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RESEARCH ARTICLE

Effort Mobilization and Lapses of Sustained Attention

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Abstract

The current study examined whether effort mobilization would enhance sustained attention and reduce lapses of attention. Participants performed a sustained attention task and were randomly assigned to either an effort condition where they were instructed to "Try Hard" on a subset of trials or were assigned to a control condition with no "Try Hard" instructions. Pupillary responses were continuously recorded, and periodically during the task participants were presented with thought probes to determine whether they were on or off task. The results suggested within the effort condition there were no behavioral differences between Try Hard and "Standard" trials. Preparatory pupil responses were increased in Try Hard trials, but there were no differences for phasic pupillary responses to stimulus onset. In contrast, examining differences between the effort and control conditions suggested that participants who received the Try Hard instructions demonstrated faster overall performance, a reduction in very long reaction times, and reported fewer off-task thoughts compared with participants in the control condition. Participants in the effort condition also demonstrated a larger ramp-up in pupillary responses during the preparatory interval and a larger phasic response to stimulus onset compared with participants in the control condition. These results are consistent with attention allocation models suggesting that participants in the effort condition mobilized more attentional effort than participants in the control condition, resulting in enhanced sustained attention and a reduction in lapses of attention. These results also are consistent with recent theories, which suggest that the locus coeruleus norepinephrine system is associated with effort mobilization.

Keywords Lapses of attention · Effort · Sustained attention

Our ability to maintain and sustain attention on goal-relevant tasks is fundamental for a number of everyday behaviors. Sustained attention is a core aspect of attention control abilities that is distinct from our ability to select and divide attention (Posner & Petersen, 1990; Robertson & O'Connell, 2010; Sturm & Willmes, 2001; van Zomeren & Brouwer, 1994). A great deal of research suggests that sustaining attention on task is a difficult and effortful process not only for long duration tasks, but also for the continuous allocation of attention over just a few seconds resulting in fluctuations and lapses in attention (Langner & Eickhoff, 2013; Parasuraman et al., 1998; Posner, 1978; Unsworth et al., 2020; Unsworth & Robison, 2020). Sometimes, attention is focused on the current task leading to high levels of task engagement and subsequent performance, and other times, the intensity of attention is temporarily lessened leading to reduced levels of task engagement and poorer subsequent performance (i.e., lapses of attention). These attentional lapses reflect temporary shifts of attention away from the task at hand, which can result in failures to perform an intended action. Lapses of attention are thought to arise, in part, due to a number of energetic factors, such as motivation (e.g., intrinsic motivation to do well, extrinsic motivators, such as incentives, etc.), arousal (e.g., circadian rhythm, sleep deprivation, etc.), and alertness (i.e., the overall readiness to respond to external information). Given the importance of our attentional system in a diverse array of situations, it is necessary to understand the nature of these lapses and what factors can mitigate the propensity for lapses. The main goal of the current study was to examine whether mobilizing effort can lead to a reduction in lapses of attention.

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Reducing Lapses

Given the problematic nature of lapses to a number of tasks, prior research has examined how various factors can reduce

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lapses of attention. For example, prior research has suggested that fast-paced tasks can help to maintain attention on task and reduce lapses of attention (De Jong et al., 1999; Unsworth & Robison, 2018, 2020). Furthermore, recent research suggests that motivation levels are associated with lapses of attention. Several studies have demonstrated strong correlations between self-reports of motivation and lapses of attention, such that individuals reporting higher levels of motivation tend to demonstrate fewer lapses of attention in a variety of tasks (Robison & Unsworth, 2015, 2018; Seli et al., 2015; Unsworth & McMillan, 2013; Unsworth, Robison, & Miller, in press). Additional research has begun to examine whether different motivators can reduce the occurrence of lapses of attention. For example, Esterman et al. (2014); see also Esterman, Grosso, et al., 2016a; Esterman, Poole, et al., 2016b) examined how various motivators (i.e., money, money plus feedback, getting out early from the experiment) would affect lapses of attention in a go/no-go sustained attention task (the gradual onset continuous performance task). They found that accuracy increased and variability in reaction times (RTs; as a maker of lapses) decreased with each motivator compared with a control condition with no reward. Thus, different types of rewards served to reduce lapses of attention while performing a sustained attention task.

Massar et al. (2016); see also Massar et al., Massar et al., 2019) similarly demonstrated that lapses of attention can be reduced with monetary rewards during a sustained attention task. Participants performed a variant of the psychomotor vigilance task (PVT; Dinges & Powell, 1985; Lim & Dinges, 2008) in which participants see a row of zeros and are told that when the numbers begin counting up (like a stop watch) they must press a key as fast as possible. Massar et al. had participants perform the standard task first. Then, participants performed two blocks in which they were rewarded 1¢ cent or 10¢ for every trial where their RTs were faster or equal to their median RT in the initial block of trials. They found that lapses (RTs > 500 ms) were significantly reduced in the rewarded blocks compared to the initial baseline block. Additionally, they found that the high reward block resulted in a larger reduction in lapses compared with the low reward block, suggesting that lapses of attention could be reduced with monetary incentives.

Robison et al. (in press) recently examined whether goal-setting, feedback, and incentives alter performance on the PVT. A great deal of prior research has suggested that one potent way to maximize performance on a variety of tasks is to set specific, difficult goals (Locke & Latham, 1990). According to goal-setting theory, motivators such as monetary incentives work, in part, because participants are more likely to set higher goals resulting in better overall performance (Locke, 1968). Thus, goal-setting mediates the relation between incentives and performance (Locke, 1968). Robison et al. examined these notions by assigning some participants a difficult goal in the PVT (i.e., keep your RT below 300 ms), an easy goal (i.e., keep our RT below 800 ms), or no specific goal (i.e., be fast). Robison et al. found that goals resulted in faster RTs overall, and critically lead to a reduction in the longest RTs (lapses), and this was especially true when given a hard goal and feedback. In another experiment Robison et al. examined whether incentives (money or get out early) would influence performance, but unlike prior research, incentives did not reduce the occurrence of lapses. Thus, there was some evidence suggesting that setting specific, difficult goals resulted in a reduction in lapses of attention (indicated by particularly long RTs) in the PVT.

Additional research has suggested that similar motivation manipulations can result in a reduction in self-reports of mind-wandering and off-task thinking (Mrazek et al., 2012; Seli et al., 2019). In these studies, participants typically performed a task and were periodically presented with thought-probes and were required to report whether their attention was currently focused on-task or whether they were thinking of things unrelated to the task (Antrobus, 1968; see Smallwood & Schooler, 2015 for a review). Reports of off-task thinking (e.g., mind-wandering, external distraction, mind-blanking) are typically associated with worse performance compared with reports of on-task focus (Smallwood & Schooler, 2015; Stawarczyk et al., 2011; Unsworth & Robison, 2016). In terms of motivational manipulations, Mrazek et al. (2012) found that monetary incentives reduced reports of off-task thinking during a working memory task (see also Antrobus et al., 1966). Seli et al. (2019) found that reports of off-task thinking were reduced when participants were told that they could get out of the experiment early with good performance. Thus, various motivation manipulations can reduce not only behavioral markers of lapses of attention, but also reduce self-reports of off-task thinking. Although it should be noted that these effects are not always found, as the experiments by Robison et al. (in press) described previously also utilized thought-probes and found that the various manipulations did not influence reports of off-task thinking.

