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A Multimodal Analysis of Sustained Attention in Younger and Older Adults

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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 (RT), thought probes, and pupillometry to measure sustained attention in samples of younger and older adults. The RT 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 (TEPRs), corroborating the behavioral and self-report data. Finally, older adults did not show a shallowing of TEPRs across time, corroborating the finding that their RTs 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

Given that aging is associated with declines in attention and inhibitory control (Hasher et al., 2007; Hasher & Zacks, 1988), one would expect older adults to have a relative inability to sustain their attention. However, older adults sometimes show better performance on measures of sustained attention compared to younger adults (see Vallesi et al., 2021 for a recent meta-analysis). Sustained attention can also be measured via the *vigilance decrement*, 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), simple reaction time (RT) tasks (Massar et al., 2016; Massar, Lim, Sasmita, & Chee, 2019; Robison et al., 2021; Unsworth & Robison, 2016, 2020), *n*-back tasks (Hopstaken et al., 2015a, 2015b; Hopstaken et al., 2016), and go/no-go tasks (McVay & Kane, 2009, 2012a). Parasuraman et al. (1989) showed that older adults had lower discrimination ability overall, compared to younger adults, but older adults 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 go/no-go task, Staub et al. (2014b) 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 task-unrelated thoughts (TUTs) than younger adults (see also Brache et al., 2010; Staub et al., 2014a, 2015). Staub et al. (2013, 2014a, 2014b, 2015) argue that traditional vigilance tasks, which require responses on a rare subset of trials, differ substantially from tasks like the Sustained Attention to Response Task (SART), which require frequent responses and withholding of responses on a rare subset of trials. Thus, Staub et al. argue that traditional vigilance tasks may overwhelm the available cognitive resources that older adults possess by consuming bottom-up processing capabilities, which may lead to worse performance on such tasks. The SART makes relatively fewer demands on bottom-up processing, but requires top-down control to inhibit incorrect go responses. Further, older adults tend to favor accuracy over speed, and this is a beneficial strategy in the SART (Vallesi et al., 2021). Therefore, age differences in sustained attention—or lack thereof—may be confounded by the bottom-up processing demands of a task.

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 attention away from 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 et al., 2015; Giambra, 1989, 2000; Jackson et al., 2013; Jackson & Balota, 2012; Krawietz

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All data and analysis code are publicly available on the Open Science Framework (https://osf.io/63wcj/).

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et al., 2012; Moran et al., 2021; Shake et al., 2016; Staub et al., 2014b; Zavagnin et al., 2014). This seems to contradict the 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 attention-demanding situations (Kane et al., 2007, 2016; McVay & Kane, 2009, 2012a, 2012b; Mrazek et al., 2012; Robison et al., 2017; Robison & Unsworth, 2015; Robison et al., 2020; Rummel & Boywitt, 2014; Unsworth et al., 2012; Unsworth & McMillan, 2013, 2014, Unsworth et al., 2021).

Several hypotheses offer explanations for this perplexing relationship between aging and mind-wandering. One hypothesis is that mind-wandering is a resource-demanding process (Smallwood & Schooler, 2006). 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 et al. (2013) compared younger and older adults' sustained attention performance preceding various TUT 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 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, several experiments have challenged this hypothesis: Frank et al. (2015) found that older adults' TUT reports were just as veridical as younger adults' in relation to objective mind-wandering-related eye-movement patterns, and Giambra (1973) indicates that older adults report a more positive view of mind-wandering than younger adults.

Third, the Control failure × Current concerns hypothesis suggests that the relationship is driven by age differences in how the testing context cues personally relevant concerns (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 that older adults still report less mind-wandering than younger adults even when tested outside the laboratory (Diede et al., 2022; Jackson et al., 2013).

Finally, age-group differences in mind-wandering may be due to dispositional factors such as conscientiousness, task interest, and motivation. 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. Further, Krawietz et al. (2012) found that including interest as a covariate eliminated the age difference in mind-wandering. Frank et al. (2015) and Seli et al. (2021) reported that participants' motivation partially mediated the relationship between age and mind-wandering, and Nicosia and Balota (2021) found that 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 Psychomotor Vigilance Task (PVT) to measure sustained attention 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 RT task with an unpredictable stimulus onset time, and thus requires consistent attention both within and across trials.

Because the PVT is a simple RT 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, Lim, & Huettel, 2019; Massar et al., 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* RTs and *changes* in RT across time. The processing speed theory of cognitive aging (Salthouse, 1996) would predict slower RTs 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 frequent mind-wandering during the PVT, with participants reporting TUTs 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 responses in young adults. Historically, pupil dilation has been used as a physiological index of mental effort (Beatty, 1982; Beatty & Lucero-Wagoner, 2000). For example, prior work has shown that the pupil dilates when people encode information to be retrieved later (Kahneman & Beatty, 1966; Kahneman & Peavler, 1969), when people experience cognitive conflict (Laeng et al., 2011; van der Wel & van Steenbergen, 2018), and when they are trying solve difficult math problems (Hess & Polt, 1964). In the PVT, the magnitude of the pupillary response tends to decline across time (Robison, 2018; Unsworth & Robison, 2016), is larger when participants report being on-task versus off-task (Unsworth & Robison, 2017b), and correlates with individual differences in performance on the task (Unsworth & Robison, 2017b). The magnitude of the pupillary response is also sensitive to motivational incentives (Massar, Lim, & Huettel, 2019, Massar et al., 2016). Thus, we can compare the magnitude of pupillary responses, the change in magnitude across trials, and differences in magnitude across 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 with which it occurs. If the pupillary response is an indirect indicator of a neural process, and neural processing is slower among older adults (Salthouse, 1996), then the pupillary response may occur over a later time course than for younger adults. Latency differences would also be predicted by neural response theories of aging (Bartzokis, 2004, 2011; Lu et al., 2011, 2013). However, few studies have specifically examined the latency of pupillary response as they relate to age-related changes in processing speed. In one study, Porter et al. (2010) did not find differences between younger and older adults in the latency of pupillary responses during a visual search task. However in an auditory task, Zekveld et al. (2011) found that age was correlated with longer peak latencies and larger mean pupillary dilations.

Overall, our goal was to test theories regarding age-related change in processing speed and attention. Specifically, we hoped to answer several questions: First, how do younger and older adults compare in processing speed in a simple RT task? Second, how does the vigilance decrement differ between younger and older adults? Third, what subjective factors might account for age-related differences in both sustained attention and subjective task engagement (i.e., mind-wandering)? Finally, will pupillary measures of effort corroborate the behavioral and subjective differences between younger and older adults? These final 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

Transparency and Openness

All data and analysis code are publicly available on the Open Science Framework (https://osf.io/63wcj/). The design and analysis plan were not preregistered prior to data collection. The data were analyzed and plotted in *R* using the *tidyverse* (Wickham, 2017), *lmerTest* (Kuznetsova et al., 2017), *cowplot* (Wilke, 2020), *psych* (Revelle, 2018), and *lavaan* (Rosseel, 2012) packages. The manuscript was written in *R* Markdown using the *papaja* package (Aust & Barth, 2018). The sample size for the older adult group was maximized per available funds to compensate participants. The sample size for the younger adult group was selected to match the older adult sample.

