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The Importance of Arousal for Variation in Working Memory Capacity and Attention Control: A Latent Variable Pupillometry Study

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A great deal of prior research has examined the relation between working memory capacity (WMC) and attention control. The current study explored the role of arousal in individual differences in WMC and attention control. Participants performed multiple WMC and attention control tasks. During the attention control tasks participants were periodically probed regarding their current attentional state and both baseline and task-evoked pupillary responses were recorded as indicators of tonic arousal and phasic arousal because of attentional effort, respectively. Latent variable analyses demonstrated that variability in both baseline pupil diameter and task-evoked responses was related to WMC, attention control, and off-task thinking. Furthermore, structural equation models suggested that variability in both baseline pupil diameter and task-evoked pupillary responses predicted off-task thinking, which in turn predicted variation in WMC and attention control. These results provide important evidence linking moment-to-moment fluctuations in arousal to individual differences in WMC and attention control.

Keywords: working memory capacity, attention control, arousal, mind-wandering, pupillometry

Working memory reflects our ability to actively maintain, manipulate, and retrieve task relevant information. A great deal of research has demonstrated that individual differences in working memory capacity (WMC) strongly predict performance in a number of domains from low-level attention and memory tasks to higher-level reasoning and comprehension (see Engle & Kane, 2004; Unsworth & Engle, 2007 for reviews). One prominent theory of individual differences in WMC suggests that this variation is because of individual differences in attention control (or executive attention) abilities (Engle & Kane, 2004; Kane & Engle, 2002; Unsworth & Engle, 2007). In the current article we extend prior attention control theories of WMC by suggesting that individual differences in WMC and attention control are largely because of fluctuations in arousal which result in more frequent lapses of attention and more inconsistent attention control.

WMC and Attention Control

Attention control refers to the set of attentional processes that aid in the ability to actively maintain information in the presence of interference and distraction. In particular, attention control abilities are necessary when goal-relevant information must be maintained in a highly active state in the presence of potent internal and external distraction (Engle & Kane, 2004). Any lapse of attention (or goal neglect; Duncan, 1995) will likely lead to a loss of the task goal and will result in attention being automatically captured by internal (e.g., mind-wandering; Kane et al., 2007; McVay & Kane, 2012) or external distraction (e.g., Fukuda & Vogel, 2009; Robison & Unsworth, 2015; Unsworth, Fukuda, Awh, & Vogel, 2014; Unsworth & McMillan, 2014). Thus, a key aspect of attention control is the ability to actively maintain the current goal in a highly active state and prevent attentional capture.

Across a number of studies individual differences in WMC have been shown to be related to performance on a number of attention control tasks. For example, variation in WMC has been shown to predict differences in antisaccade performance (Kane, Bleckley, Conway, & Engle, 2001; Unsworth, Schrock, & Engle, 2004), Stroop interference (Kane & Engle, 2003; Meier & Kane, 2013; Morey et al., 2012), flanker interference (Heitz & Engle, 2007; Redick & Engle, 2006), dichotic listening (Colflesh & Conway, 2007; Conway, Cowan, & Bunting, 2001), performance on the psychomotor vigilance task (Unsworth, Redick, Lakey, & Young, 2010; Unsworth & Spillers, 2010), performance on the Sustained Attention to Response Task (SART; McVay & Kane, 2009), performance on versions of go/no-go tasks (Redick, Calvo, Gay, & Engle, 2011), performance on the AX-CPT task (Redick, 2014; Redick & Engle, 2011; Richmond, Redick, & Braver, 2015), performance on cued visual search tasks (Poole & Kane, 2009), and performance on some versions of the Simon task (Meier & Kane, 2015). These relations have been found not only when examining individual attention control measures, but also when examining latent variables composed of the shared variance among multiple attention control tasks. Across a number of studies WMC and attention control have been found to correlate approximately $r = .60$ at the latent level suggesting a good deal of shared variance between these two constructs (Kane et al.,

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2016; McVay & Kane, 2012; Unsworth & Spillers, 2010; Unsworth et al., 2014; Unsworth & McMillan, 2014).

In addition to demonstrating relations between WMC and performance on measures of attention control, recent work has shown that WMC is related to lapses of attention in both laboratory and real-world settings (e.g., Kane et al., 2007). For example, Unsworth, Brewer, and Spillers (2012) found that WMC and attention control assessed in the laboratory predicted reports of everyday attentional failures from diaries. Specifically, low WMC and low attention control individuals reported more external distraction, more absent-mindedness, and more mind-wandering than high WMC individuals. In addition to assessing lapses of attention in everyday settings, a great deal of recent research has focused on examining lapses of attention during laboratory based attention control tasks and whether WMC predicts the occurrence of these lapses. For example, McVay and Kane (2009) utilized thought probe techniques in which periodically throughout a task participants are probed as to their current state (on-task or off-task). Prior work with these techniques has found that participants report mind-wandering during many cognitive tasks and that the degree of mind-wandering varies as a function of a number of task variables (McVay & Kane, 2010; Smallwood & Schooler, 2006). More important, mind-wandering rates correlate with task performance such that performance is lower when participants report that they were mind-wandering on the preceding trial compared with when participants report that they are currently focused on the task (McVay & Kane, 2010; Smallwood & Schooler, 2006). Relying on these thought-probe techniques McVay and Kane (2009) found that low WMC individuals reported more mind-wandering during the SART than high WMC individuals, and mind-wandering rates partially mediated the relation between WMC and task performance (see also McVay & Kane, 2012; Unsworth & McMillan, 2013). In a similar vein, Unsworth and McMillan (2014) had participants perform a number of WMC and attention control tasks in which we probed participants about not only whether they were mind-wandering, but also whether they were distracted by information in the external environment (Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011). We reasoned that low ability individuals will be more likely than high ability individuals to have their attention captured by both internal (mind-wandering) and external distractors (see also Robison & Unsworth, 2015). In line with this reasoning, Unsworth and McMillan (2014) found that mind-wandering and external distraction were correlated at the latent level and both were correlated with WMC and attention control. More important, the variance shared among external distraction, mind-wandering, and performance on the attention control tasks was strongly correlated with WMC, suggesting that lapses of attention are an important reason for the WMC-attention control relation.

Collectively, prior research suggests that a key aspect of the WMC-attention control relation is whether one can consistently apply control across trials. That is, trial-to-trial variability in attention control is critically important. High WMC and attention control individuals are better able to consistently maintain attention on task than low WMC and attention control individuals. This results in low WMC and attention control individuals experiencing more fluctuations and lapses of attention than high WMC and attention control individuals. Supporting evidence comes from a number of recent studies that have shown that low WMC individuals have more slow RTs and more variability in RTs during attention control tasks than high WMC individuals (McVay & Kane, 2012b; Schmiedek, Oberauer, Wilhelm, Süss, & Wittmann, 2007; Unsworth, 2015; Unsworth et al., 2010, 2012). In particular, Unsworth (2015) found that variability of RTs in attention control tasks (but not variability in RTs on lexical decision tasks) correlated with WMC. Furthermore, variability in RTs (particularly slow RTs) on attention control tasks predicted mind-wandering rates (both in and out of the laboratory) and WMC (see also Kane et al., 2016). Thus, the consistency of attention control may be the key factor that relates to WMC and other cognitive abilities. These results suggest that low WMC individuals experienced more trial-to-trial fluctuations in attention than high WMC individuals, suggesting that inconsistency in attention control is a likely reason for poorer performance seen by low WMC individuals on various tasks.