Collectively, prior research suggests that increasing motivation tends to lead to a reduction in lapses of attention (both behavioral and self-reports). Presumably, this is due to an increase in attentional effort (Botvinick & Braver, 2015; Westbrook & Braver, 2015). That is, when motivated, participants mobilize effort to increase the intensity of attention to the task, resulting in better overall task performance and a reduction in lapses of attention. For example, Massar et al. (2016) specifically suggested that “rewards boost sustained attention through higher effort” (p. 21). Similarly, it has long been suggested in goal-setting research that goals serve to direct effort toward a task and increase the intensity of effort toward that task (Locke & Latham, 1990; Robison et al., in press). Thus, mobilizing effort seems to be a key reason why motivation manipulations can reduce the occurrence of lapses of attention.

Effort Mobilization

The idea that attentional effort is important for task performance has a long history in psychology and is a key component of various cognitive-energetic models of performance (Botvinick & Braver, 2015; Hockey, 1997, 2013; Kahneman, 1973; Kanfer, 1987; Kanfer & Ackerman, 1989; Kurzban et al., 2013; Norman & Bobrow, 1975; Sarter et al., 2006; Shenhav et al., 2017; Westbrook & Braver, 2015; Wickens, 1986). Attentional effort reflects the amount of available attentional resources that are allocated to a task, which determines overall task engagement. Attentional effort reflects phasic changes in goal-directed arousal (Kahneman, 1973). As such, attentional effort is influenced by a number of factors including motivation, presence or absence of incentives, current arousal levels, task difficulty, personality factors, self-efficacy, task goals, as well as the costs and benefits of allocating effort. In general, attentional effort regulates the extent to which control is engaged in the current task (Shenhav et al., 2017).

Attention allocation models suggest that there is a general limit on attentional resources (partially dependent on arousal levels), and these resources are allocated based, in part, on task demands such that more demanding tasks require more resources than less demanding tasks (Broadbent, 1971; Hockey, 1997; Kahneman, 1973; Kanfer & Ackerman, 1989; Norman & Bobrow, 1975). As such, these models are important for examining the intensive aspect of attention whereby attentional effort can be increased or decreased, resulting in changes in task performance (Ackerman, 2011; Hockey, 1997, 2011; Kanfer, 2011; Kanfer & Ackerman, 1989; Wickens, 1986). A key aspect of many of these models is the notion that individuals rarely allocate all of their attentional resources to task performance (Hockey, 1997; Kalsbeek, 1968; Kanfer & Ackerman, 1989; Schmidtke, 1976). Rather, individuals allocate an initial proportion of their attention to a task, with some attention being spared (Ackerman, 2011; Hockey, 1997, 2013; Kalsbeek, 1968; Kanfer & Ackerman, 1989; Schmidtke, 1976). Kalsbeek (1968; see also Schmidtke, 1976) referred to this as “willing to spare capacity” and differentiated it from “emergency capacity.” For example, participants might initially only allocate 75% of their available capacity to task. If asked to try harder on the task, participants might mobilize additional effort, increasing their overall allocation to the task. Thus, according to these accounts it should be possible to mobilize additional attentional effort to a task, resulting in increased task performance.

To examine the notion of effort mobilization, prior studies have had participants perform a choice RT task and on some trials participants were instructed to increase their effort and try harder. For example, Kleinsorge (2001) had participants perform a choice RT task, and for 20% of trials, they were pre-cued to speed up their responses (effort trials). If they were able to decrease their RT below their mean from the practice blocks, they received a small monetary reward. Kleinsorge found that participants were faster on effort trials compared to standard (noneffort) trials. This was especially true when the pre-cue interval was long (1200 ms), suggesting that participants had sufficient time to mobilize effort and prepare for the upcoming trial. Furthermore, examining the RT distributions suggested that the speed up associated with the effort trials was present in all RT bins (disproportionality so in the fastest bins). Kleinsorge (2001) suggested the results indicate that participants can mobilize extra effort to enhance performance, that effort mobilization takes time, and that effort mobilization tends to impact overall processing (and not just a reduction in lapses). In a follow-up study, Falkenstein et al. (2003) replicated and extended these results by demonstrating that effort mobilization was associated with an enhancement of the contingent negative variation during the preparatory interval suggesting that with sufficient time, participants increased their effort in preparation of the upcoming trial. In a related study, Steinborn et al. (2017) had participants perform a choice RT task and on 20% of trials they were instructed to try harder. Steinborn et al. (2017) found that try hard trials were associated with overall faster RTs, less RT variability, and a specific reduction in the slowest RTs. Steinborn et al. argued that the try hard instructions resulted in a short-term mobilization of effort which protected the system against attentional failures. Thus, in three prior studies there is evidence that instructing participants to increase effort/try harder on a subset of trials resulted in increased task performance likely via enhanced effort mobilization during the preparatory interval. Furthermore, in one of these studies (Steinborn et al., 2017), there was evidence that effort mobilization reduced lapses of attention.

LC-NE, Effort Mobilization, and Pupillary Responses

Research suggests that sustained attention is linked with a predominantly right lateralized cortical network that includes the frontal-parietal network, the salience network, and the default mode network (Fortenbaugh et al., 2017; Langner & Eickhoff, 2013; Parasuraman et al., 1998; Posner & Petersen, 1990; Robertson & O’Connell, 2010; Sadaghiani & D’Esposito, 2015; Sturm & Willmes, 2001). Collectively, this system is important for maintaining arousal and attention on task relevant stimuli and for reorienting attention back to task relevant stimuli following errors or lapses of attention. In addition to cortical areas, the locus coeruleus norepinephrine system (LC-NE) is also thought to be important for sustaining attention and alertness (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Parasuraman et al., 1998; Poe et al., 2020; Posner & Petersen, 1990; Robertson & O'Connell, 2010; Samuels & Szabadi, 2008). Recent research suggests that the LC-NE is important for modulating prefrontal cortex representations based on attentional control demands (Cohen et al., 2004). In particular, the LC-NE system is important for regulating the current attentional state and recent research suggests that fluctuations in LC-NE functioning are associated with fluctuations and lapses in attention (Mittner et al., 2016; Lenartowicz et al., 2013; Smith & Nutt, 1996; Unsworth & Robison, 2016, 2017, 2018; Unsworth & Robison, 2018, Unsworth & Robison, 2020; van den Brink, Murphy, & Nieuwenhuis, van den Brink et al., 2016).