Participants

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. Washington University maintains a database of older adults who have agreed to be contacted regarding opportunities to participate research studies. Participants in the present study were recruited via phone calls informing them of eligibility. The older adults were compensated with cash ($10/hr). Data for participants' age, health status, and education levels are listed in Table 1.

Table 1
Age, Health, and Education Data for Each Age Group

Demographic variable	Younger adults	Older adults
Mean age (*SD*)	19.88 (1.43)	75.37 (7.53)
Male	31%	34%
Female	66%	66%
White	55%	95%
Black/African American	3%	3%
Asian	38%	0%
Hispanic or Latino	12%	0%
American Indian/Native Alaskan	2%	2%
"Excellent" health	43%	19%
"Good" health	53%	55%
"O.K." health	0%	18%
"Fair" health	0%	5%
"Poor" health	2%	0%
Health limits activities "not at all"	92%	55%
Health limits activities "a little"	5%	31%
Health limits activities "some"	2%	11%
Health limits activities "A lot"	0%	2%
Some high school	0%	2%
High school diploma	100%	34%
College degree	0%	42%
Graduate degree	0%	23%

Procedure

The laboratory sessions lasted about 2 hr. In order, participants completed the following tasks: PVT, Raven Advanced Progressive Matrices (Raven et al., 1962), number series (Thurstone, 1938), letter sets (Ekstrom et al., 1976), a general knowledge quiz, a synonym quiz, and an antonym quiz (Hambrick et al., 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 cognitive abilities. 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

Each trial began with a row of black fixation crosses centered on a gray background. This fixation screen appeared for 2 s. 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 to 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 s, revealing the RT for that trial (e.g., 00.378). Then, after a 1-s blank intertrial interval, the next trial began. There were 160 trials in total. For statistical analyses, the trials were divided into five 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. The task took about 30 min to complete. Each block took about 5 min. The remaining time comprised instruction screens and practice trials.

Thought Probes

The thought probe screens asked participants to "Please characterize your current conscious experience." There were five 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). Thought probes appeared on 30 randomly sampled trials.

Self-Report Questionnaires

After the PVT, participants were asked to rate, on a scale from 1 to 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 to 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 1,000 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-s 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

Data were screened for outliers by eliminating any data point outside ±3 *SD*s of each group mean.

Results

Descriptive statistics for all measures are listed in Table 2.

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.

Reaction Times

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 nonsignificant main effect of age group ($b = 23.89$, $SE = 14.73$, $p = .11$). Older adults' RTs were slightly but not significantly slower overall (see Figure 1A). The main effects were qualified by a Significant block × 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

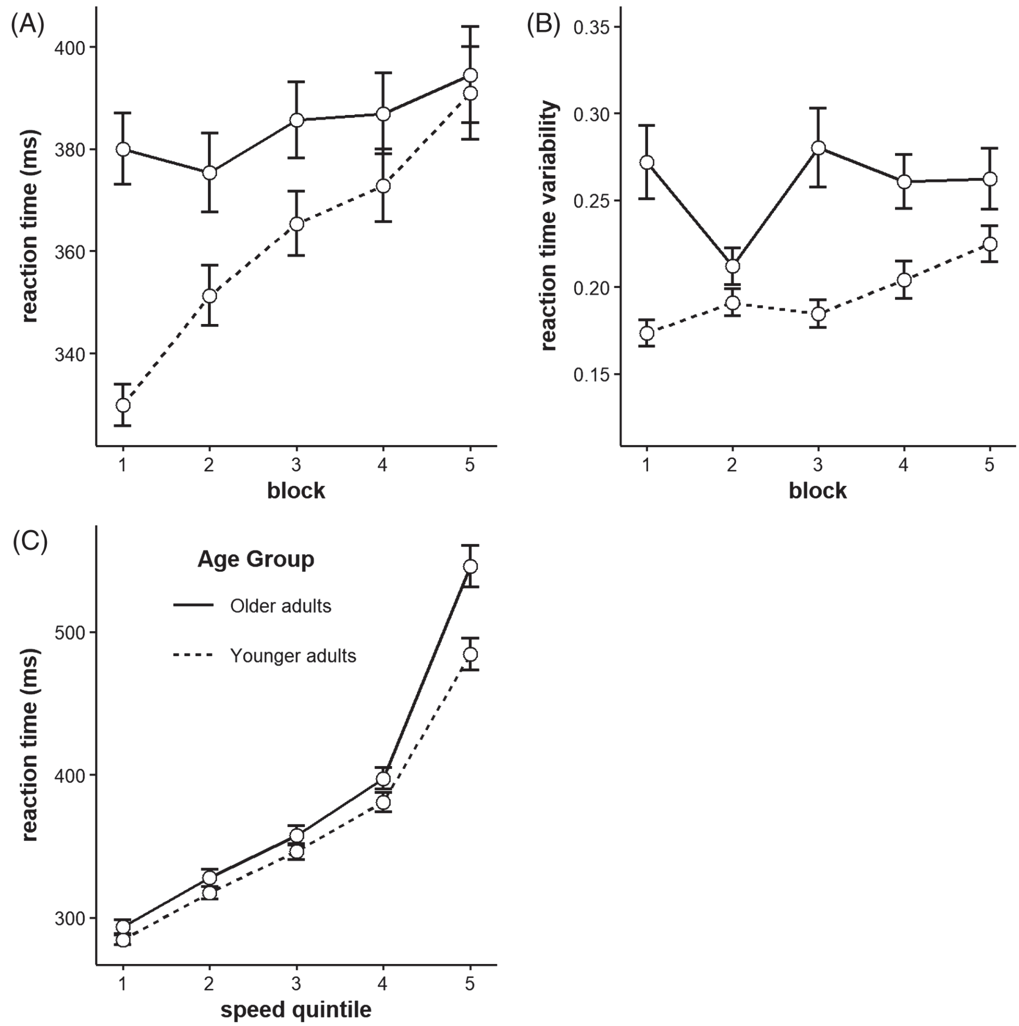
Table 2
Descriptive Statistics for Each Dependent Measure by Age Group

Age group	Measure	*M*	*SD*	Range	Skew	Kurtosis
Younger adults	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, 1352.16]	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	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. TEPR = task-evoked pupillary response; TUT = task-unrelated thought.

Figure 1

(A) Reaction Times, and (B) Intraindividual Variability in Reaction Times, and (C) Reaction Times by Speed Quintile



Note. Error bars represent ± one standard error.