Arousal and the Regulation of Attentional State

Arousal has long been considered important in determining attention and performance (e.g., Broadbent, 1971; Eysenck, 1992; Hasher & Zacks, 1979; Kahneman, 1973; Yerkes & Dodson, 1908). For example, in the classic Yerkes-Dodson (1908) law arousal and performance are related in an inverted-U shaped function such that at high and low levels of arousal individuals are disengaged from the task at hand leading to lower levels of performance. At intermediate levels of arousal, task engagement is optimal leading to the highest levels of task performance. Furthermore, it is assumed that arousal and performance interact with task difficulty such that easy tasks require more arousal than difficult or complex tasks.

In a similar vein, Kahneman (1973) suggested that attentional capacity was determined in part by arousal. Specifically, in Kahneman's model, attention is capacity limited and it is assumed that overall arousal levels determine capacity at any given moment. Furthermore, it is assumed that attention is allocated based on enduring dispositions (i.e., processing and orienting to novel stimuli; involuntary attention), momentary intentions (such as the current task set/goal; voluntary attention), as well as the overall evaluation of demands (monitoring and feedback) on capacity. Thus, in this model there is a tight linkage between attentional capacity and arousal, such that fluctuations in arousal can determine capacity at any given time. When arousal is optimal, attentional capacity will be at its maximum, but when arousal is too high or too low attentional capacity will be reduced leading to reductions in performance. In particular, Kahneman (1973) suggested that when arousal is low this may prevent the adoption of the correct task set leading to lowered performance. Furthermore, when arousal is low this may interfere with the monitoring and evaluation of performance leading to an insufficient increase in arousal and subsequently lowered performance. Likewise, Kahneman suggested that when arousal is too high this can disrupt the overall allocation of attention to the current task such that the allocation of attention fluctuates more widely and there can be an increased narrowing of attention leading to difficulty discriminating relevant from irrelevant stimuli based on Easterbrook's (1959) hypothesis. Overall, within Kahneman's model attentional capacity is determined by current arousal levels that can impact task performance on a moment-by-moment basis.

Recent work by Lenartowicz, Simpson, and Cohen (2013) has further suggested that arousal levels and the degree to which attention is focused either internally or externally determines current levels of attention control. In particular, they suggested a landscape of attentional lapses wherein when arousal is low and attention is focused internally, mind-wandering and zoning out occurs. When arousal is low and attention is focused externally, attentional capture from bottom-up sources is expected to occur. When arousal is high and attention is focused internally this can lead to internal distraction in the form of ruminations and racing thoughts. Similarly, Mandler (1975) suggested that when arousal is high, participants tend to generate their own internal cues and attention drifts away from the current task to these internal cues leading to performance decrements. Lenartowicz et al. (2013) further suggested that when arousal is high and attention is focused externally this can lead to external distraction resulting in oversensitivity to external stimuli. Thus, Lenartowicz et al. (2013) suggest that the type of lapse of attention is determined by arousal levels and by whether attention is directed to external stimuli or to internal thoughts. Similarly, within Kahneman's (1973) model when arousal is optimal voluntary attention is engaged and performance tends to be good. However, when arousal is too low or too high, involuntary attention determines the allocation of attention to salient stimuli (either internally such as mind-wandering, or externally such as distractions).

The current arousal state is also regulated by various neuromodulatory systems (e.g., Aston-Jones & Cohen, 2005; Pfaff, Martin, & Faber, 2012; Robbins, 1997). The locus coeruleus norepinephrine system (LC-NE) is important for determining general arousal state and attentional interest (Berridge & Waterhouse, 2003; Samuels & Szabadi, 2008a, 2008b; Szabadi, 2013). Recent research suggests that there is an inverted-U relationship between LC tonic activity and performance on various cognitive tasks (see Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Cohen, Aston-Jones, & Gilzenrat, 2004 for reviews), similar to the arousal-performance curve (Yerkes & Dodson, 1908). Specifically, it is assumed that when tonic LC activity is low (hypoarousal), individuals are inattentive, nonalert, and disengaged from the current task leading to poor behavioral performance and little to no phasic LC activity in response to task-relevant stimuli. As tonic LC activity increases to an intermediate range attention becomes more focused, LC phasic activity increases for target stimuli, and behavioral performance is optimal. However, as tonic LC activity increases further, the individual experiences a more distractible attentional state (hyperarousal) leading to task disengagement, lowered LC phasic activity, and a reduction in behavioral performance. Intracranial recordings in rats and monkeys and psychopharmacological studies in animals and humans provide evidence in support of the notion of an inverted-U relationship between the LC-NE system, attention control, and behavioral performance (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Chamberlain & Robbins, 2013; Ramos & Arnsten, 2007). Collectively prior work suggests a tight linkage between attention and arousal such that high or low levels of arousal are related to lowered attention control and increased susceptibility to a variety of lapses of attention from internal and external sources. Furthermore, the LC-NE system is critically important for regulating arousal and attentional state to achieve optimal levels of task performance.

Pupil Diameter as an Index of Arousal and Attentional Effort

A potential candidate as a psychophysiological marker for changes in arousal and attentional state is pupil diameter. In particular, both tonic/baseline pupil size and phasic changes in pupil size are important indicators of arousal and attentional effort (Granholm & Steinhauer, 2004).[1] Specifically, tonic pupil size can be taken as an overall indicator of current arousal levels. For example, prior research has consistently shown that under conditions of fatigue or low levels of alertness and arousal, baseline pupil diameter is smaller and more variable than when alert (Hou, Freeman, Langley, Szabadi, & Bradshaw, 2005; Morad, Lemberg, Yofe, & Dagan, 2000). Additionally, in sustained attention tasks tonic pupil size tends to decrease and overall pupil variability tends to increase with time on task demonstrating a vigilance decrement (Fried et al., 2014; Unsworth & Robison, 2016a). These changes in baseline pupil diameter are consistent with increases in pupillary unrest, suggesting that as time on task increases, alertness and arousal decrease and fluctuations in attention increase (Hopstaken, van der Linden, Bakker, & Kompier, 2015a, 2015b; Lowenstein, Feinberg, & Lowenfeld, 1963; McLaren, Erie, & Brubaker, 1992; Morad et al., 2000; Unsworth & Robison, 2016a; Wilhelm et al., 2001). Similarly, changes in pretrial baseline pupil diameter have also been implicated in the detection of lapses of attention. For example Murphy, Robertson, Balsters, and O'connell (2011) found an inverted-U relationship between baseline pupil size and performance such that RT variability was greater when baseline pupil was very small or very large, but RT variability was lowest at intermediate baseline levels. Kristjansson, Stern, Brown, and Rohrbaugh (2009) similarly found that baseline pupil diameter was much smaller on trials preceding very slow RTs (indicative of lapses of attention) compared with trials where RT was close to the mean. In another study, Murphy, Vandekerckhove, and Nieuwenhuis (2014) found that baseline pupil diameter predicted trial-to-trial variability in drift rate suggesting that increased arousal predicted inconsistency in RTs. Finally, recent research has found that mind-wandering rates are related to both larger (Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2013) and smaller (Grandchamp, Braboszcz, & Delorme, 2014; Mittner et al., 2014; Unsworth & Robison, 2016a) baseline pupil diameters compared

[1] Pupil diameter is controlled by both the sympathetic and parasympathetic nervous systems. The dilator pupillae is innervated by adrenergic input from the sympathetic nervous system resulting in dilation, whereas the sphincter pupillae is innervated by cholinergic input from the parasympathetic nervous system resulting in constriction. Pupil dilation can occur either from activation of the sympathetic nervous system or the inhibition of the parasympathetic nervous system, and both may be important for sustained processing (Steinhauer, Siegle, Condray, & Pless, 2004). Thus, pupil dilation can occur via a complex interaction of the sympathetic and parasympathetic nervous systems. Most work has assumed that attentional effort is linked with sympathetic activation via linkages with the LC-NE. However, recent research by Sarter, Gehring, and Kozak (2006) suggests the importance of cholinergic factors to attentional effort. Thus, future work should examine potential interactions between sympathetic and parasympathetic nervous systems in relation to attentional effort and pupil dilation/constriction.

with on-task thoughts (see also Kang et al., 2014; Smallwood et al., 2011, 2012). Thus, prior work suggests that overall baseline/tonic levels of pupil diameter are an indicator of arousal levels and the current attentional state.