Theoretically, effort mobilization is associated with functioning of the LC-NE system (Bouret & Richmond, 2015; Poe et al., 2020; Sara & Bouret, 2012; Varazzani et al., 2015). For example, Varazzani et al. (2015) found that LC activity in monkeys was correlated with the amount of effort required on a trial. Varazzani et al. also found that pupillary responses tracked the amount of effort allocated and were correlated with LC activity. These results are consistent with much prior research suggesting that phasic pupil dilation changes as a function of the cognitive demands of a task (see Beatty & Lucero-Wagoner, 2000 for a review). Kahneman (1973) and Beatty (1982) suggested that these phasic pupillary responses are reliable and valid psychophysiological markers of attentional effort. Recent research has also suggested that pupil dilations are indirectly related to the functioning of the LC-NE system (Alnæs et al., 2014; Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Joshi et al., 2016; Joshi & Gold, 2020; McGinley et al., 2015; Murphy et al., 2014; Reimer et al., 2016; Samuels & Szabadi, 2008; Varazzani et al., 2015). Prior research also suggested that pupillary responses can be informative for examining fluctuations and lapses of attention linked to changes in the intensity of attention (attentional effort) associated with the functioning of the LC-NE system (Konishi et al., 2017; Kristjansson et al., 2009; Unsworth & Robison, 2015, 2016, 2017, 2018; Unsworth & Robison, 2018; van den Brink et al., 2016). Thus, it should be possible to utilize pupillary responses to track effort mobilization and to assess the extent to which effort mobilization is associated with a reduction in lapses of attention. For example, Massar et al. (2016) found that a high-reward condition was associated with overall better sustained performance (and fewer lapses) and larger pupillary responses compared to the no-reward condition. Similarly, a number of studies have found that rewards are associated with larger pupillary responses in a number of cognitive control tasks (Chiew & Braver, 2013, 2014; da Silva Castanheira et al., in press; Frömer et al., 2020; Kostandyan et al., 2019). Collectively prior research suggests that in some situations participants can mobilize effort to increase task performance and effort mobilization is likely associated with LC-NE functioning.

Current Study

Although prior research suggests an encouraging link between effort mobilization and increased task performance, more work remains to be done. In particular, in the current study, we examined the extent to which effort mobilization would enhance sustained attention performance, and in particular, reduce the occurrence of lapses of attention. To examine this, participants performed a variant of the PVT. Participants were randomly assigned to either the control condition or the effort condition. In the control condition, participants performed a fairly standard version of the PVT. In the effort condition, participants performed the same PVT task, but on 20% of trials they were instructed to "Try Hard" before the onset of the trial. Before beginning the task, participants in the Try Hard condition were told that on the Try Hard trials they should try their hardest to be as fast as possible. They were told that they should try to be fast during the entire task, but that on Try Hard trials, they should concentrate and pay attention to be as fast as possible. The percent of trials that were designated as Try Hard and the general instructions were similar to prior research (Falkenstein et al., 2003; Kleinsorge, 2001; Steinborn et al., 2017), which has suggested that effort trials should be rare compared with standard trials. Utilizing this experimental setup, we addressed three primary questions. First, we examined whether we could reduce lapses of attention and improve overall sustained attention performance with Try Hard instructions. Prior research has suggested that effort/try hard instructions increase overall performance on choice RT tasks, but it is not clear whether these results will generalize to a more specific sustained attention task. Furthermore, only one prior study (Steinborn et al., 2017) suggested that effort mobilization was specifically associated with a reduction in lapses. Thus, it is not clear that effort mobilization has a distinct effect on reducing lapses or whether it simply increases performance overall. To examine this aspect, we measured both behavioral lapses (indexed by particularly slow RTs) as well as self-reports of off-task thinking (e.g., mind-wandering). Prior research only examined changes in RTs and did not examine potential changes in reports of off-task thinking.

Second, we examined whether differences between conditions would be associated with differences in pupillary responses indicating increased effort. As noted previously, task-evoked changes in pupillary responses have long been associated with changes in effort. Thus, we utilized pupillary responses as a means of tracking potential changes in effort. Specifically, we examined pupillary responses during the preparatory interval prior to stimulus onset as well as pupillary responses to stimulus onset. Prior research with the PVT has suggested that lapses of attention (both behavioral and self-report) are associated with reduced pupillary responses during the preparatory interval (Unsworth et al., 2018; Unsworth et al., 2020). Given prior research suggests that effort mobilization during preparation is critical (Falkenstein et al., 2003; Kleinsorge, 2001; Steinborn et al., 2017), we should expect to find an increased pupillary response during preparation when effort is mobilized (Chiew & Braver, 2013). Additionally, prior research has suggested that pupillary responses to stimulus onset (phasic responses) are reduced for lapses of attention and are generally increased when participants are engaged in the task (Massar et al., 2016; Unsworth et al., 2018; Unsworth et al., 2020; Unsworth & Robison, 2016; van den Brink et al., 2016). Thus, we should expect to see increased phasic responses when effort is mobilized.

Finally, we examined whether potential changes associated with Try Hard instructions would occur as both transient (within-subjects) and sustained (between-subjects) modulations of effort. That is, prior effort mobilization studies all utilized a within-subjects design, suggesting transient trial-to-trial modulations of effort. However, none of these studies had a between-subjects condition to examine whether there are more sustained/global changes in effort mobilization. As noted previously, many attention allocation models assume that individuals first set an initial allocation of attention to a task and can allocate additional attentional effort if needed. It is possible that participants in the Try Hard condition not only increase their effort on specific Try Hard trials, but also allocate a greater amount of effort initially, resulting in better overall performance and increased pupillary responses compared to the control condition. Some prior studies examining incentives have suggested the importance of examining both sustained (between blocks/conditions) and transient (within blocks/conditions) in terms of both performance and pupillary responses (Chiew & Braver, 2013; Kostandyan et al., 2019; Massar et al., 2016). Collectively, in the current study, we examined whether Try Hard instructions improve performance and reduce lapses of attention, whether pupillary responses would track changes in effort, and whether there are both transient trial-by-trial and sustained task-level modulations of effort

Method

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in our study. Data will be made available on the Open Science Framework.

Participants

Participants were 83 individuals between the ages of 18 and 35 years, recruited from the subject-pool at the University of Oregon. Participants were randomly assigned to either the Control condition or the Try Hard condition. We tested participants over one full academic quarter, using the end of the quarter as our stopping rule for data collection with the goal of getting a minimum of 35 participants per condition. With this sample size, we have sufficient power to detect medium to large effects (Cohen's *d*) for both within and between-subjects conditions. There were 42 participants in the Control condition and 41 participants in the Try Hard condition. One participant was excluded from the Try Hard condition for not complying with task instructions and not responding on trials during the task, thus leaving a final sample of 40 participants in that condition.