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 = .10).

Next we analyzed group differences in two additional measures: Intraindividual variability in RTs and RTs by speed quintile. To analyze intraindividual variability, we computed each participant's coefficient of variation (standard deviation/mean; CoV) of RTs in each block. 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 = .02), and a significant main effect of age (b = 0.03, SE = 0.007, p < .001), such that older adults showed more intraindividual variability in RT than younger adults (see Figure 1B). The Block × Age group interaction was not significant (b = −0.005, SE = 0.003, p = .10).

To examine RTs by speed quintile, we first rank-ordered individuals' RTs from shortest to longest. Then, we binned RTs into five quintiles by speed (fastest 20% to slowest 20% of trials). The model indicated a Significant quintile × Age interaction (b = 6.94, SE = 0.48, p < .001), such that larger age 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 responded particularly slowly (see Figure 1C). An additional way to perform this analysis is by entering the fastest quintile and age into a model predicting the slowest RTs (e.g., Salthouse, 1993). Doing so revealed significant main effects of both the fastest RTs (b = 1.70, SE = 0.24, t = 7.22, $p \leq$ .001) and age (b = −49.03, SE = 15.27, t = −3.21, p = .002; R^2 = 38%). This again indicates that age differences in RTs are the largest when younger and older adults are at their slowest.

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 three-way interaction among block, quintile, and age ($b = -1.82$, $SE = 0.35$, $p < .001$). This pattern is plotted in Figure 2.

Older adults' RT distributions did not shift, on average. But younger adults slowest RTs tended to increase across the task. In other words, the vigilance decrement was present primarily in the slow end of the distribution.

Pupillary Results

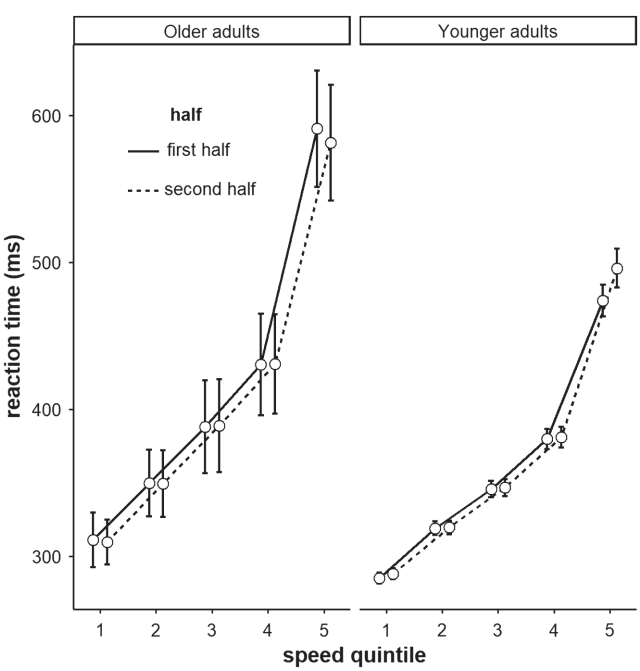
There were two sets of pupillary measures. The first was pretrial pupil diameter, which was measured as the average pupil diameter over the 2-s fixation screen preceding each trial, and the second was TEPRs, which were computed as a change in pupil diameter in response to stimulus onset on each trial.

Pretrial Pupil Size

Consistent with prior work, older adults had significantly smaller pupil sizes than younger adults, Figure 3A, $M_{older} = 580.53$ a.u., $M_{younger} = 893.25$ a.u., $t(102) = -9.30$, $p < .001$; Bak et al., 2017; Birren et al., 1950; Winn et al., 1994. We also analyzed pretrial pupil dynamics across blocks. Pretrial pupil size is plotted by block and age group in arbitrary units in Figure 3B and in individually standardized units in Figure 3C. Younger and older adults showed different patterns across blocks, confirmed by the Presence of a block × Age group interaction ($b = -0.03$, $SE = 0.01$, $p = .003$). Whereas older adults tended to show a small but significant monotonic decrease in pretrial pupil size across blocks ($b = -0.03$, $SE = 0.02$, $p = .03$), younger adults actually tended to show a small but significant increase ($b = 0.03$, $SE = 0.01$, $p = .04$). Although the effect in younger adults appeared curvilinear, the quadratic effect did not reach significance ($b = 0.02$, $SE = 0.01$, $p = .06$).

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 × 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 ($b = 1.40$, $SE = 0.65$, $p = .04$).[1] This pattern is shown in Figure 3D.

Figure 2
Reaction Times First Half and Second Half



Note. Error bars represent ± one standard error of the mean.

Task-Evoked Pupillary Responses (TEPRs)

The grand-averaged TEPRs for each age group are shown in Figure 4. Magnitude of TEPRs 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. 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, $t(114) = 9.73$, $p < .001$; see Figure 4).

