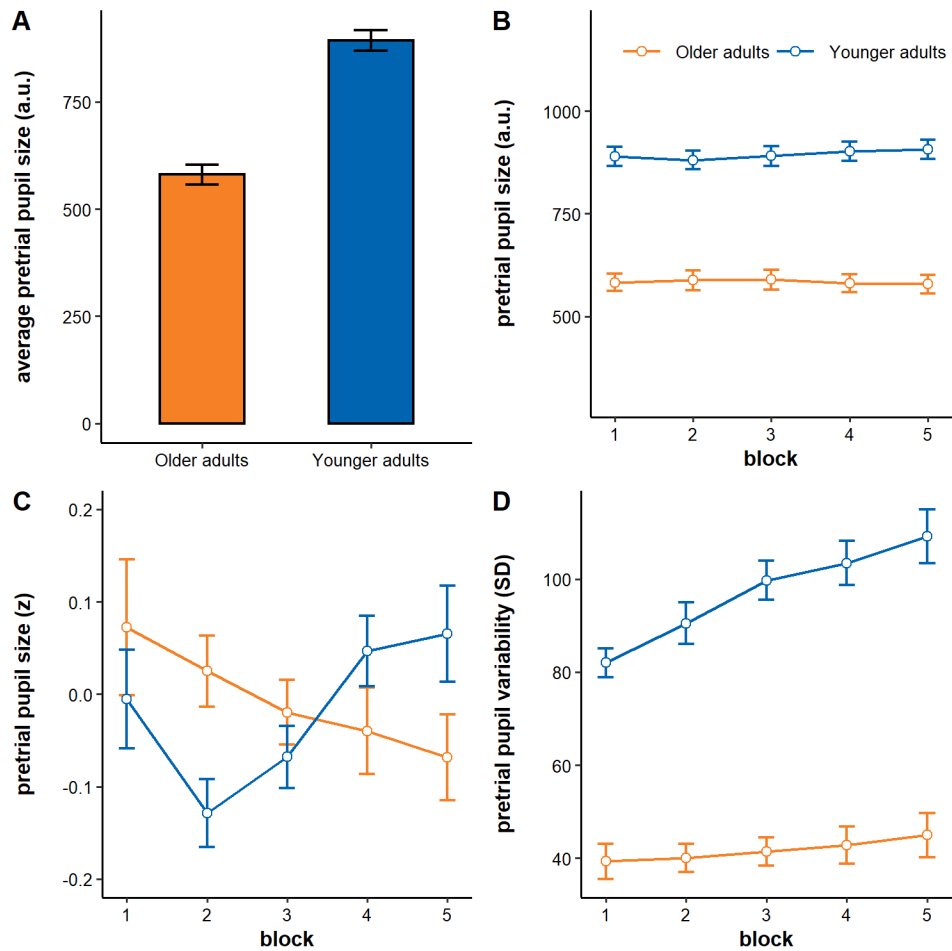


Figure 9. A) Average pretrial pupil size by age group, B) Pretrial pupil size by block and age group in arbitrary units, C) Intraindividually-standardized pupil size by block and age group, D) Intraindividual variability (standard deviation) in pretrial pupil size by block and age group. Error bars represent \pm one standard error.