Procedure

Participants were tested individually in a dark room with a white computer background screen (illuminance = 35.52 lux). After providing informed consent and after calibrating the eyetracker, participants performed a variant of the psychomotor vigilance task (Dinges & Powell, 1985; Unsworth & Robison, 2016). In the Try Hard condition, participants were given specific instructions for the Try Hard trials. Specifically, the instructions stated: "Prior to some trials you will see an instruction saying 'TRY HARD.' On these trials, it is especially important that you try your hardest to be as fast as possible. While you should try to be fast during the entire task, it is critically important that on these TRY HARD trials you really try hard to be as fast as possible. Thus, it is important to really concentrate and pay attention to be as fast as possible." In the Try Hard condition, participants were first presented with either a row of eight black X's (XXXXXXXX) on 80% of trials or the try hard instructions (TRY HARD) on 20% of trials for 1,000 ms on a white background. Pupil diameter was similar when the X's (M = 2.78, SD = 0.32) were presented onscreen compared to when the try hard instructions (M = 2.77, SD = 0.32) were presented, $t(39) = 0.68$, $p = 0.50$, suggesting no differences in pupillary light responses to the stimuli. In the Control condition, participants were always presented with the X's for 1,000 ms. Participants were then presented with a row of five black fixation crosses in the middle of the screen on a white background for 2,000 ms. Participants were then presented with a row of zeros in blue Arial font 24 (visual angle 1.21°) in the center of the screen. After a variable interstimulus interval (ISI; equally distributed from 2-10 s in 500-ms increments), the zeros began to count up in 17-ms intervals from 0 ms (as determined by the 60-Hz monitor refresh rate). The participants' task was to press the spacebar as quickly as possible once the numbers started counting up. After pressing the spacebar the RT was left on screen in red for 1 s to provide feedback to the participants. Following feedback, a 500-ms blank screen was presented, and then either the next trial started or participants were presented with a thought-probe. Participants performed 100 trials, and the experiment lasted approximately 30 min. Thought probes were randomly presented after 20% of the trials. In the Try Hard condition, 10 thought probes followed the Try Hard trials and 10 thought probes followed the standard trials. The thought probes asked participants to classify their thoughts on the immediately preceding trial. The response options for the thought probes were based on prior investigations of mind-wandering and other thought content (i.e., external distraction, task-related interference; mind-blanking; Robison & Unsworth, 2018; Stawarczyk et al., 2011; Unsworth & Robison, 2016; Ward & Wegner, 2013). Probes asked participants to report the current contents of their consciousness. Specifically, they saw a screen that said,

Please characterize your current conscious experience:

1) I am totally focused on the current task.
2) I am thinking about my performance on the task.
3) I am distracted by sights/sounds/temperature or by physical sensations (hungry/thirsty).
4) I am intentionally thinking about things unrelated to the task.
5) I am unintentionally thinking about things unrelated to the task.
6) My mind is blank.

Responses 3-6 (external distraction, mind-wandering, and mind blanking) were taken as the measure of off-task thinking. For all of the RT results reported, false alarms (i.e., hitting the spacebar before the numbers started counting) were excluded. In addition, RTs that fell below 150 ms were excluded from all RT analyses. For behavioral measures, we examined overall mean RT, number of trials with RTs ≥500 ms, which is a standard measure of lapses in this task (Dinges & Powell, 1985), as well as the full RT distributions. Specifically, we rank ordered each individual's RTs from fastest to slowest and created five bins (quintiles) for each individual. Thus, the first quintile represents the fastest 20% of trials and the last quintile represents the slowest 20% of trials. In our prior research, we focused on the slowest 20% of trials as a measure of lapses and noted that this measure tended to correlate highly with the number of trials with RTs ≥500 ms, as well as overall variability in RTs (Unsworth et al., 2020). Indeed, in the current experiment, the slowest 20% of trials and RTs ≥500 ms were strongly correlated (r = 0.88, p < 0.001). We included the results for trials with RTs ≥500 ms for completeness and to make comparisons easier with prior research using the psychomotor vigilance task.

Eye Tracking

Pupil diameter was continuously recorded binocularly at 120 Hz using a Tobii T120 eyetracker. Participants were seated 60 cm from the monitor with the use of chinrest. Stimuli were presented on the Tobii T120 eyetracker 17 in monitor with a 1,024 x 768 screen resolution. Data from each participant's left eye was used. Missing data points due to blinks, off-screen fixations, and/or eyetracker malfunction were removed. We did not exclude whole trials for missing data.

Baseline pupil was computed as the average pupil diameter during the fixation screen (2,000 ms). Pupillary responses during the ISI were corrected by subtracting out the baseline and locked to when the numbers appeared on-screen on a trial-by-trial basis for each participant. To examine the time course of pupillary responses during the ISI, the pupil data were averaged into a series of 200 ms time windows following the appearance of the numbers for each trial. Phasic responses to the onset of the stimulus were corrected by subtracting out the last 200 ms of the ISI and locked to when the numbers began counting up on a trial-by-trial basis for each participant. To examine the time course of the phasic pupillary responses, the pupil data were averaged into a series of 20-ms time windows following stimulus onset for each trial. We examined pupillary responses during the ISI as well as the phasic responses for stimulus onset.

Results

First, we present results for the within-subject analyses examining differences between the Try Hard trials and the Standard trials for both behavioral and pupillometry measures. Next, we present results for the between-subject analyses examining differences between the Try Hard condition (all trials) and the Control condition for both behavioral and pupillometry measures.

Within-Subject Analyses

Behavioral Measures

Comparing the Try Hard trials to the Standard trials with a paired samples t-test, suggested no difference in mean RTs (M Try Hard = 355.73, SD = 45; M Standard = 360.20, SD = 40), $t(39)$ = 1.00, p = 0.33, d = 0.18. See *Supplemental Materials* for analyses of time-on-task effects. There also was no difference in the proportion of lapse trials (M Try Hard = 0.06, SD = 0.08; M Standard = 0.06, SD = 0.05), $t(39)$ = −0.44, p = 0.66, d = 0.07. Next, we examined differences in the full RT distributions for the Try Hard and Standard trials. As noted previously, each individual's RTs were rank ordered from fastest to slowest. Next, these rank ordered responses were placed into five bins such that 20% of each individual's responses were placed into each bin. These quintiles were then averaged across participants to examine differences in the distributions across trial types. The data was analyzed with a 2 (Trial Type) x 5 (Quintile) repeated measures analysis of variance. The main effect of trial type was not significant, $F(1, 39)$ = 1.22,

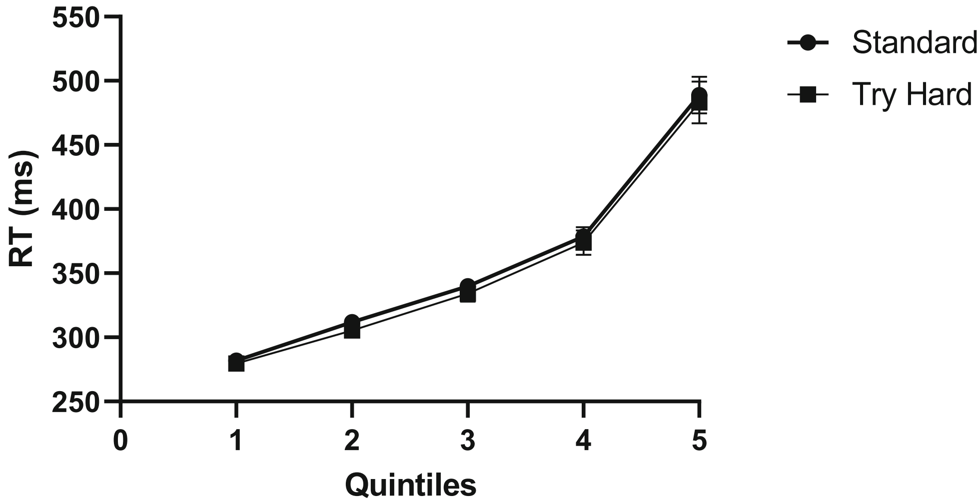


Fig. 1 Quintile plots as a function of trial type. Error bars represent one standard error of the mean. Error bars are present for all quintiles, but are very small for the fastest quintiles