Whereas baseline pupil size seems to provide an index of overall arousal, phasic pupillary responses seem to indicate phasic arousal. Changes in phasic arousal can occur due unexpected irrelevant stimuli (such as a loud noise) resulting in an orienting response. Likewise, changes in phasic arousal can occur because of task relevant changes in attentional effort. Specifically, these pupillary responses are known as task-evoked pupillary responses (TEPRs) in which the pupil dilates relative to baseline levels because of increases in attentional effort. For example, Hess and Polt (1964) demonstrated that the pupils dilated as a function of problem difficulty in a mental multiplication task with higher peak dilations for the hardest problems. Similarly, Kahneman and Beatty (1966) demonstrated that pupillary dilation increased as more items were required for recall in a standard short-term memory (STM) task (see also Peavler, 1974; Unsworth & Robison, 2015). A number of studies have demonstrated similar TEPRs in a variety of tasks (see Beatty & Lucero-Wagoner, 2000 for a review; see also Goldinger & Papesh, 2012; Laeng, Sirois, & Gredebäck, 2012 for recent reviews). These and other results led Kahneman (1973) and Beatty (1982) to suggest that TEPRs are a reliable and valid psychophysiological marker of cognitive effort and the intensity of attention. Thus, Kahneman (1973) suggested that pupillary responses can be used to examine a participant's "momentary involvement in the task" (p. 19).

Important for the current discussion, prior research suggests that TEPRs are sensitive to attention control demands and working memory load. For example, prior studies have found that incongruent trials on Stroop, flankers, and Simon tasks elicit a larger TEPR than congruent or neutral trials (e.g., Brown et al., 1999; Geva, Zivan, Warsha, & Olchik, 2013; Laeng, Ørbo, Holmlund, & Miozzo, 2011; van Steenbergen & Band, 2013; van Steenbergen, Band, & Hommel, 2015). Similarly, antisaccade trials elicit larger TEPRs than prosaccade trials (Karatekin, Bingham, & White, 2010; Wang, Brien, & Munoz, 2015) and antisaccades are related to greater preparatory pupil dilations than prosaccades (Wang et al., 2015). In a similar vein research examining pupillary responses during working memory tasks has found that as the amount of information in working memory increases so do TEPRs (e.g., Heitz, Schrock, Payne, & Engle, 2008; Kahneman & Beatty, 1966; Peavler, 1974; Tsukahara, Harrison, & Engle, 2016; Unsworth & Robison, 2015). Furthermore, prior research has found that when participants report mind-wandering during attention control tasks, these trials are associated with smaller TEPRs than trials where participants report being on-task (Mittner et al., 2014; Unsworth & Robison, 2016a). Thus, TEPRs track attention control and working memory demands in a variety of tasks suggesting that greater attentional effort is associated with larger TEPRs and mind-wandering and off-task thinking are associated with smaller TEPRs.

Overall these results are consistent with the notion that pupil dilations reflect arousal levels and attentional state and are indirectly related to the functioning of the LC-NE system (Aston-Jones & Cohen, 2005; Eldar, Cohen, & Niv, 2013; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Jepma & Nieuwenhuis, 2011; Joshi, Kalwani, & Gold, 2016; Phillips, Szabadi, & Bradshaw, 2000; Samuels & Szabadi, 2008a; Varazzani, San-Galli, Gilardeau, & Bouret, 2015). Specifically, when LC tonic levels are low and arousal is low, baseline pupil diameter and TEPRs tend to be small. When individuals are hyperaroused and tonic LC levels are very high baseline pupil diameter is relatively large and TEPRs are small. However, when LC tonic levels are optimal overall baseline pupil diameter is at intermediate levels and TEPRs are at their largest. Additionally, recent neuroimaging work has shown that activity in the LC is correlated with changes in pupil diameter (Alnæs et al., 2014; Murphy et al., 2014). Collectively, this work suggests that baseline pupil diameter and TEPRs can be seen as reporter variables indexing arousal levels and attentional effort and are an indirect index of LC-NE functioning.

The Current Study

Previously we described how individual differences in WMC and attention control are strongly related, and we suggested that much of this relation is because of fluctuations in attention control. If fluctuations of attention control are a key factor in the WMC-attention control relation, then what gives rise to these fluctuations? That is, what is the reason for the strong relation between WMC and attention control? Here we propose that overall and moment-to-moment changes in arousal are important for individual differences in WMC and attention control. Specifically, we suggest that attention control failures may be because of an inability to maintain moment-to-moment optimal arousal levels resulting in fluctuations in the ability to control attention in a goal-directed manner. That is, deficits in attention control are partially because of arousal levels such that low WMC and attention control individuals are less able to consistently engage and sustain attention to the task at hand compared with high WMC and attention control individuals.

If arousal levels are an important factor in individual differences in WMC and attention control, then individual differences in pupil diameter (both pretrial baseline and TEPRs) should be related to individual differences in WMC, attention control, and task-disengagement in the form of the off-task thoughts. In particular, there are three potential ways in which arousal levels are related to individual differences in WMC and attention control (see Table 1).

Table 1
Possible Theoretical Differences Between High and Low WMC Individuals in Attention Control

Possibility	Baseline	TEPR	Performance	Off-task
Low WMC high arousal	↑	↓	↓	↑
Low WMC low arousal	↓	↓	↓	↑
Low WMC fluctuations in arousal	Variable	Variable	↓	↑
Low WMC no difference in arousal	=	=	↓	↑
Low WMC less capacity	=	↓	↓	↓ ?
Low WMC less efficient	=	↑	↓	↓ ?

Note. Each possibility compares low working memory capacity (WMC) individuals to high WMC individuals. For example, in the low WMC high arousal possibility, low WMC individuals would have larger baseline pupil diameters, smaller TEPRs, worse performance, and more off-task thoughts compared with high WMC individuals. See text for details. TEPR = task-evoked pupillary responses.

One possibility is that low WMC individuals have higher tonic arousal levels (*Low WMC high arousal*) resulting in lowered attention control and increased task disengagement. This would suggest that low WMC individuals are constantly in a hyper-aroused state associated with task disengagement and impulsivity because of lowered attention control (Lenartowicz et al., 2013). In terms of pupillary responses this would result in low WMC individuals having larger pretrial baseline pupils and lower TEPRs than high WMC individuals.

Another possibility is that low WMC individuals may have overall lower tonic arousal levels (*Low WMC low arousal*) resulting in lowered attention control and increased task-disengagement (more off-task thinking) than high WMC individuals. This would suggest that low WMC individuals are constantly in a hypoaroused state associated with inattentiveness and lowered levels of alertness. In terms of pupillary responses this would result in low WMC individuals having lower pretrial baseline pupils and lower TEPRs than high WMC individuals. Evidence consistent with this hypothesis comes from prior work by Heitz et al. (2008; see also Tsukahara et al., 2016) who found that low WMC individuals tended to have lower baseline pupils than high WMC individuals (see also Janisse, 1977 for a review of similar results).