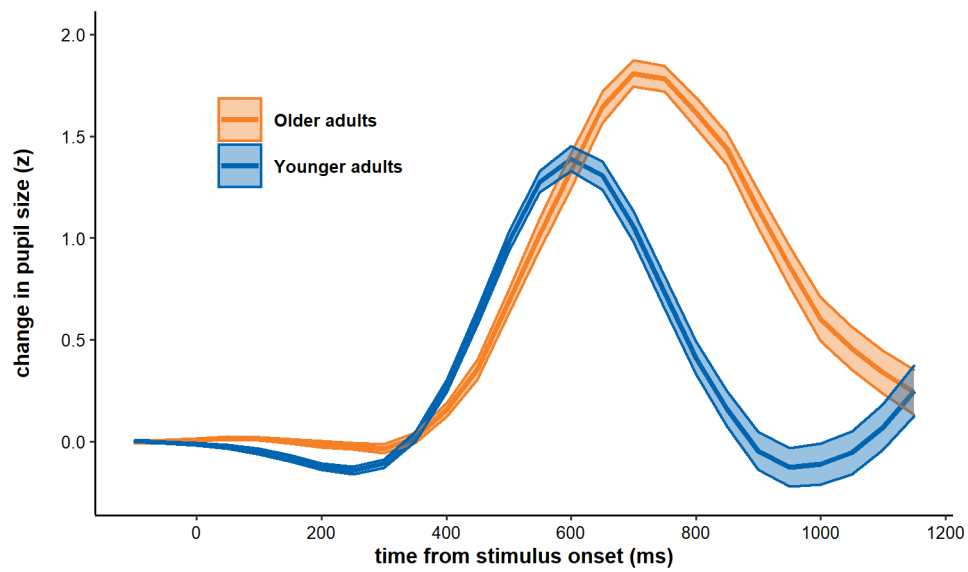


Figure 10. Average task-evoked pupillary responses by age group. Older adults exhibited larger but later-peaking pupillary responses. Shaded error bars represent +/- one standard error.

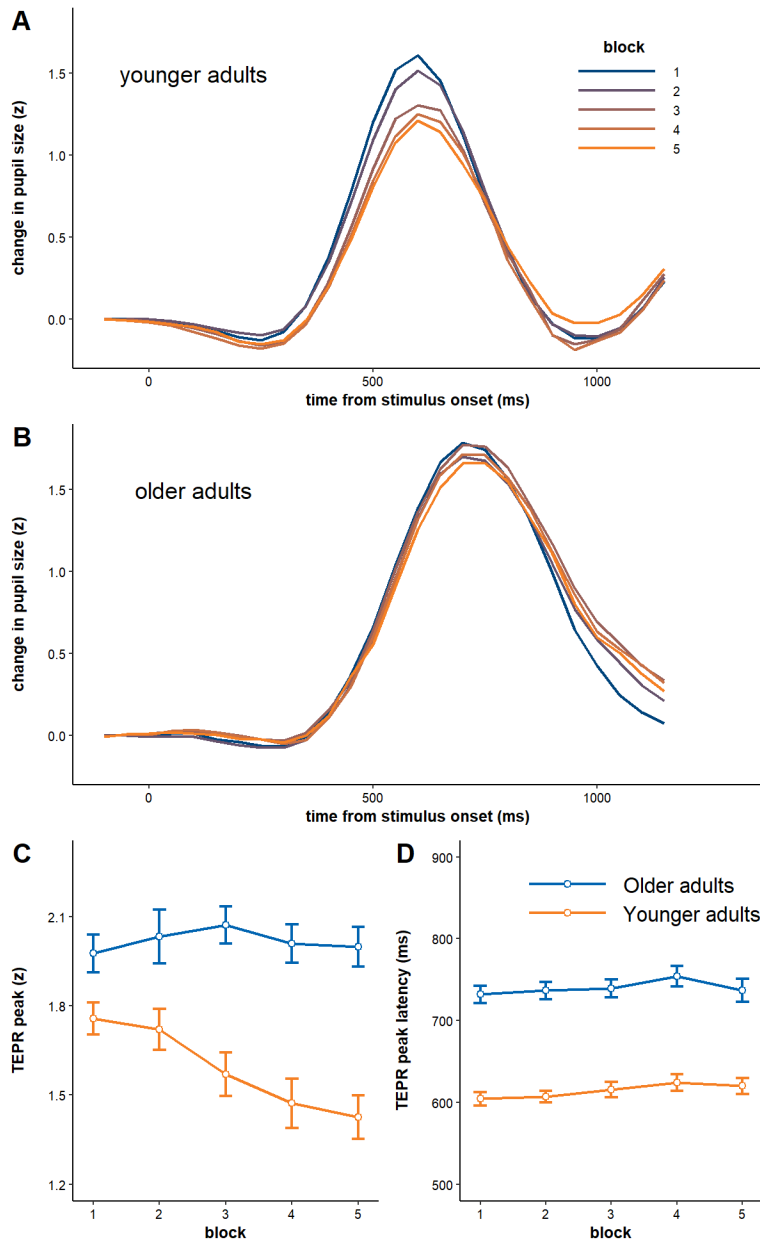


Figure 11. A) Average task-evoked pupillary responses by block among younger adults, B) Average task-evoked pupillary response by block among older adults, C) Peak of task-evoked response by block and age group, D) Latency of task-evoked response by block and age group. Error bars represent +/- one standard error.