MSE = 2,056.48, $p = 0.28$, partial $\eta^2 = 0.03$. There was a main effect of quintile as would be expected, $F(4, 156) = 279.86$, *MSE* = 1,827.89, $p < 0.001$, partial $\eta^2 = 0.88$. Importantly, the trial type x quintile interaction was not significant, $F(4, 156) = 0.06$, *MSE* = 87.50, $p = 0.99$, partial $\eta^2 = 0.002$. As shown in Figure 1, there were no differences between the Try Hard and Standard trials in any of the RT bins.

Examining differences in the proportion of off-task thoughts with a paired samples *t*-test, similarly suggested no differences between Try Hard and Standard trials (*M* Try Hard = 0.49, *SD* = 0.25; *M* Standard = 0.51, *SD* = 0.29), $t(39) = 0.99$, $p = 0.33$, $d = 0.11$. [1] See *Supplemental Materials* for analyses of each off-task response option separately. Overall, the results suggested no differences between the Try Hard and Standard trials on the behavioral measures.

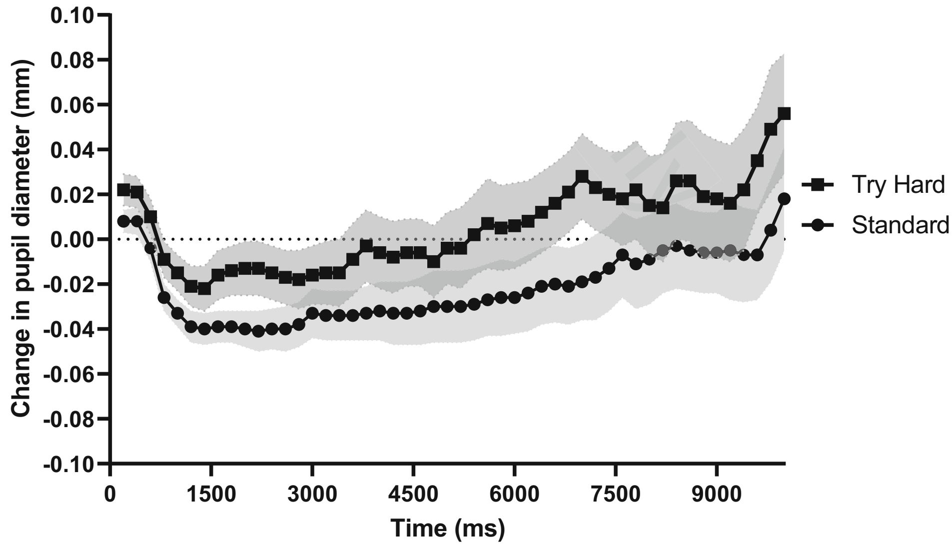
Pupillary Responses

First, we examined pupillary responses during the ISI as a means of examining potential differences in effort mobilization associated with preparatory processes. As noted previously, pupillary responses during the ISI were baseline corrected and averaged into a series of 200-ms time windows following the appearance of the numbers for each trial. All ISIs from 2-10 s were averaged together into a single pupillary response for each participant. Thus, there were naturally more trials entering into the shortest ISIs, because all ISIs included at least 2 s. Overall similar results are obtained when only examining the 10-s ISI condition. Furthermore, two participants had missing values in some of the time bins and were excluded from these analyses. The data was analyzed with a 2 (Trial Type) x 50 (Time Bin) repeated measures analysis of variance. Examining the pupillary response during the ISI as a function of trial type suggested a significant effect of trial type, $F(1, 37) = 8.37$, *MSE* = 0.08, $p = 0.006$, partial $\eta^2 = 0.19$, such that pupillary responses were larger for the Try Hard trials compared with the Standard Trials (*M* Try Hard = 0.005, *SE* = 0.01; *M* Standard = −0.022, *SE* = 0.01), as seen in Figure 2a. There also was a significant effect of time, $F(49, 1813) = 3.54$, *MSE* = 0.006, $p < 0.001$, partial $\eta^2 = 0.09$, such that pupillary responses tended to increase over time. However, the interaction between trial type and time was not significant, $F(49, 1813) = 0.46$, *MSE* = 0.003, $p = 1.00$, partial $\eta^2 = 0.01$. Thus, Try Hard trials were associated with larger overall pupillary responses during the ISI than Standard Trials, but the strength of this relation did not change as a function of time.

Next, we examined differences in phasic pupillary responses to stimulus onset (i.e., when the numbers began counting up). As noted above, phasic responses to the onset of the stimulus were corrected by subtracting out the last 200 ms of the ISI and locked to when the numbers began counting up on a trial-by-trial basis for each participant. To examine the time course of the phasic pupillary responses, the pupil data were averaged into a series of 20-ms time windows following stimulus onset for each trial. Data were analyzed with a 2 (Trial Type) x 55 (Time Bin) repeated measures analysis of variance. Examining the phasic pupillary responses as a function of trial type suggested no significant effect of trial type, $F(1, 39) = 0.09$, *MSE* = 0.02, $p = 0.77$, partial $\eta^2 = 0.002$. There was a significant effect of time, $F(54, 2106) = 27.42$, *MSE* = 0.003, $p < 0.001$, partial $\eta^2 = 0.41$, such that there was a clear phasic pupillary response. However, the interaction between trial type and time was not significant, $F(54, 2106) = 0.27$, *MSE* = 0.000, $p = 1.00$, partial $\eta^2 = 0.007$. Figure 2b shows that there were no differences in the phasic pupillary responses as a function of Trial Type.

[1] Differences between Try Hard (*M* = 0.25, *SD* = 0.17) and Standard trials (*M* = 0.19, *SD* = 0.15) on task-related interference (probe response option 2) did not reach conventional levels of significance, $t(39) = 1.98$, $p = 0.054$.