A third possibility is that low WMC individuals have more moment-to-moment fluctuations in tonic arousal levels (*Low WMC fluctuations in arousal*) resulting in arousal levels that are sometimes too low and sometimes too high. That is, low WMC individuals fluctuate more between optimal, too little, and too much arousal throughout a task compared with high WMC individuals. This would mean that much of the time low WMC individuals would perform just as well as high WMC individuals given that they would typically have similar tonic arousal levels. However, given moment-to-moment fluctuations in arousal levels, low WMC individuals would be more likely to have lapses of attention associated with either too low or too high arousal levels compared with high WMC individuals. This would result in greater susceptibility to lapses of attention, more mind-wandering and more attentional capture from potent external distractors. In terms of pupillary responses this would suggest that low WMC individuals should have more variability in pupil diameter (both pretrial baselines and TEPRs) than high WMC individuals. Evidence consistent with this hypothesis comes from Unsworth and Robison (2015) who found that variability in pretrial baseline pupil diameter was negatively related with WMC. Thus, there are three potential ways in which arousal levels and changes in arousal levels could influence performance and account for individual differences in WMC and attention control. Of course, we should also acknowledge that a fourth possibility of no relation between arousal and individual differences in WMC and attention control is also possible. This null possibility would suggest that individual differences in WMC and attention control are because of something other than arousal levels. In terms of pupillary responses this would suggest no relations between WMC and pupil diameter (both pretrial baseline and TEPRs).

In addition to arousal explanations of the relation between WMC and attention control, two additional explanations are possible (see Table 1).[2] Specifically, it is possible that the relation between WMC and attention control is because of differences in overall attentional capacity whereby high WMC individuals have more capacity than low WMC individuals (*Low WMC less capacity*), thereby allowing high WMC individuals to allocate more resources to the task at hand than low WMC individuals (e.g., Cantor & Engle, 1993; Just & Carpenter, 1992, 1993). This would result in higher performance on attention control tasks for high WMC individuals than low WMC individuals. In terms of pupillary responses this would likely suggest no differences in pretrial baseline pupil diameter, but high WMC individuals should have larger TEPRs than low WMC individuals, especially on tasks requiring greater capacity. Evidence consistent with this hypothesis is the finding that high WMC individuals have higher TEPRs than low WMC individuals on working memory tasks where the number of items that need to be maintained are at or over capacity limits (Tsukahara et al., 2016; Unsworth & Robison, 2015). Similarly, high ability individuals tend to demonstrate higher TEPRs especially on tasks of greater difficulty (e.g., Bornemann et al., 2010; Granholm, Morris, Sarkin, Asarnow, & Jeste, 1997; Karatekin, White, & Bingham, 2008; Rondeel, van Steenbergen, Holland, & van Knippenberg, 2015; van der Meer et al., 2010; Dix & van der Meer, 2015). Thus, high ability individuals outperform low ability individuals on attention control tasks because high ability individuals have greater attentional capacities that can be devoted to the task at hand than low ability individuals. In terms of off-task thinking, it is not entirely clear what this possibility would predict when participants are performing attention control tasks. For example, it is possible that because low WMC individuals have less attentional capacity, they are less able to maintain attention on task and are more susceptible to automatic forms of attentional capture such as mind-wandering. At the same time it is possible that high WMC individuals do not allocate all of their resources to the current task and, thus, have spare capacity that can be used to engage in off-task thinking. This would predict a positive correlation between WMC and off-task thinking. Evidence consistent with this notion comes from several studies that have found a positive relation between WMC and mind-wandering (e.g., Levinson, Smallwood, & Davidson, 2012; Rummel & Boywitt, 2014). Thus, the relation between WMC and off-task thinking may depend on the attentional capacity demands of the current task.

A final related possibility is that high and low WMC individuals have the same arousal and attentional capacity levels, but high WMC individuals are more efficient at allocating attentional resources to the task at hand than low WMC individuals (*Low WMC less efficient*). The notion that differences arise because of variation in efficiency has a long and complex history in cognitive neuroscience (Poldrack, 2015). The efficiency hypothesis suggests that the better performance of high WMC individuals on attention control tasks compared with low WMC individuals is because of a more efficient allocation of attention to the current task in which high WMC individuals are actually allocating less attention than low WMC individuals. In terms of pupillary responses this possibility suggests no differences in pretrial baseline pupil diameter, but critically predicts that low WMC individuals should have larger TEPRs than high WMC individuals, indicating that they are

[2] An additional possibility not tested in the current article is that WMC differences in attention control are because of low WMC individuals having compromised monitoring abilities and subsequent adjustments in control. That is, low WMC individuals may not be aware of their lapses of attention or errors and, thus, subsequent adjustments in control are insufficient or absent and performance continues to suffer.

allocating more attention to the task at hand. Evidence for this possibility comes from early work by Ahern and Beatty (1979) where high ability individuals (based on SAT scores) outperformed low ability individuals on mental multiplication tasks and had smaller TEPRs than the low ability individuals (see Janisse, 1977 for a review of similar results; see van der Meer et al., 2010 for a similar hypothesis regarding individual differences in fluid intelligence). Ahern and Beatty interpreted the results as suggesting that individual differences were not because of differences in capacity or effort, but rather were because of the fact that high ability individuals were more efficient at allocating attentional resources than low ability individuals. Similar to the capacity possibility, the efficiency possibility seems to predict a positive relation between WMC and off-task thinking such that high WMC individuals are more efficient at allocating attention to the current task, resulting in more spare capacity that can be used for off-task thinking.

Overall, there are a number of possible reasons for the strong and consistent relation between WMC and attention control. Critically, as shown in Table 1 these different possibilities can be distinguished based on the pattern of both pretrial baseline pupil diameter and TEPRs along with task performance and propensity for off-task thinking. If individual differences in arousal (too high, too low, or more fluctuations) are an important reason for individual differences in attention control and their relation with WMC, then a specific pattern should emerge across these various measures. If other factors such as overall differences in attentional capacity or efficiency are important for the relation between WMC and attention control, then some other specific pattern should emerge across the various measures.

Before continuing we should note that an important aspect of our argument rests on the assumption that baseline pupil diameter is a good measure of arousal at the subject level. That is, much prior research has utilized baseline pupil diameter to examine arousal levels within participants (e.g., changing arousal levels because of fatigue). At the same time a number of studies have also utilized baseline pupil diameter to examine tonic arousal levels between participants (see Janisse, 1977 for an early review). For example, Stelmack and Mandelzys (1975) found that introverts had larger baseline pupil diameters than extroverts and suggested that introverts had higher tonic levels of arousal than extroverts. Similarly, Yechiam and Telpaz (2011) found that high risk takers had larger baseline pupil diameters than low risk takers. As noted previously Heitz et al. (2008; see also Tsukahara et al., 2016) found that high WMC individuals had larger baseline pupil diameters than low WMC individuals consistent with differences in tonic arousal levels. Likewise, van der Meer et al. (2010) found that individuals with high fluid intelligence had larger baseline pupil diameters than individuals with low fluid intelligence (see also Bornemann et al., 2010). Furthermore, Wass, de Barbaro, and Clackson (2015) demonstrated that various autonomic arousal measures (including baseline pupil diameter) are correlated in infants. Finally, a number of studies have found that persons with Autism Spectrum Disorder have larger baseline pupil diameters than age matched controls and differences in baseline pupil diameter are related to salivary correlates of NE functioning (Anderson & Colombo, 2009; Anderson, Colombo, & Unruh, 2013). Thus, a number of between participant studies have utilized baseline pupil diameter as a potential marker of individual differences in tonic arousal levels. Of course, like any measure, baseline pupil diameter is not a pure measure of arousal given that other factors influence it even under conditions of constant luminance such as age, overall physical size of the pupil, ingestion of caffeine or nicotine, and so forth (Loewenfeld, 1993; Tryon, 1975). Thus, although baseline pupil diameter can be used to examine between and within participant differences in arousal, arousal is not the only factor that influences it.