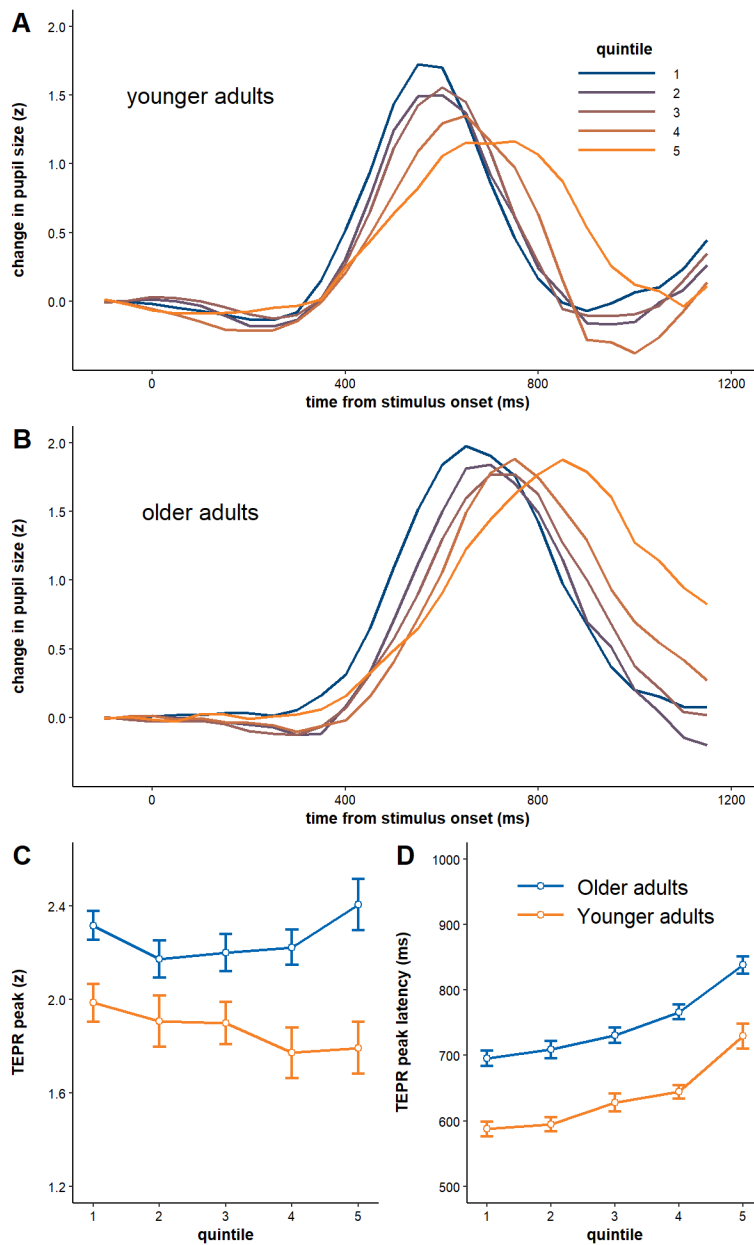


Figure 12. A) Average task-evoked pupillary responses by speed quintile among younger adults, B) Average task-evoked pupillary response by block among older adults, C) Peak of task-evoked response by speed quintile and age group, D) Latency of task-evoked response by speed quintile and age group. Error bars represent +/- one standard error.