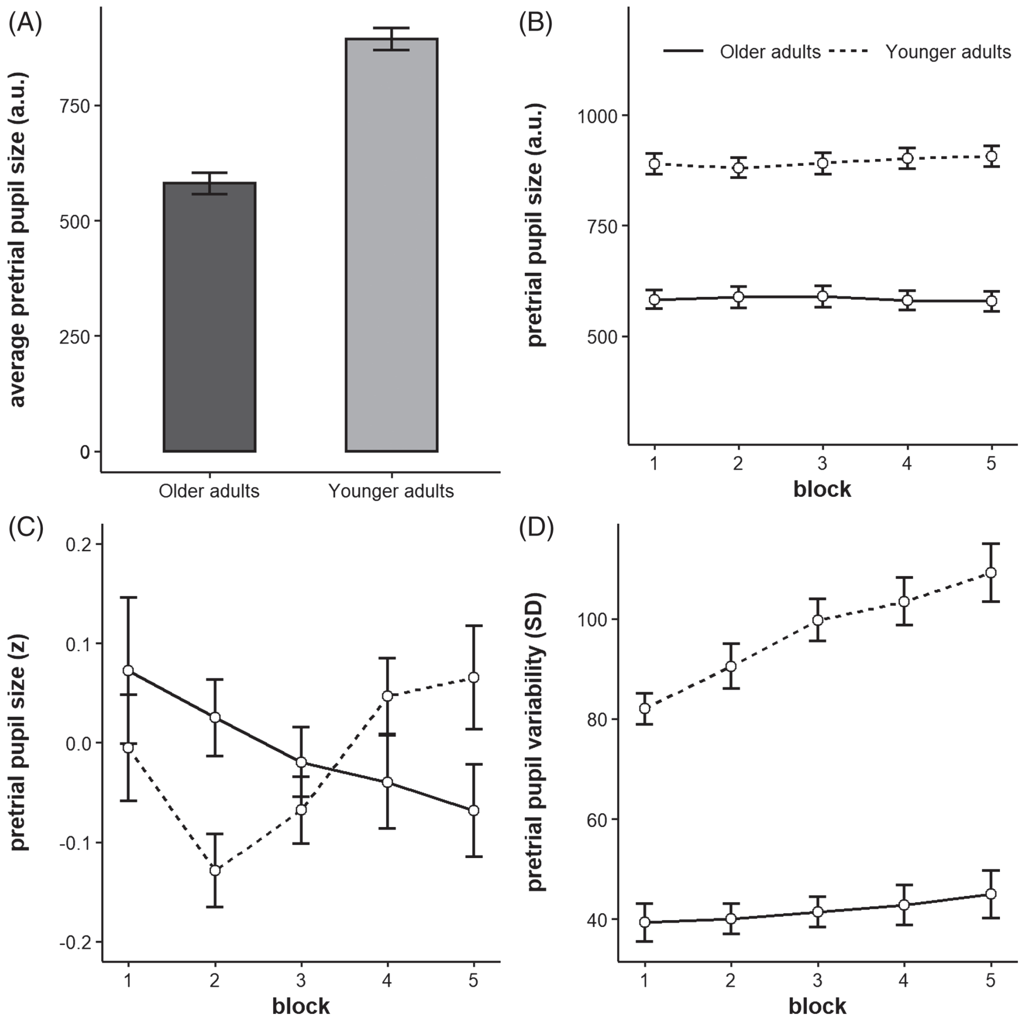
Our next analysis compared the time-on-task dynamics in TEPRs (both peak and latency). The averages are plotted by block and age group in Figure 5. Regarding TEPR magnitude, there was a significant main effect of age group ($b = 0.21$, $SE = 0.04$, $p < .001$), a significant main effect of block ($b = -0.04$, $SE = 0.01$, $p < .001$), and a Significant block × 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 ($b = 0.002$, $SE = 0.01$, $p = .89$). 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 ($b = 4.28$, $SE = 1.59$, $p = .009$), but no Significant block × Age group interaction ($b = -0.63$, $SE = 1.59$, $p = .69$).

Next, we examined how the TEPRs differed on particularly fast trials versus particularly slow trials for younger and older adults. This was a novel, albeit exploratory, analysis. But it allowed us to assess whether faster RTs were 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 6. 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

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

Figure 3

(A) Average Pretrial Pupil Size, (B) Pretrial Pupil Size by Block, (C) Intraindividually Standardized Pupil Size, (D) Intraindividual Variability (Standard Deviation) in Pretrial Pupil Size



Note. Error bars represent ± one standard error.

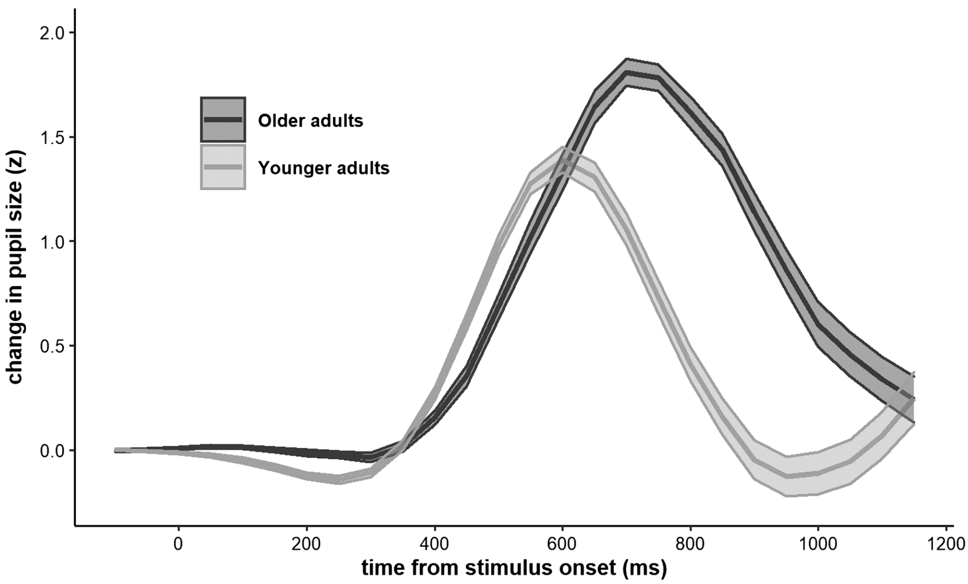
speed quintile as the independent variable rather than block. The model on TEPR magnitude revealed a small, nonsignificant main effect of quintile ($b = -0.01$, $SE = 0.02$, $p = .44$), a significant main effect of age ($b = 0.20$, $SE = 0.04$, $p < .001$), and a small and Marginally significant quintile × Age group interaction ($b = 0.04$, $SE = 0.02$, $p = .05$). Running the model separately on younger and older adults revealed that whereas older adults show a nonsignificant positive effect of quintile on TEPR magnitudes ($b = 0.02$, $SE = 0.03$, $p = .36$), younger adults showed a small and nonsignificant negative effect ($b = -0.05$, $SE = 0.03$, $p = .07$; see Figure 6C). 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 × Quintile interaction on latency ($b = 0.70$, $SE = 2.67$, $p = .79$), so both younger and older adults showed roughly equal effects (see Figure 6D). 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 7. 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- versus off-task reports on peaks ($b = 0.16$, $SE = 0.05$, $p < .001$), but there was no significant Report × Age group interaction ($b = -0.06$, $SE = 0.05$, $p = .22$). 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 × Report interaction ($b = 7.06$, $SE = 5.69$, $p =$

Figure 4

Average Task-Evoked Pupillary Responses by Age Group



Note. Older adults exhibited larger but later-peaking pupillary responses. Shaded error bars represent ± one standard error.

.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.

Thought Probe Responses

Next we analyzed thought probe responses by age group and block. On-task responses significantly decreased across blocks ($b = -0.07$, $SE = 0.007$, $p < .001$), and older adults reported more on-task thoughts than younger adults ($b = 0.12$, $SE = 0.02$, $p < .001$). The Block × Age group interaction was not significant ($b = 0.004$, $SE = 0.007$, $p = .60$). There was no significant age group difference in reports of task-related interference ($b = 0.02$, $SE = 0.02$, $p = .28$), and these reports did not significantly change across blocks ($b = -0.009$, $SE = 0.008$, $p = .24$). The Block × Age group interaction was modest in size but did not reach significance ($b = 0.01$, $SE = 0.008$, $p = .07$). Reports of external distraction were rare, and there was no difference between age groups ($b = -0.02$, $SE = 0.010$, $p = .12$), but they did significantly increase across time ($b = 0.01$, $SE = 0.004$, $p = .003$). There was no Block × Age group interaction ($b = 0.00004$, $SE = 0.004$, $p = .99$).