To examine the role of arousal (as well as other possibilities) in the WMC-attention control relation we conducted a structural equation modeling study in which participants performed multiple WMC and attention control tasks. Specifically, participants (N = 165) performed versions of the operation span, symmetry span, and reading span tasks as measures of WMC. For attention control participants performed versions of the antisaccade task, the Stroop task, and the psychomotor vigilance task. During the attention control tasks we utilized thought-probe techniques to assess individual differences in off-task thoughts (i.e., mind-wandering, inattention, and external distraction) under attention demanding conditions. More important, during the attention control tasks we simultaneously recorded pupil diameter as a potential index of arousal. Pupillary responses were only recorded during the attention control tasks because we were primarily interested in examining how arousal is related to task disengagement in those types of tasks specifically. Unfortunately, because of a data collection error in the antisaccade task, intact pupil responses were only obtained for the Stroop and psychomotor vigilance tasks. Below we examine pupillary responses in the two attention control tasks and examine individual differences in pupillary responses and their relation with individual differences in WMC, attention control, and the propensity for off-task thinking.

Method

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in our study.

Participants

In total, 175 participants (63.4% women) were recruited from the subject-pool at the University of Oregon, a comprehensive state university (M first year student SAT scores = 1,110, M first year student ACT scores = 25). Participants from this pool demonstrate similar levels of performance and variability on the cognitive ability measures to studies conducted at other comprehensive state universities such as University of North Carolina Greensboro (Kane et al., 2016) and University of Georgia (Unsworth & Spillers, 2010) as well as studies with a mix of community volunteers and university students (Unsworth et al., 2014). Data from 10 participants were dropped because the participants failed to complete two or more tasks (mostly the attention control tasks). The remaining 165 participants were between the ages of 18 and 35 (M = 19.48, SD = 2.17) and received course credit for their participation. Each participant was tested individually in a laboratory session lasting approximately 2 hr. We tested participants over two full academic quarters, using the end of the second quarter as our stopping rule for data collection. Note some of the data has been reported in Robison, Gath, and Unsworth (2017) and, thus, the current data and that data are not from independent samples.

Specifically, 119 (68%) of the current participants are shared with Robison et al. (2017). The purpose of that study was to examine relations among neuroticism, WMC, attention control, and mind-wandering.

Materials and Procedure

After signing informed consent, all participants completed operation span, symmetry span, reading span, psychomotor vigilance task, antisaccade, Stroop, Ravens Advanced Progressive Matrices, letter sets, syllogisms, and a visual working memory filtering task. All tasks were administered in the order listed above. The Ravens Advanced Progressive Matrices, letter sets, syllogisms, and visual working memory filtering task were part of another project and not discussed here. Following the tasks participants filled out a battery of questionnaires that were part of a different project (Robison et al., 2017) and not discussed here. The WMC and attention control tasks (including the thought probes) are the same as those in Robison et al. (2017).

Thought Probes

During the attention control tasks, participants were periodically presented with thought probes asking them to classify their immediately preceding thoughts. The thought probes asked participants to press one of five keys to indicate what they were thinking just before the appearance of the probe. Specifically, participants saw:

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 daydreaming/my mind is wandering about things unrelated to the task.
5. I am not very alert/my mind is blank.

During the introduction to the task, participants were given specific instructions regarding the different categories. Response 1 was considered on-task. Response 2 measures task-related interference and was not included in the analyses. Responses 3–5 were considered as off-task thinking. Prior research has demonstrated that the different off-task probes are correlated at the individual differences level and that variance common to the various off-task probes is what is important for the relation between WMC and attention control (Unsworth & McMillan, 2014). Thus, responses 3–5 were combined into a single off-task measure for each attention control task.

WMC Tasks

Operation span. Participants solved a series of math operations while trying to remember a set of unrelated letters (see Unsworth, Heitz, Schrock, & Engle, 2005). Participants were required to solve a math operation, and after solving the operation, they were presented with a letter for 1 s. Immediately after the letter was presented the next operation was presented. At recall participants were asked to recall letters from the current set in the correct order by clicking on the appropriate letters. For all of the span measures, items were scored correct if the item was recalled correctly from the current list. Participants were given practice on the operations and letter recall tasks only, as well as two practice lists of the complex, combined task. List length varied randomly from three to seven items, and there were two lists of each list length for a maximum possible score of 50. The score was total number of correctly recalled items.

Symmetry span. Participants recalled sequences of red squares within a matrix while performing a symmetry-judgment task (see Unsworth, Redick, Heitz, Broadway, & Engle, 2009). In the symmetry-judgment task, participants were shown an 8 × 8 matrix with some squares filled in black. Participants decided whether the design was symmetrical about its vertical axis. The pattern was symmetrical half of the time. Immediately after determining whether the pattern was symmetrical, participants were presented with a 4 × 4 matrix with one of the cells filled in red for 650 ms. At recall, participants recalled the sequence of red-square locations by clicking on the cells of an empty matrix. Participants were given practice on the symmetry-judgment and square recall task as well as two practice lists of the combined task. List length varied randomly from two to five items, and there were two lists of each list length for a maximum possible score of 28. We used the same scoring procedure as we used in the operation span task.

Reading span. While trying to remember an unrelated set of letters, participants were required to read a sentence and indicated whether or not it made sense (see Unsworth et al., 2009). Half of the sentences made sense, while the other half did not. Nonsense sentences were created by changing one word in an otherwise normal sentence. After participants gave their response, they were presented with a letter for 1 s. At recall, participants were asked to recall letters from the current set in the correct order by clicking on the appropriate letters. Participants were given practice on the sentence judgment task and the letter recall task, as well as two practice lists of the combined task. List length varied randomly from three to seven items, and there were two lists of each list length for a maximum possible score of 50. We used the same scoring procedure as we used in the operation span and symmetry span tasks.

Attention Control (AC) Tasks

Psychomotor vigilance task (PVT). Before each trial, there was a 2 s baseline period with "+++++" in the center of the screen to determine baseline pupil diameter (luminance = 208 lux). After this, participants were then presented with a row of zeros in the center of the screen (luminance = 212 lux) and after a variable wait time (equally distributed from 2–10 s in in 500 ms increments) the zeros began to count up in 17 ms intervals from 0 ms. 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 for 1 s to provide feedback to the participants. After feedback, a 500 ms blank screen was presented and then either the next trial started or participants were presented with a thought-probe. The entire task lasted for 10 min for each individual (75 total trials). The dependent variable was the average RT for the slowest 20% of trials (Dinges & Powell, 1985). Fifteen thought probes were randomly presented after trials.