(a)



(b)

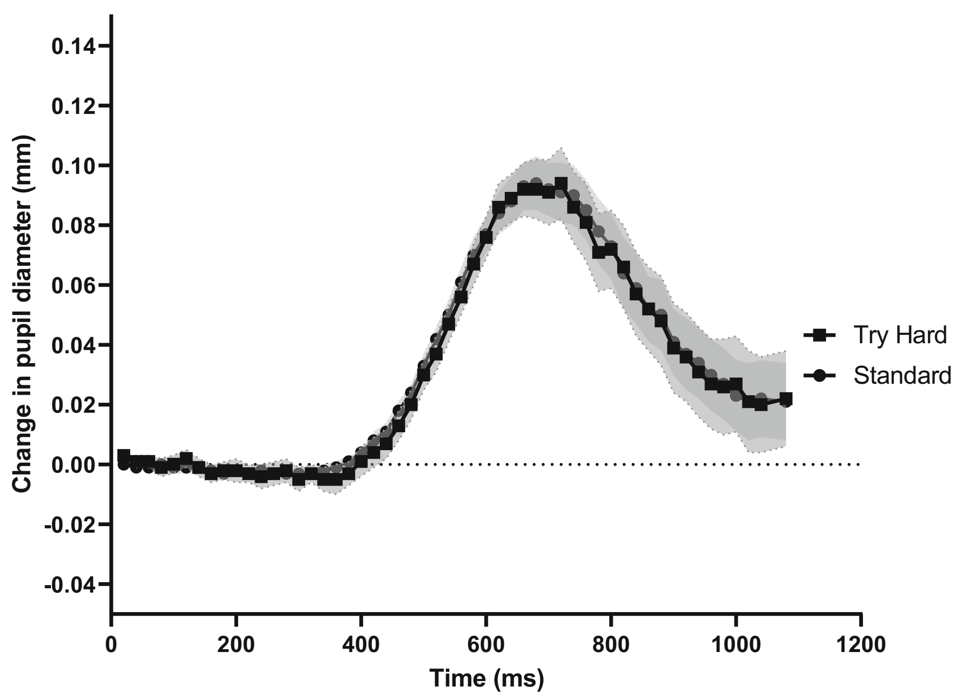


Fig. 2 **(a)** Change in pupil diameter as a function of time during the ISI and trial type. **(b) C**hange in pupil diameter as a function of time after stimulus onset and trial type. Shaded areas reflect one standard error of the mean

Between-Subject Analyses

Behavioral Measures

Comparing the Try Hard and Control conditions with an independent samples *t*-test, suggested a significant difference in mean RTs with faster RTs in the Try Hard condition compared with the Control condition: (*M* Try Hard = 359.30, *SD* = 40; *M* Control = 397.57, *SD* = 62), $t(80) = 3.30$, $p = 0.001$, $d = 0.74$. There was also a significant difference in the number of lapse trials (*M* Try Hard = 7.08, *SD* = 6.4; *M* Control = 12.98, *SD* = 11.21), $t(80) = 2.91$, $p = 0.005$, $d = 0.65$. Next, we examined differences in the full RT distributions for the Try Hard and Control conditions. The data was analyzed with a 2

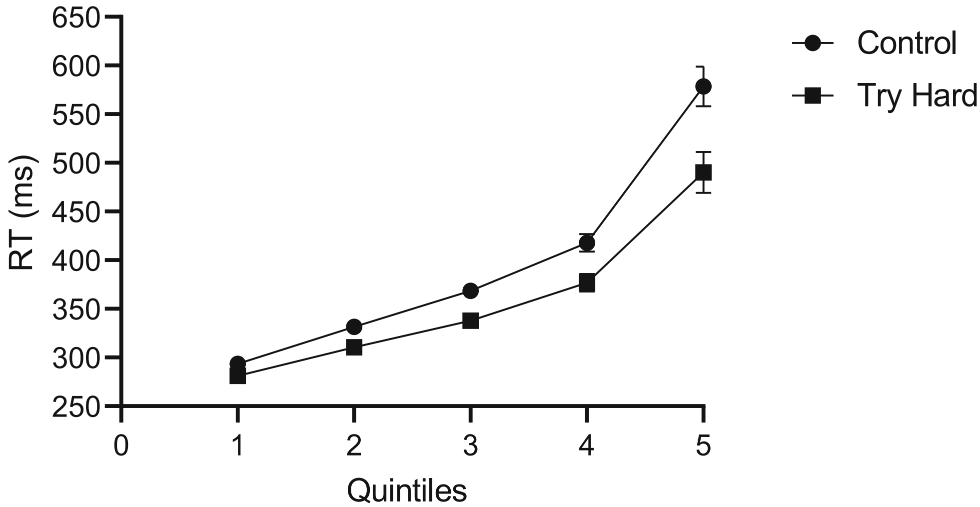


Fig. 3 Quintile plots as a function of condition. Error bars represent 1 standard error of the mean. Error bars are present for all quintiles but are very small for the fastest quintiles

(Condition) x 5 (Quintile) repeated measures analysis of variance with condition as a between-subjects factor. The main effect of condition was significant, $F(1, 80) = 10.99$, $MSE = 13{,}924.35$, $p = 0.001$, partial $\eta^2 = 0.12$. There was a main effect of quintile as would be expected, $F(4, 320) = 287.11$, $MSE = 2{,}629.53$, $p < 0.001$, partial $\eta^2 = 0.78$. Importantly, the condition x quintile interaction was significant, $F(4, 320) = 6.89$, $MSE = 2{,}629.53$, $p = 0.009$, partial $\eta^2 = 0.08$. Figure 3 shows differences at all RT bins, but the differences increased for the slowest RTs, suggesting that much of the difference between conditions was due to a reduction in the slow tail of the distribution in the Try Hard condition compared with the Control condition. [2]

Examining differences in the proportion of off-task thoughts similarly suggested a difference between Try Hard and Control conditions (M Try Hard = 0.50, $SD = 0.25$; M Standard = 0.62, $SD = 0.24$), $t(80) = 2.18$, $p = 0.03$, $d = 0.49$). Overall, the results suggested a number of differences between the Try Hard and Control conditions suggesting better overall performance and fewer lapses in the Try Hard condition.

Pupillary Responses

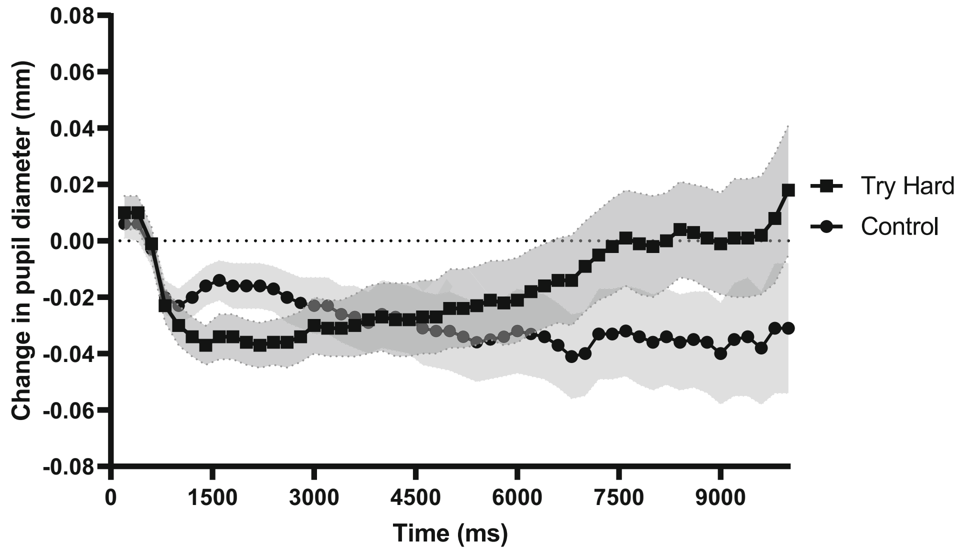
First, we examined pupillary responses during the ISI as a means of examining potential differences in effort mobilization associated with preparatory processes across conditions. The data was analyzed with a 2 (Condition) x 50 (Time Bin) repeated measures analysis of variance with condition as a between-subjects factor. Examining the pupillary response during the ISI as a function of condition suggested no effect of condition, $F(1, 80) = 0.49$, $MSE = 0.26$, $p = 0.49$, partial $\eta^2 = 0.006$. The effect of time was significant, $F(49, 3920) = 2.18$, $MSE = 0.003$, $p < 0.001$, partial $\eta^2 = 0.03$, such that pupillary responses initially decreased and then tended to increase over time. Importantly, the interaction between condition and time was significant, $F(49, 3920) = 3.10$, $MSE = 0.003$, $p < 0.001$, partial $\eta^2 = 0.04$. As shown in Figure 4a, pupillary responses tended to increase over time (following an initial dip likely due to a slight change in luminance from the baseline screen) in the Try Hard condition but tended to decrease in the Control condition.[3]