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 × Age group interaction on mind-wandering ($b = 0.001$, $SE = 0.005$, $p = .84$). 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 × Age group interaction, such that younger adults showed a steeper increase in mind-blanking across time than older adults ($b = -0.02$, $SE = 0.005$, $p < .001$).

Posttask Self-Report Scales

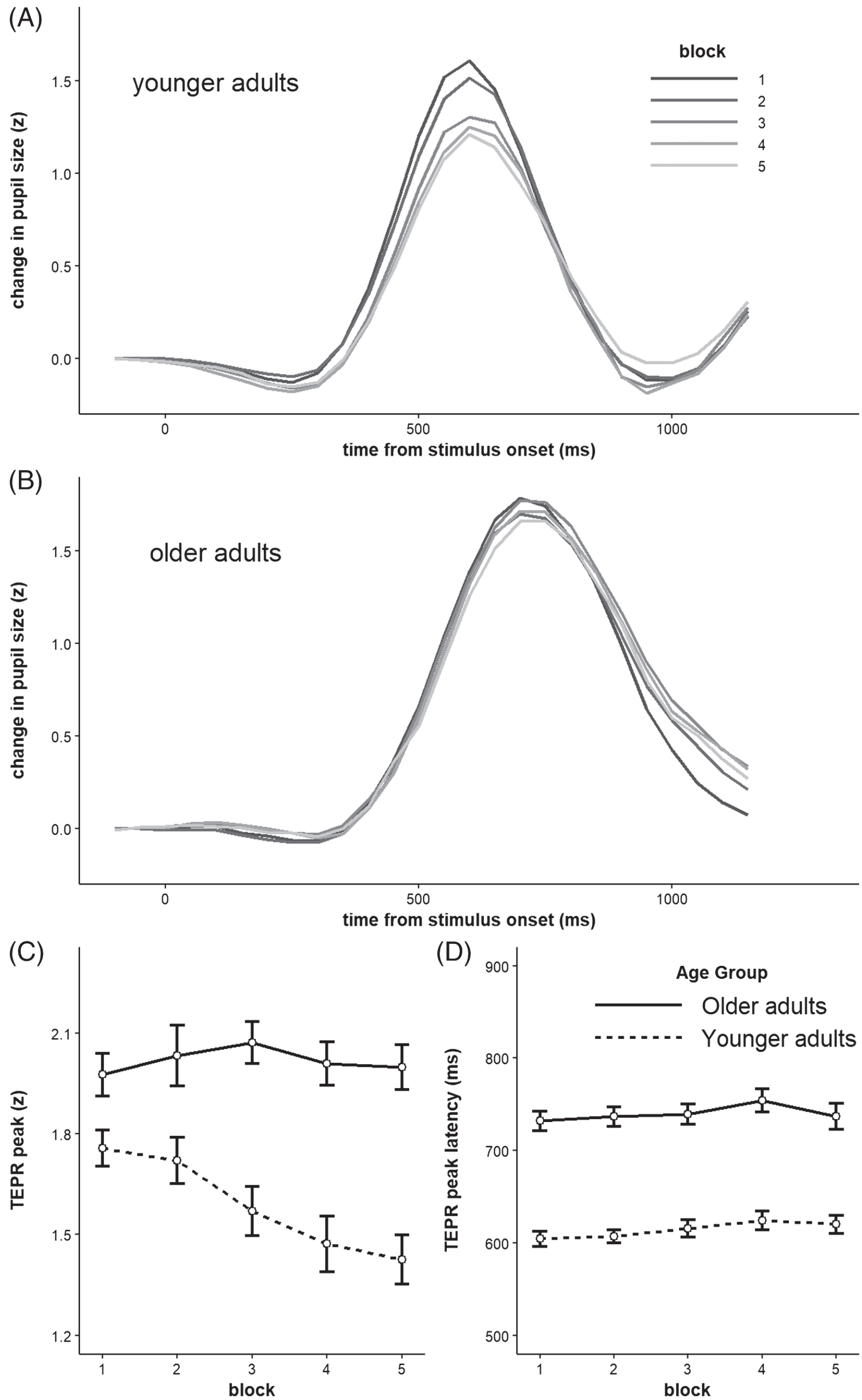
The average self-report ratings are plotted by age group in Figure 8. Older adults reported being significantly more motivated than younger adults, $t(120) = 4.11$, $p < .001$, and significantly less drowsy, $t(120) = -6.39$, $p < .001$. Overall, older adults rated the PVT as more demanding, $t(120) = 4.40$, $p < .001$. 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, $t(120) = 2.43$, $p = .02$, and requiring more effort, $t(120) = 3.74$, $p < .001$. Younger and older adults did not differ on how frustrating they found the task, $t(120) = -0.50$, $p = .62$, nor on how well they felt they performed on the task, $t(120) = 0.59$, $p = .56$.

Mediation of Age-Related Differences in Sustained Attention

Older adults showed no vigilance decrement in the present study, which is also rather paradoxical given age-related differences in attention. 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: $b = 0.001$, $p = .97$, 95% CI [−0.07, 0.07]; drowsiness: $b = 0.13$, $p = .01$, 95% CI [0.03, 0.24];