Stroop. Before each trial, there was a 2 s baseline period with "+++++" in the center of the screen to determine baseline pupil diameter (luminance = 208 lux). After this, participants were presented with a color word (red, green, or blue) presented in one of three different font colors (red, green, or blue: average luminance = 214 lux). The participants' task was to indicate the font color via key press (red = 1, green = 2, and blue = 3). Participants were told to press the corresponding key as quickly and accurately as possible. Participants received 15 trials of response mapping practice and 6 trials of practice with the real task. Participants then received 100 real trials. Of these Trials 67% were congruent such that the word and the font color matched (i.e., red printed in red) and the other 33% were incongruent (i.e., red printed in green). The dependent variable was the RT for incongruent trials. Twelve thought probes were randomly presented after incongruent trials.

Antisaccade. Before each trial, there was a 2 s baseline period with "+++++" in the center of the screen to determine baseline pupil diameter (luminance = 12 lux). After this, participants were instructed to stare at a fixation point which was onscreen for a variable amount of time (200–2,200 ms). A flashing white "=" was then flashed either to the left or right of fixation (11.33° of visual angle) for 100 ms (luminance = 10 lux). This was followed by the target stimulus (a B, P, or R) onscreen for 100 ms. This was followed by masking stimuli (an H for 50 ms followed by an 8 which remained onscreen until a response was given). The participants' task was to identify the target letter by pressing a key for B, P, or R (the keys 4, 5, or 6) as quickly and accurately as possible. In the prosaccade condition the flashing cue (=) and the target appeared in the same location. In the antisaccade condition the target appeared in the opposite location as the flashing cue. Participants received, in order, 10 practice trials to learn the response mapping, 15 trials of the prosaccade condition, and 50 trials of the antisaccade condition. The dependent variable was proportion correct on the antisaccade trials. Eleven thought probes were randomly presented after trials.

Eye Tracking

For the three attention control tasks participants were tested individually in a dimly lit room. Pupil diameter was continuously recorded binocularly at 120 Hz using a Tobii T120 eyetracker, integrated in a 17-inch TFT monitor. Data from each participant's left eye was used. Participants were seated approximately 60 cm from the monitor and did not use a chinrest or other immobilization device. The Tobii T120 provides accurate tracking even with a good degree of head movement. Average distance from the eye tracker was not correlated with any of the variables in the current study (all *r*s < .10). Missing data points because of blinks, off-screen fixations, and/or eyetracker malfunction were removed.

Pretrial baseline responses were computed as the average pupil diameter during the fixation screen (2000 ms) for each task. TEPRs were corrected by subtracting out baseline pupil and were time locked to when the stimulus was presented on a trial-by-trial basis for each participant. Specifically, in the psychomotor vigilance TEPRs were time locked to when the zeros began counting and in the Stroop TEPRs were time locked to the appearance of the colored word. To examine the time course of the TEPRs, the pupil data were averaged into a series of 20 ms time windows after stimulus onset for each trial. The dependent measures are the peak task-evoked response and *SD* of the task-evoked response. Peak task-evoked responses were used to stay consistent with prior research that has examined pupillary responses in these (Brown et al., 2014; Karatekin, Bingham, & White, 2010; Laeng et al., 2011; Unsworth & Robison, 2016a) and other attention control tasks (Braem, Coenen, Bombeke, van Bochove, & Notebaert, 2015; Geva et al., 2013; van Steenbergen, & Band, 2013). Overall similar results were obtained when examining average dilation during stimulus presentation. As noted previously, because of a data collection error in the antisaccade task, intact pupil responses were only obtained for the Stroop and psychomotor vigilance tasks.

Results

Descriptive Statistics

Descriptive statistics for all of the measures are shown in Table 2. As can be seen, the measures had generally acceptable values of internal consistency and most of the measures were approximately normally distributed with values of skewness and kurtosis under the generally accepted values (i.e., skewness <2 and kurtosis <4; see Kline, 1998). Correlations, shown in Table 3, were weak to moderate in magnitude with measures of the same construct generally correlating stronger with one another than with measures of

Table 2
Descriptive Statistics and Reliability Estimates for All Measures

Measure	*M*	*SD*	Skew	Kurtosis	Reliability	*N*
Ospan	36.74	8.99	−.87	.82	.77	164
Symspan	19.30	5.34	−.49	−.34	.73	165
Rspan	36.27	9.56	−.81	−.95	.77	165
Anti	.64	.17	−.47	−.36	.86	161
Stroop	812	184	1.01	2.28	.86	157
PVT	452	83	.93	1.04	.92	152
Aoff	4.00	3.44	.53	−.91	.62	161
Soff	4.20	3.63	.67	−.64	.71	157
Poff	4.93	3.89	.76	−.08	.70	152
PBaseM	2.64	.29	.44	.46	.95	152
PBaseSD	.19	.05	.75	.23	.91	152
SBaseM	2.54	.28	.67	1.61	.97	156
SBaseSD	.20	.06	.93	1.20	.88	156
PTEPR	.11	.06	.63	.71	.83	152
PTEPRSD	.21	.08	2.06	6.51	.70	152
STEPR	.08	.06	.53	.77	.82	155
STEPRSD	.22	.09	3.01	7.74	.76	155

Note. Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; Stroop = color word Stroop task; PVT = psychomotor vigilance task; Aoff = average number of off-task thoughts Antisaccade; Soff = average number of off-task thoughts Stroop; Poff = average number of off-task thoughts psychomotor vigilance task; PBaseM = mean raw baseline pupil diameter (in milliliter, mm) during psychomotor vigilance task; PBaseSD = *SD* of raw baseline pupil diameter (in mm) during psychomotor vigilance task; SBaseM = mean raw baseline pupil diameter (in mm) during Stroop; SBaseSD = *SD* of raw baseline pupil diameter (in mm) during Stroop; PTEPR = mean task-evoked pupillary response (mm change) during psychomotor vigilance task; STEPR = mean task-evoked pupillary response (mm change) during Stroop; PTEPRSD *SD* task-evoked pupillary response (mm change) during psychomotor vigilance task; STEPRSD *SD* task-evoked pupillary response (mm change) during Stroop. Reliabilities are αs for all measures.

Table 3
Correlations Among All Measures

Measure	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Ospan	—																
2. Symspan	.36	—															
3. Rspan	.57	.32	—														
4. Anti	.24	.20	.31	—													
5. Stroop	−.35	−.23	−.33	−.38	—												
6. PVT	−.27	−.14	−.19	−.50	.40	—											
7. Aoff	−.17	−.01	−.20	−.26	.19	.37	—										
8. Soff	−.15	−.05	−.13	−.25	.34	.35	.67	—									
9. Poff	−.19	.00	−.12	−.21	.21	.53	.60	.55	—								
10. PbaseM	−.17	−.08	−.18	−.04	.17	.03	.09	.18	.08	—							
11. PBaseSD	−.19	−.01	−.22	−.08	.22	.17	.07	.13	.21	.45	—						
12. SBaseM	−.10	−.07	−.12	−.04	.07	.02	.14	.17	.10	.92	.38	—					
13. SBaseSD	−.13	−.02	−.13	−.04	.20	.09	.18	.24	.17	.41	.69	.44	—				
14. PTEPR	.12	.12	.09	.18	−.01	−.25	−.20	−.15	−.23	.20	.22	.08	.20	—			
15. STEPR	−.06	−.02	−.06	.00	.06	.05	.10	.06	.11	.17	.36	.14	.32	.28	—		
16. PTEPRSD	−.29	.02	−.18	−.07	.17	.26	.07	.10	.26	.27	.79	.24	.48	.06	.28	—	
17. STEPRSD	−.09	−.01	−.05	−.16	.30	.18	.21	.34	.20	.11	.37	.15	.59	.10	.24	.31	—

Note. Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; Stroop = color word Stroop task; PVT = psychomotor vigilance task; Aoff = average number of off-task thoughts Antisaccade; Soff = average number of off-task thoughts Stroop; Poff = average number of off-task thoughts psychomotor vigilance task; PBaseM = mean raw baseline pupil diameter (in milliliters, mm) during psychomotor vigilance task; PBaseSD = *SD* of raw baseline pupil diameter (in mm) during psychomotor vigilance task; SBaseM = mean raw baseline pupil diameter (in mm) during Stroop; SBaseSD = *SD* of raw baseline pupil diameter (in mm) during Stroop; PTEPR = mean task-evoked pupillary response (mm change) during psychomotor vigilance task; STEPR = mean task-evoked pupillary response (mm change) during Stroop; PTEPRSD *SD* task-evoked pupillary response (mm change) during psychomotor vigilance task; STEPRSD *SD* task-evoked pupillary response (mm change) during Stroop.

other constructs, indicating both convergent and discriminant validity within the data. Because some of the same participants were reported in Robison et al. (2017) the descriptive statistics and the correlations are similar, but not identical to those reported in Robison et al. More important, none of the critical pupillary results were reported in Robison et al. (2017).