Next we examined differences in phasic pupillary responses to stimulus onset (i.e., when the numbers began counting up). Data were analyzed with a 2 (Condition) x 55 (Time Bin) repeated measures analysis of variance with condition as a between-subjects factor. Examining the phasic pupillary responses as a function of condition suggested that the effect of condition was not quite significant, $F(1, 80) = 3.90$, $MSE = 0.052$, $p = 0.052$, partial $\eta^2 = 0.05$. There was a significant effect of time, $F(54, 4320) = 63.62$, $MSE = 0.001$, $p < 0.001$, partial $\eta^2 = 0.44$, such that there was a clear phasic pupillary response. Importantly, the interaction between condition and time was significant, $F(54, 4320) = 3.15$, $MSE = 0.001$, $p < 0.001$, partial $\eta^2 = 0.04$. As seen in Fig. 4b, phasic pupillary responses in the Try Hard condition were larger than those in the Control condition. Overall, the results suggested that the Try Hard condition was associated with a greater ramp up in pupil dilation during the preparatory interval and a larger phasic response to stimulus onset than the Control condition, suggesting a greater intensity of attention to the task.

[2] We also examined false alarms (hitting the spacebar before the numbers began counting up) and found no differences between the Try Hard ($M = 3.18$, $SD = 2.90$) and Control ($M = 3.76$, $SD = 3.16$) conditions in number of false alarms, $t(80) = 0.88$, $p = 0.38$.

[3] Nearly identical ISI and phasic pupillary results were found when only examining the Standard Trials from the Try Hard condition.

(a)



(b)

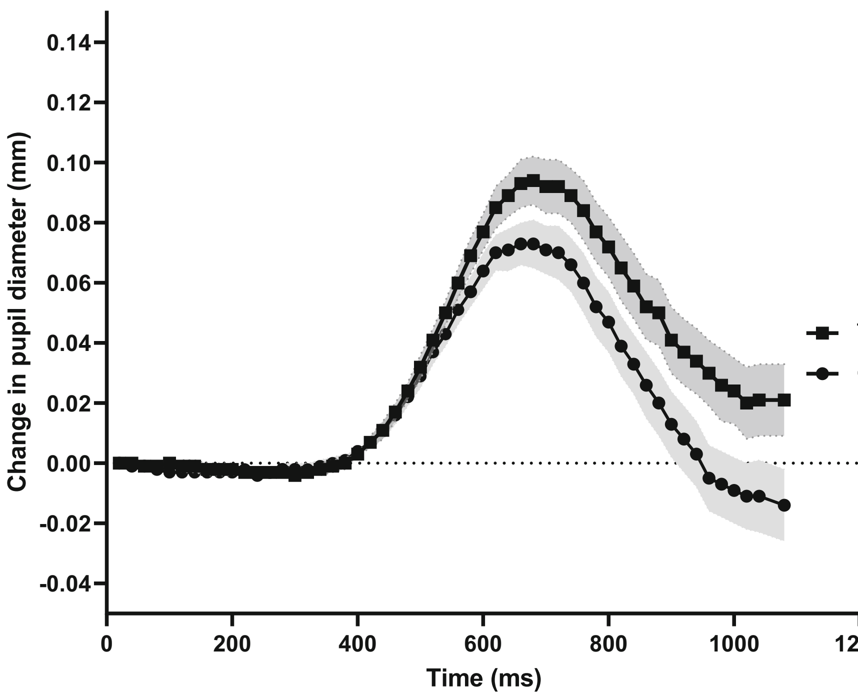


Fig. 4 (**a**) Change in pupil diameter as a function of time during the ISI and condition. **(b)** Change in pupil diameter as a function of time after stimulus onset and condition. Shaded areas reflect one standard error of the mean

Discussion

We examined behavioral and pupillary correlates of effort mobilization during sustained attention. Participants performed a sustained attention task in which participants in an effort condition were instructed to Try Hard on a subset of trials and participants in the control condition received no Try Hard instructions. As noted in the *Introduction,* we addressed three primary questions: (1) Will Try Hard instructions improve performance and reduce lapses of attention? (2) Will pupillary responses during both the preparatory interval and at stimulus onset track potential changes in effort? (3) Are there both transient trial-by-trial and sustained task-level modulations of effort? Examining within-subject differences between Try Hard and Standard trials suggested no differences in any of the behavioral measures. Thus, the Try Hard instructions did not lead to a reduction in lapses of attention (behavioral or self-report). Note, a potential confound for the self-report measure was that the thought-probes were presented for half of the Try Hard trials but were presented for only approximately 13% of the Standard trials. Thus, the Try Hard trials were predictive of the thought probes. However, even with this confound, there were still no differences between the Try Hard and Standard trials in terms of self-reports of off-task thinking. Future research should attempt to equalize rates of thought probes for Try Hard and Standard trials. Examining pupillary responses suggested an increased dilation response during the preparatory interval for the Try Hard trials compared with the Standard trials, but no differences for the phasic pupillary responses to stimulus onset. Thus, participants seemed to mobilize effort during the preparatory interval, but this did not result in increased intensity of attention to the stimulus and did not translate into a performance benefit. As such, these results suggest little evidence for transient trial-by-trial modulations of effort and a reduction of lapses in the current sustained attention task.

Conversely, examining between-subject differences between the Try Hard condition and the Control condition suggested differences in all behavioral measures such that participants in the Try Hard condition demonstrated better overall performance and fewer lapses of attention (both behavioral and self-report) compared with participants in the Control Condition. Similarly, examining pupillary responses suggested that participants in the Try Hard condition demonstrated greater dilation responses during both the preparatory interval and for stimulus onset compared with the Control condition. These results are consistent with the notion that participants mobilized effort during the preparatory interval, resulting in an increased intensity of attention to the stimulus and a reduction in lapses of attention. Collectively, these results provide evidence for sustained task-level modulations of effort and a reduction of lapses in the current sustained attention task.