Figure 5

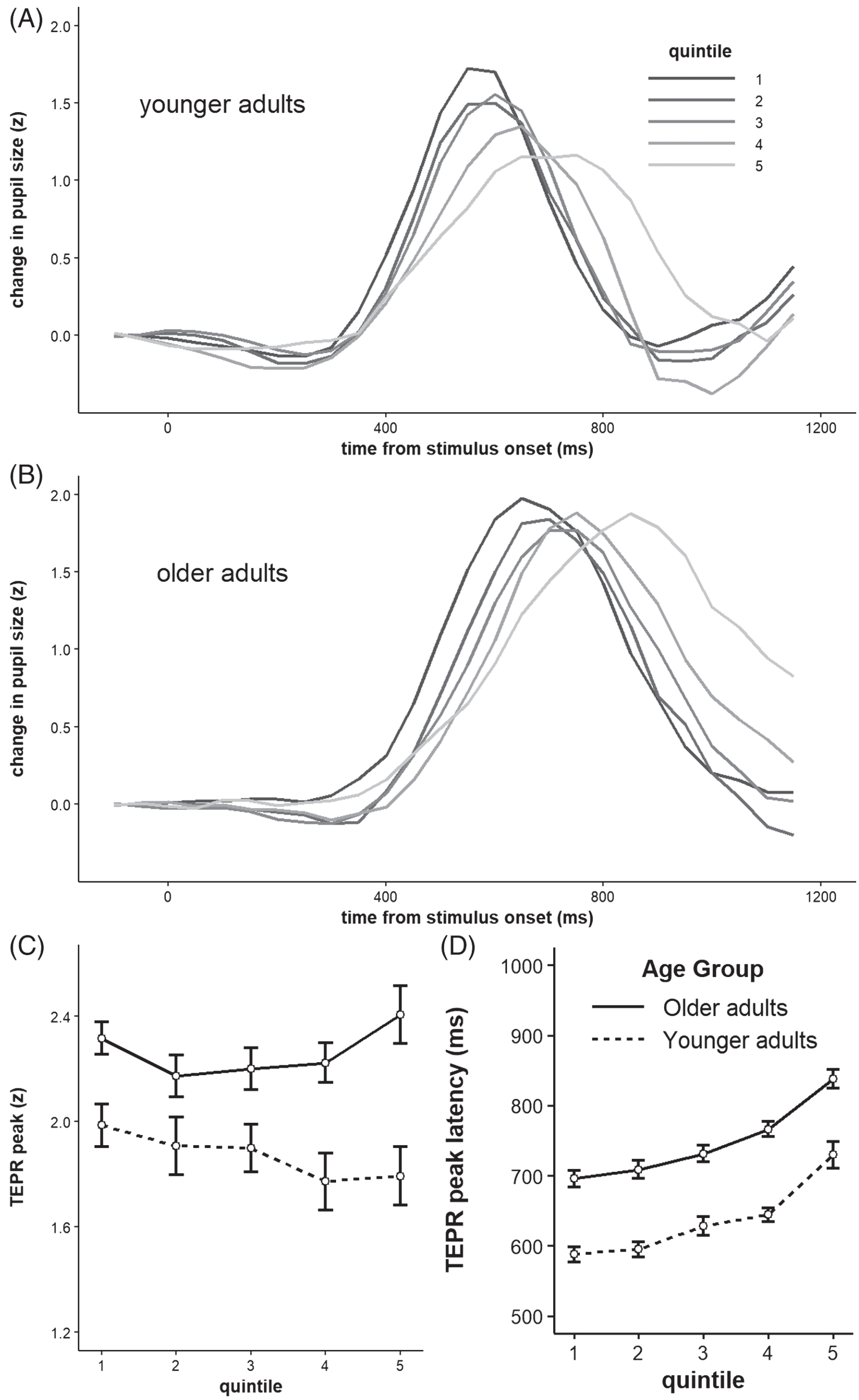
(A) Average Task-Evoked Pupillary Responses by Block Among Younger Adults, (B) Average Task-Evoked Pupillary Response by Block Among Older Adults, (C) Peak of Task-Evoked Response by Block and Age Group, (D) Latency of Task-Evoked Response by Block and Age Group



Note. Error bars represent ± one standard error.

Figure 6

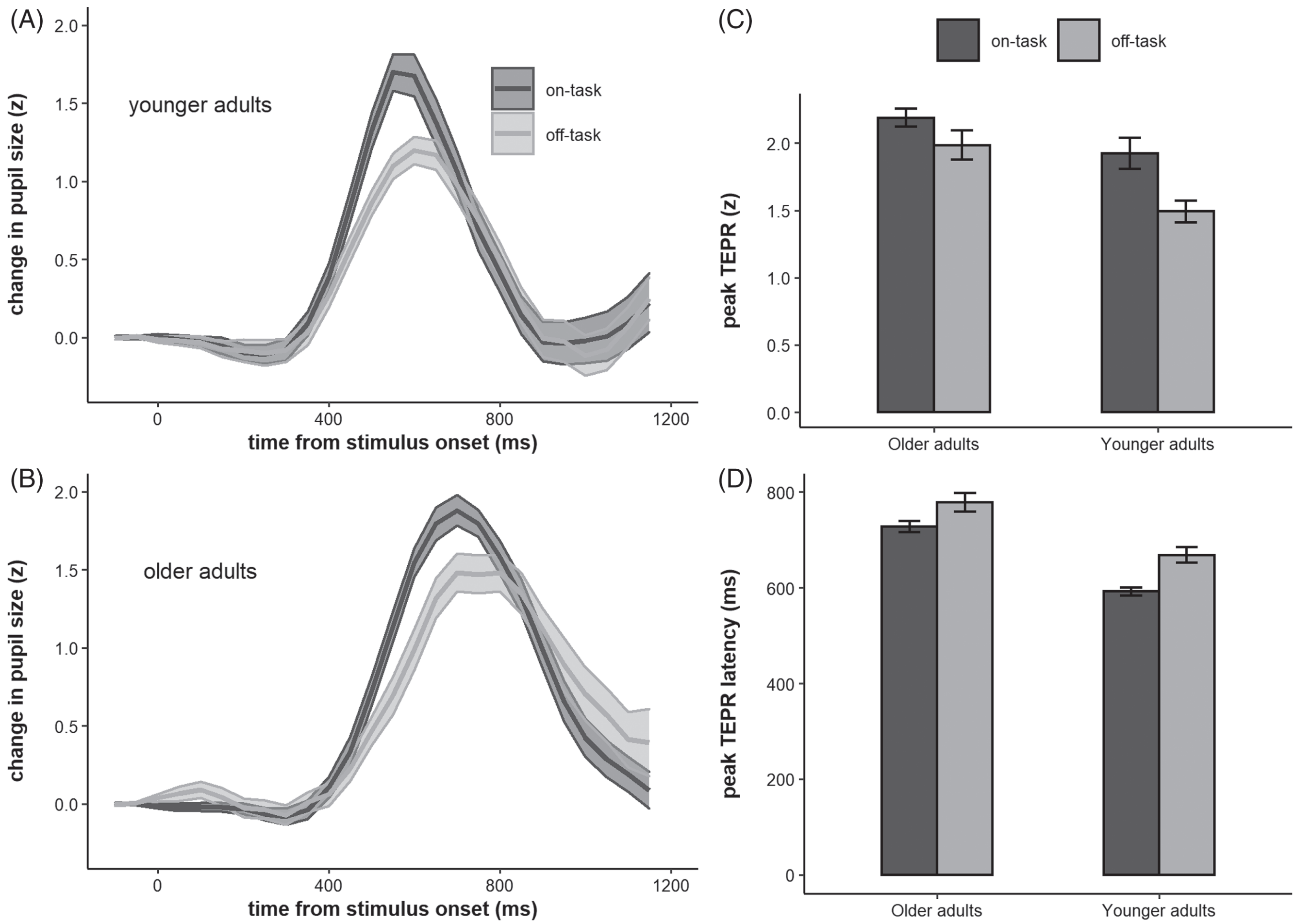
(A) Average Task-Evoked Pupillary Responses by Speed Quintile Among Younger Adults, (B) Average Task-Evoked Pupillary Response by Block Among Older Adults, (C) Peak of Task-Evoked Response by Speed Quintile and Age Group, (D) Latency of Task-Evoked Response by Speed Quintile and Age Group



Note. Error bars represent ± one standard error.