On- Versus Off-Task States

Behavioral results. Before examining individual differences we first examined differences between on- and off-task states in the psychomotor vigilance, Stroop, and antisaccade tasks. Examining percentages of on- versus off-task states in each task suggested roughly equal amounts of time were spent on- versus off-task. Specifically, in the psychomotor vigilance task participants spent 32.9% (SD = 25.9) of their time off-task and 36.3% (SD = 31.6) on-task, $t(151) = -.83$, $p = .41$, $d = .06$. Similarly, in the Stroop task participants spent 36.3% (SD = 30.4) of their time off-task and 44.2% (SD = 34.9) on-task, $t(156) = -1.61$, $p = .11$, $d = .13$. Likewise in the anitsaccade task participants spent 36.4% (SD = 31.3) of their time off-task and 35.7% (SD = 33.1) on-task, $t(160)$ .15, $p = .89$, $d = .00$.

Next, examining RT differences for correct trials suggested that, consistent with prior research, off-task states were associated with slower RTs (M = 392, SD = 74) than on-task states (M = 327, SD = 47) in the psychomotor vigilance task, $t(117) = 9.04$, $p < .01$, $d = .86$ (Unsworth & Robison, 2016a). A similar pattern was found when examining overall RTs in the Stroop task with off-task states being associated with slower RTs (M = 847, SD = 252) than on-task states (M = 743, SD = 217), $t(100) = 4.18$, $p < .01$, $d = .42$. Likewise in the antisaccade task with off-task states were associated with slower RTs (M = 1030, SD = 505) than on-task states (M = 863, SD = 495), $t(76) = 2.16$, $p = .034$, $d = .25$. These results suggest that participants were slower during off-task states compared with on-task states in both attention control tasks.

Comparing accuracy for on- versus off-task states suggested that on-task states in the Stroop task were associated with higher accuracy (M = .98, SD .05) compared with off-task states (M = .85, SD .26), $t(100) = 5.19$, $p < .01$, $d = .66$. Examining accuracy in the antisaccade similarly suggested that on-task states were associated with higher accuracy (M = .79, SD .27) compared with off-task states (M = .53, SD .33), $t(93) = 6.28$, $p < .01$, $d = .66$. Thus, when participants reported being off-task they were slower and less accurate than when they reported being on-task.

Pupillary responses. Next, we examined pupillary responses in the psychomotor vigilance and Stroop tasks. In particular, similar to prior research we examined whether off-task states could be differentiated from on-task states by examining both pretrial baseline pupil diameter and TEPRs. As shown in Figure 1a, examining the psychomotor vigilance task suggested that off-task thoughts were associated with smaller pretrial baseline pupil diameters than on-task thoughts, $t(117) = -3.12$, $p < .01$, $d = -.29$. Note, pretrial baselines were z-scored normalized within each participant to correct for individual differences in pupil diameter. This normalization process was only done for these analyses and not for the individual differences analyses that follow. As shown in Figure 1b, a similar pattern was found when examining pretrial baselines in the Stroop task, $t(100) = -3.31$, $p < .01$, $d = -.33$.

Next we examined the TEPRs for on- and off-task thinking. Note, the TEPRs are baseline corrected by subtracting out mean pupil dilation during the pretrial baseline for each trial. As shown in Figure 1c, examining the psychomotor vigilance task suggested that off-task thoughts were associated with smaller TEPRs than on-task thoughts, $t(102) = -2.58$, $p = .011$,

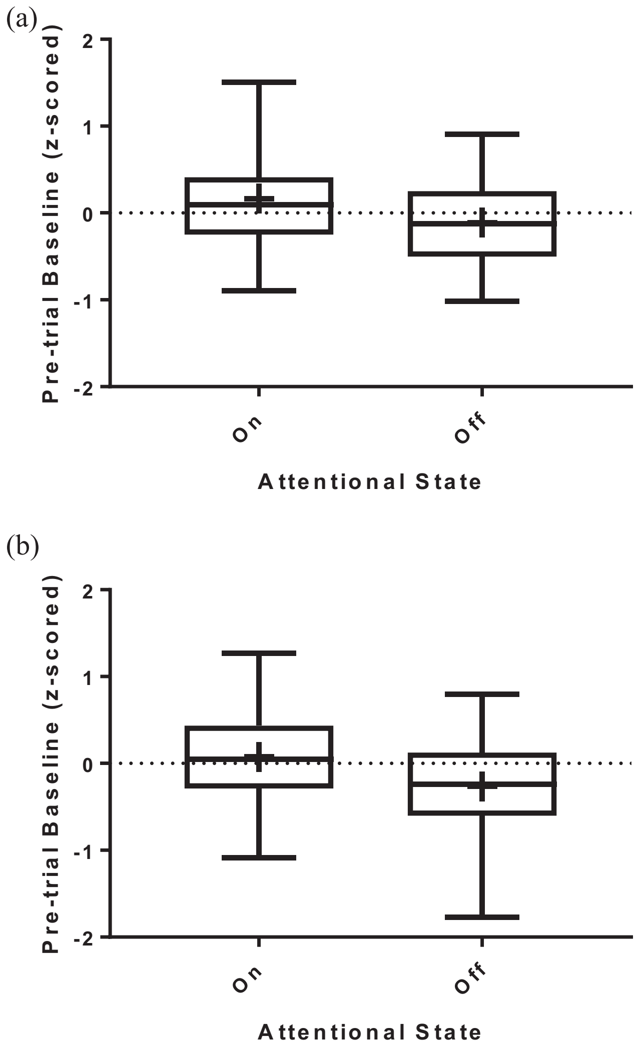

Figure 1. (a) Box plot of normalized mean pretrial baseline pupil diameter as a function of attentional state in the psychomotor vigilance task. (b) Box plot of normalized mean pretrial baseline pupil diameter as a function of attentional state in the Stroop task. (c) Grand averaged task-evoked pupillary responses as a function of attentional state in the psychomotor vigilance task. Time zero indicates when the numbers began counting. (d) Grand averaged task-evoked pupillary responses as a function of attentional state in the Stroop task. Time zero indicates the appearance of the colored word.

$d = -.25$. As shown in Figure 1d, a similar pattern was found when examining TEPRs in the Stroop task, $t(74) = -2.16$, $p = .034$, $d = -.25$. Note that the pupil waveforms are used mainly for visualization, while the dependent measure in the analysis is the peak task-evoked response. Thus, consistent with prior research when participants engaged in off-task thinking their pretrial baselines and TEPRs were smaller than when they engaged in on-task thinking (Grandchamp et al., 2014; Mittner et al., 20014; Unsworth & Robison, 2016). Furthermore, these results are consistent with the notion that low arousal levels are associated with task disengagement and lowered phasic responding to task relevant stimuli.