In terms of attention allocation models (Broadbent, 1971; Hockey, 1997; Kahneman, 1973; Kanfer & Ackerman, 1989; Norman & Bobrow, 1975), the current results suggest that participants in the Try Hard condition allocated more effort overall than participants in the Control condition resulting in better performance and fewer lapses of attention overall. This increase in effort was demonstrated in increased pupillary responses during the preparatory interval (i.e., increased preparatory attention) and increased pupillary responses to stimulus onset suggesting greater intensity of attention and overall higher levels of task engagement. A potential alternative explanation is that the Try Hard instructions simply increased overall arousal without any specific increase in effort. That is, these types of tasks can be boring resulting in lowered arousal and lowered performance. Perhaps the Try Hard instructions resulted in a general increase in arousal which then resulted in better performance. If differences between conditions were due to general arousal, we would expect overall baseline pupil diameter to differ between conditions with the Try Hard condition demonstrating a larger baseline pupil than the Control condition. However, there were no differences between conditions in baseline pupil diameter (M Try Hard = 2.77, SD = 0.33; M Control = 2.75, SD = 0.25), $t(80) = -0.31$, $p = 0.76$, d = 0.07. Rather, there were specific differences in changes in pupil diameter during the preparatory interval and to stimulus onset associated with changes in effort. Furthermore, we note that Type I errors are possible such that the randomization of participants to conditions did not result in equal abilities across groups. We think this is unlikely given the only difference across conditions was the Try Hard instructions. But, we cannot discount the possibility of a Type I error. Future research is needed to demonstrate that the results are robust and replicate with both between and within subject designs. Overall, the current results provide evidence for the notion that the Try Hard instructions resulted in task-level (sustained) effort mobilization.

While the results suggested evidence for sustained modulations of effort, the within-subject results suggested little evidence for transient modulations of effort in terms of the behavioral and pupillary measures. The only difference that emerged was a difference in pupillary responses during the preparatory interval, suggesting that participants increased effort on the Try Hard trials; however, this did not translate into a performance difference. These results are inconsistent with prior research which has examined effort/try hard instructions. Specifically, prior research has found within-subject differences between Try Hard and Standard trials, suggesting faster RTs and reduced lapses (based on particularly slow RTs) on the Try Hard trials (Falkenstein et al., 2003; Kleinsorge, 2001; Steinborn et al., 2017). Naturally, we need to ask what could lead to these discrepant results. One possibility is differences in the tasks used. Specifically, prior research used a choice (2 or 4) RT task, whereas the current study used a simple RT task. As such, RTs in the current task were 100-200 ms faster than in prior research. Given the skewed nature of RT distributions, it is possible that there was less room to move the distribution downward given that RTs in the fastest quintile were already very fast. That is, the current simple RT task may be more data-limited (rather than resource limited; Norman & Bobrow, 1975), suggesting that the allocation of additional effort had no effect on performance. Another difference is that prior studies utilized many more trials (481-1,440) than the current study (100). Furthermore, the difference between Try Hard and Standard trials in prior studies ranged from 25-87 ms. Given that these effects can be small, it may be necessary to have a large number of trials and small standard errors to detect these effects. Finally, in two prior studies (Falkenstein et al., 2003; Kleinsorge, 2001), participants received a monetary reward for trials in which they increased their RTs compared with the Standard trials. This addition of a monetary reward could have resulted in more effort being allocated compared to just the Try Hard instructions. Thus, tasks differences could have led to discrepant results.

Additionally, it is possible that participants did increase their effort on Try Hard trials, as indicated by increased pupil dilation during the preparatory interval, but this increase in effort did not translate to differences in performance. That is, when given the overall Try Hard instructions, participants could have allocated most of their effort to the task (resulting in task-level changes in effort), leaving little spare attentional effort. When participants got the specific Try Hard trials, they increased what little effort they had remaining, but this was not enough to actually change performance. Another possibility is that participants did mobilize effort on the Try Hard trials, but they did not allocate enough effort to actually change performance (i.e., a labor-in-vain effect). That is, they had some effort to spare, but they did not allocate enough of the spared effort to increase task performance. Future research is needed to further examine trial-by-trial modulations of effort mobilization and how they impact task performance.

The present results are broadly consistent with current theories of LC-NE functioning suggesting that the LC-NE is important for effort mobilization. As noted previously, the LC-NE is associated with arousal and attentional state (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Poe et al., 2020; Posner & Petersen, 1990; Robertson & O'Connell, 2010; Samuels & Szabadi, 2008; Sara & Bouret, 2012; Unsworth & Robison, 2017), and recent theorizing suggests that a critical function of the LC-NE is to mobilize resources (including attentional effort) needed to perform goal-directed actions (Bouret & Richmond, 2015; Jahn et al., 2020; Poe et al., 2020; Raizada & Poldrack, 2008; Sara & Bouret, 2012; Varazzani et al., 2015). For example, Bouret and Richmond (2015) had monkeys perform a task in which once they pressed a bar, they were provided with a cue indicating the possible reward for that trial and whether the trial required an action or not. Monkeys were required to keep the bar pressed and after a wait time, a target appeared indicating that they could release the bar. If their responses were fast enough (i.e., less than 800 ms after the target appeared), they received a reward for that trial. Bouret and Richmond (2015) found that LC neurons began firing shortly after the cue during the wait time and the firing rate varied as a function of the reward for that trial (increased firing rate for larger rewards). The LC neurons also demonstrated increased firing rates just prior to the action of releasing the bar. Bouret and Richmond suggested that the activity of the LC neurons reflected the mobilization of resources during the preparatory wait time and during target presentation to perform the desired action, thus suggesting a critical role of the LC in effort mobilization. The PVT task used in the current study is very similar to the task utilized by Bouret and Richmond in that participants initiate a trial and then have to wait to perform a desired action at the appearance of a target stimulus. Given associations between pupillary responses and the LC-NE system, our pupillary responses during both the preparatory wait time and at target onset are consistent with the findings from Bouret and Richmond (2015), suggesting that effort was being mobilized during these epochs. As such the current results are consistent with the notion that the LC-NE system is important in mobilizing attentional effort.

Collectively, the current results suggest that task-level modulations of attentional effort, in the form of Try Hard instructions, increase sustained attention performance, and in particular help mitigate lapses of attention. Pupillary responses during the preparatory interval and at stimulus onset tracked these task-level (sustained) differences in effort. There was little evidence for transient trial-by-trial effort mobilization (save for an overall increase in preparatory pupillary responses) that influenced task performance. These results are consistent with attention allocation models suggesting that participants in the Try Hard condition mobilized more attentional effort initially than participants in the Control condition, and effort mobilization is likely associated with functioning of the LC-NE system. Future research is needed to examine effort mobilization and the extent to which effort mobilization can enhance task performance and alleviate lapses of attention.

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