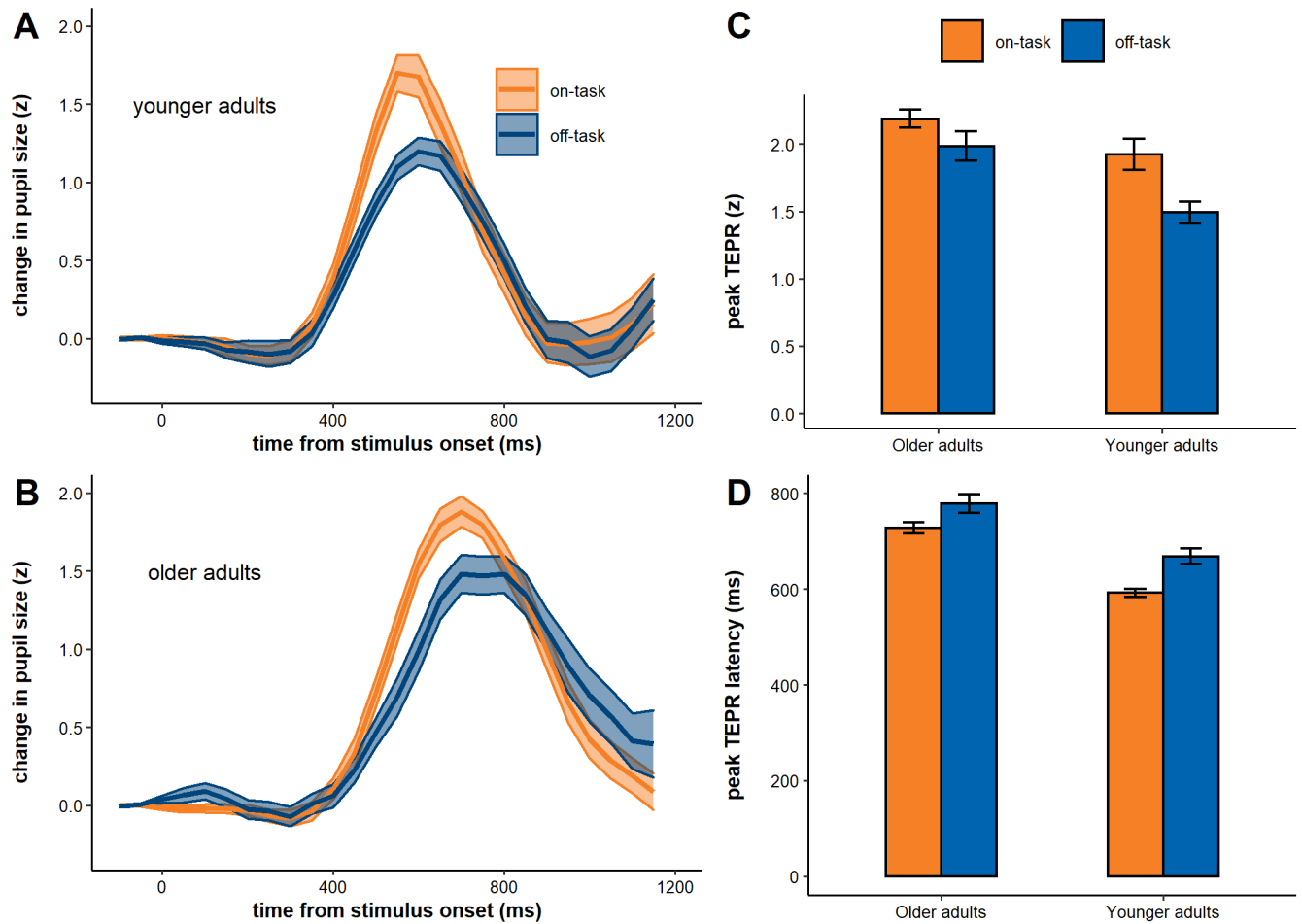


Figure 13. A) Average task-evoked pupillary responses for on- and off-task trials for older adults, B) Average task-evoked pupillary response for on- and off-task trials older adults, C) Peaks of task-evoked response for on- and off-task trials by age group, D) Latencies of task-evoked responses for on- and off-task trials by age group. Error bars represent +/- one standard error.