Figure 7

(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 for 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



Note. Error bars represent ± one standard error.

demand: $b = 0.001$, $p = .99$, 95% CI [−0.06, 0.07]). After accounting for these three subjective measures, there was still a significant direct effect of age group on the vigilance decrement ($b = -0.27$, $p = .009$, 95% CI [−0.47, −0.07]). Thus, the subjective reports could not fully explain why older adults did not show a vigilance decrement (see Figure 9).

Next, to examine whether these same subjective factors accounted 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 10.

Both demand (indirect effect: $b = -0.07$, $p = .02$, 95% CI [−0.14, −0.009]) and drowsiness (indirect effect: $b = -0.21$, $p < .001$, 95% CI [−0.31, −0.12]) significantly mediated the effect of age on TUT, and there was no longer a significant direct path between age and TUT ($b = -0.17$, $p = .06$, 95% CI [−0.34, 0.009]). The mediating effect of motivation was not quite significant (indirect effect: $b = -0.06$, $p = .06$, 95% CI [−0.12, 0.003]).

Therefore, drowsiness, demand, and motivation fully mediated the relation between age and TUT (see Figure 10).

Individual Differences

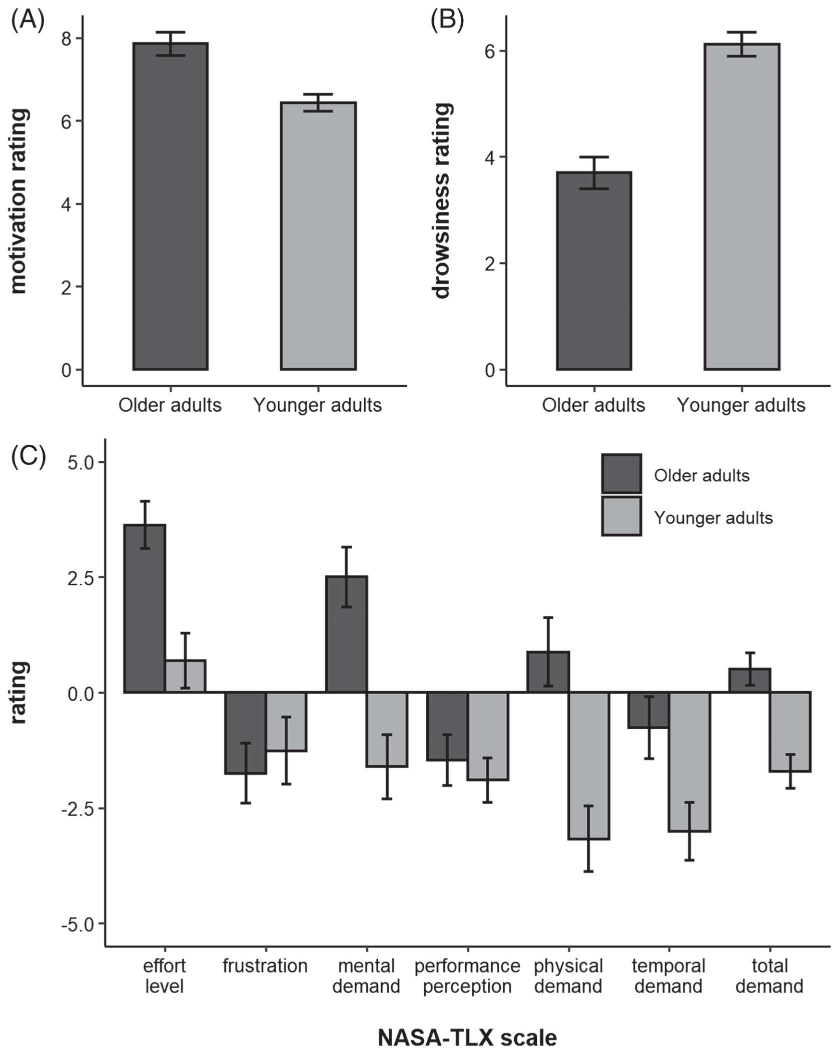
Because the present study was designed to examine age-related differences and not individual differences, the sample size was smaller than is typically desired for analyses of individual differences. However, we ran some exploratory analyses examining individual and age-related differences in pupil size and dynamics, sustained attention, and subjective reports. The individual age groups had 60 and 62 participants, respectively. So the correlations within each age group should be interpreted with a degree of caution. Table 3 lists the correlations among dependent variables in the older and younger adults separately.

Discussion

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

Figure 8

(A) Motivation Ratings, (B) Drowsiness Ratings, and (C) NASA-TLX Workload Ratings by Age Group

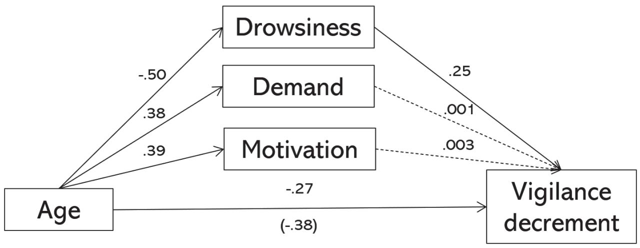


Note. Error bars represent ± one standard error; NASA-TLX = NASA-Task Load Index.

The processing speed account of cognitive aging predicts that older adults should be slower than younger adults in the PVT. However, older adults were only about 20 ms slower than younger adults on average. When looking at segments of the RT distributions, 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., 2000, 2002; McAuley et al., 2006; Spieler et al., 1996; Tse et al., 2010; West et al., 2002).

Despite this finding, older adults showed superior sustained attention compared to younger adults. Specifically, older adults did not show a vigilance decrement in RT, a pattern that has been repeatedly observed in younger adults in the PVT (Massar et al., 2016, Massar, Lim, Sasmita, & Chee, 2019; Robison et al., 2021; Unsworth & Robison, 2016, 2020). The younger adults did indeed show a large vigilance decrement, as is typical. The data were also consistent with prior work showing similar patterns in both traditional vigilance tasks (Tomporowski & Tinsley, 1996), and go/no-go tasks like the SART (Brache et al., 2010; Staub et al., 2014a, 2014b, 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 et al., 2005; Bugg, 2014; 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

Figure 9
Mediation Model on the Vigilance Decrement



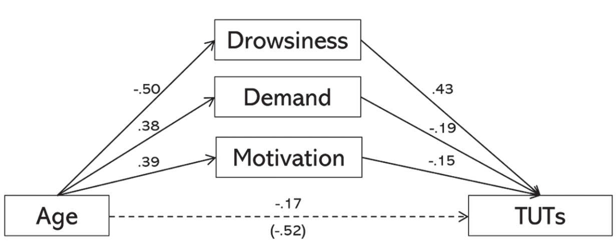
Note. Standardized parameter estimates are shown. Solid lines indicate significant paths at $p < .05$, dashed lines represent nonsignificant paths. Age is treated as a binary variable (*older adults* = 1, *younger adults* = 0) in this model.

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 remains intact in healthy aging.

Regarding the age/mind-wandering paradox, the present results were largely consistent a subjective and dispositional account (Jackson & Balota, 2012; Krawietz et al., 2012; Moran et al., 2021; Nicosia & Balota, 2021; Seli et al., 2021). Older adults reported fewer TUTs than younger adults. Older adults also reported being significantly more motivated and alert than younger adults. However, they also reported finding the task significantly more demanding. Mediation analyses showed that accounting for these subjective 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.

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 research (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, Massar, Lim, Sasmita, & Chee, 2019; 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.

Figure 10
Mediation Model on Task-Unrelated Thoughts (TUTs)



Note. Solid lines indicate significant paths at $p < .05$, dashed lines represent nonsignificant paths. Age is treated as a binary variable (*older adults* = 1, *younger adults* = 0) in this model.

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 et al., 2020; 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 in arousal typically correlates with worse sustained and controlled attention performance. If intraindividual variability in RT is indicative of shifting attentional state (Unsworth & Robison, 2017a, 2017b), older adults should show *more* variability in arousal than younger adults. The discrepancy here might be that intraindividual variability in RTs measures micro-level shifts in attentional state, lapses that occur over very brief timescales but nonetheless cause slow responding, and macro-level shifts, 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. However, it is also possible that the significantly smaller pupil diameters in older adults necessarily restricts the range of possible values, limiting the degree to which intraindividual variability can even be observed. To account for large mean differences, we also compared the intraindividual coefficient of variation across groups, and this yielded the same result as the intraindividual standard deviation. Still, this method does not fully account for the range restriction issue. Further research is necessary to disentangle these possibilities.

There were also several key age differences in TEPR dynamics. First, older adults showed larger TEPRs than younger adults. TEPRs have been used as a 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, 1982; 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, 2015b, 2016; Massar, Lim, & Huettel, 2019; Massar et al., 2016; Unsworth & Robison, 2016). But in the

Table 3
Correlations Among Dependent Variables in Older and Younger Adult Samples

Variable	1	2	3	4	5	6	7	8	9
1. Mean RT	—	.63*	−.25	.15	.43*	−.10	.13	−.45*	.13
2. Vigilance decrement	.40*	—	−.08	.29	.32	−.16	.21	−.17	.20
3. Motivation	.17	.02	—	−.32	−.58*	.07	−.16	.32	.01
4. Drowsiness	.25	.19	.05	—	.40*	.07	.28	−.34	−.08
5. Task-unrelated thoughts	.25	.25*	.05	.41*	—	−.08	.19	−.48*	−.07
6. Pretrial pupil mean	−.04	.17	−.31*	.01	.15	—	.49*	−.10	.00
7. Pretrial pupil *SD*	.20	.24	−.09	.25	.20	.49*	—	−.25	.09
8. TEPR magnitude	−.29*	−.20	.01	−.31*	−.07	−.03	−.38*	—	.38
9. TEPR latency	.67*	.31*	.10	.15	.19	−.02	.26	−.06	—

Note. Correlations among the older adults ($N = 62$) are listed below the diagonal, and correlations among the younger adults ($N = 60$) are listed above the diagonal. TEPR = task-evoked pupillary response; RT = reaction time.
* significant correlations at $p < .05$.

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; Massar, Lim, Sasmita, & Chee, 2019; 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 is consistent with 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 ∼20-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 correlate 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 correlates of RTs. Specifically, participants who exhibited larger and earlier-peaking TEPRs tended to have shorter RTs. In the older adult sample, these same two factors were again significant correlates of RTs. However, the correlation between of TEPR latency was much stronger in the older adults, sharing for about 40% of its variance with mean RTs. While the within-group sample sizes are small for examining these types of relations, this is a large correlation 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 locus coeruleus-norepinephrine (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 Alzheimer's disease (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." None of the participants had any diagnosed neurological impairments. Regardless, there was a strong correlation between TEPR latency and processing speed. This opens doors for future research using pupillometry, which is low-cost, portable, noninvasive, and easy to implement, to uncover the neural mechanisms underlying processing speed changes with age.

Pupil diameter provides an indirect index of LC-NE functioning (Joshi et al., 2016; Rajkowski, 1993; Varazzani et al., 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 (Dahl et al., 2021; 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 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. 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 6 years, on average), participants' cognitive functioning was measured annually with 19 tests of episodic memory, working memory, semantic memory, perceptual speed, and visuospatial ability. LC neuron density had a significant protective effect on cognitive decline, even after accounting for neuronal density in the other brain regions of interest. Finally, Dahl et al. (2021) recently showed a relation between in vivo and postmortem LC integrity and cognitive decline in older adults with and without AD. Collectively, these data suggest that LC integrity may be a protective factor in cognitive aging, and may prevent Alzheimer's-related symptoms.

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. However, the LC-NE system is not the only neuromodulatory system that affects pupil diameter, as it also coheres with cholinergic system activity over longer timescales (Reimer et al., 2016). 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 mild cognitive impairment, 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 et al., 2004; Warm et al., 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 et al., 2013; Thomson et al., 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 fully mediate the association between age and the vigilance decrement with measures of motivation, alertness, and task demands.

Limitations

The present study had several limitations which deserve mention. First, the differential sampling methodology does produce a confounding effect of intrinsic motivation. The younger adults participated in the study to fulfill a course requirement, whereas the older adults participated in exchange for money. The older adults thus elected to participate in the study, whereas the younger adults were required to participate either in this study, another study, or write summaries of research articles to fulfill their requirement. Some studies have shown that differential recruitment methods can lead to different patterns of performance in vigilance and memory tasks (e.g., Tomporowski et al., 1993). However, at least one study has shown that this does not fully account for age differences in sustained attention (Tomporowski & Tinsley, 1996). Further, the self-selection into the study by the older adult sample may have driven the high ratings for motivation. The fact that older adults reported greater motivation may not indicate that older adults feel more intrinsically motivated to sustain attention, in general, but the participants who self-selected into this study felt motivated to do well. Additionally, we only inquired about motivation after the task, which may be biased by self-perceptions of performance, and does not account for dynamic shifts of in motivation across time (e.g., Hopstaken et al., 2015a; Robison et al., 2021). Another limitation of the study is that we only had one measure of sustained attention. Part of this decision was intentional, as we wanted to have a longer task (~30 min), which produced a robust vigilance decrement and produced stereotypical pupillary responses in younger adults. However, this prevented us from generalizing to other typical sustained attention tasks (e.g., SART), and estimating age differences at a construct level.

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-min task that produces a robust decrement among younger adults. The RT data also indicated that processing speed differences were largely due to the slowest RTs. 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 TEPRs across time, despite slower-peaking pupillary responses. The pupillary data also suggested that the latency of TEPRs was a strong correlate 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 TEPRs 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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