Latent Variable Analyses

Next, to address our primary question of interest we utilized latent variable techniques to examine a number of structural equation models. Specifically, shown in Figure 2 is a simplified structural equation model of the hypothesized individual differences relations. As seen in Figure 2a, individual differences in arousal are related to individual differences in task engagement (or disengagement), which in turn are related to individual differences in attention control and WMC. Note, this model reflects a model of individual differences relations in terms of the correlational structure of the data and is not meant to be an explicit computational model. Shown in Figure 2b are our operalizations of these variables. Specifically, individual differences in pupil diameter (pretrial baseline pupil diameter, variability in pretrial baseline, TEPRs, and variability in TEPRs) are related to individual differences in off-task thoughts (mind-wandering, inattention, and external distraction), which are in turn related to individual differences in attention control and WMC. To examine these notions we specified a number of structural equation models examining pretrial baseline pupil diameter (both raw mean and raw *SD*) and TEPRs (both mean and *SD*) and their relations to off-task thinking, attention control, and WMC.

In the first set of latent variable analyses we examined pretrial baseline pupil diameter that is thought to reflect tonic arousal levels. Before examining the structural model we first specified a measurement model to examine the structure of the data. In the measurement model separate factors were specified for WMC (composed of operation, symmetry, and reading span tasks), attention control (composed of antisaccade, Stroop, and psychomotor vigilance tasks), rates of off-task thinking (composed of off-task thought reports from the antisaccade, Stroop, and psychomotor vigilance tasks), mean pretrial baseline pupil diameter (composed of pretrial baselines from Stroop and the psychomotor vigilance tasks), and *SD* of pretrial baseline pupil diameter (composed of pretrial baselines from Stroop and the psychomotor vigilance tasks). Each of the factors were allowed to correlate with one another. To fit the models we used the sample correlation matrix using all available data (pairwise correlations). For all model testing (using Lisrel 8.80), we report several fit statistics. Nonsignificant χ^2 tests indicate adequate model fit; with large samples like ours, however, they are nearly always significant. Comparative fit indices (CFI) and Nonnormed Fit Index (NNFI) of $\geq$.90 indicate adequate fit, whereas the root mean square error of approximation (RMSEA) and standardized root mean square residual (SRMR) values of $\leq$.08 indicate adequate fit (e.g., Schermelleh-Engel, Moosbrugger, & Müller, 2003). The overall fit of the model was acceptable, $\chi^2(55) = 116.46$, $p < .01$, RMSEA = .08, NNFI = .91, CFI = .95, SRMR = .05.[3] Shown in Figure 3a is the resulting model. Consistent with prior research WMC and AC were related and both were related to off-task thoughts (see also Robison et al., 2017). In terms of pupil diameter, only WMC was related to mean pretrial baseline pupil diameter. Interestingly, the correlation was negative suggesting that low WMC individuals on average had larger pretrial baseline pupil diameters than high WMC individuals. This is consis-

[3] Note that the model fits could have been improved if the error variances for each of pupillary measures from the same task were allowed to correlate. Freeing these error variances led to qualitatively similar results to those reported. For simplicity and clarity the simpler, noncorrelated error models were used throughout.

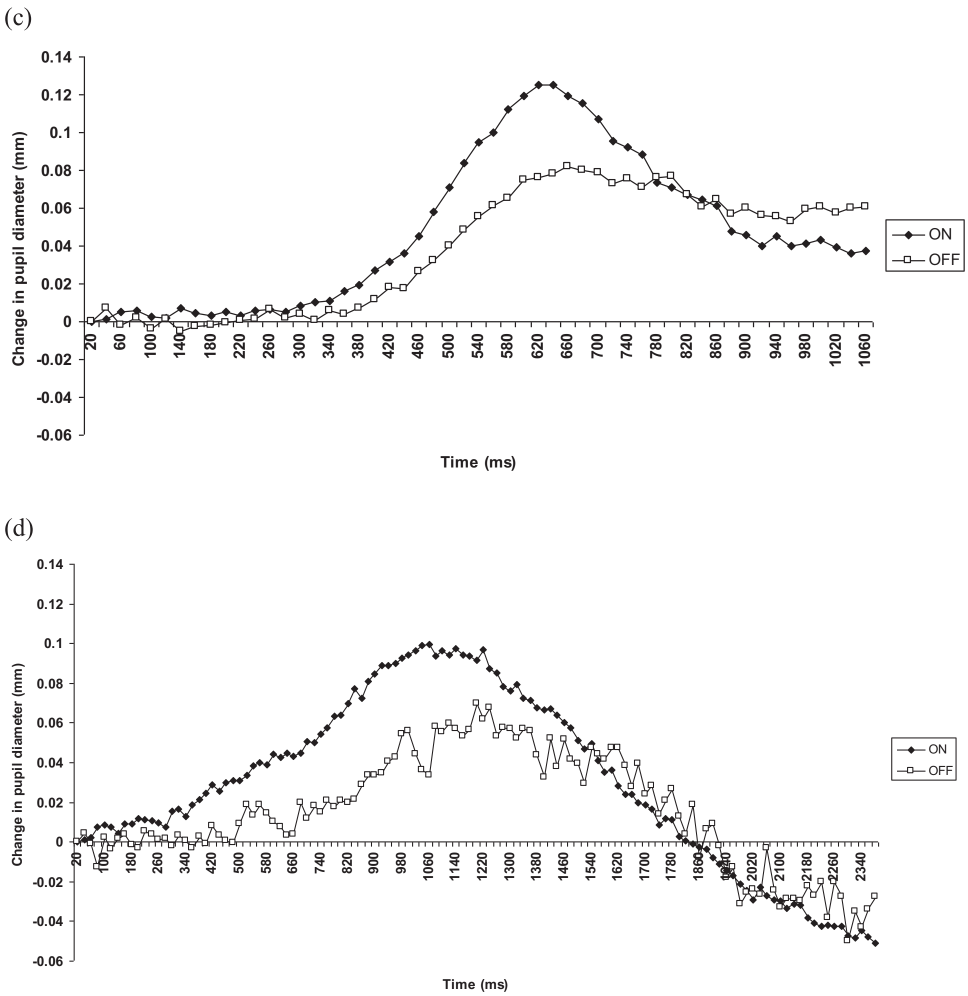

Figure 1 (continued).

tent with the notion that low WMC is associated with high tonic arousal levels (potentially related to stress and anxiety). Examining *SD* of pretrial baseline pupil diameter suggested it was associated with WMC, attention control, and off-task thinking. This finding is consistent with the notion that trial-to-trial variability in tonic arousal levels are related to WMC, attention control, and task-disengagement.

To better examine the relations we next specified a structural equation model in which both mean pretrial baseline pupil diameter and mean *SD* of baseline predicted off-tasking thinking, which in turn were related to attention control and WMC based on the model in Figure 2. Given the strong relation between mean pretrial baseline and *SD* of baseline, this model tests whether individual differences are because of overall differences in mean baseline levels (reflecting overall differences in tonic arousal) or whether differences are because of trial-to-trial variability in baseline levels. The fit of the model was acceptable, $\chi^2(60) = 126.58$, $p < .01$, RMSEA = .08, NNFI = .92, CFI = .94, SRMR = .06. Shown in Figure 3b is the resulting model which suggests that variability in baseline levels (rather than overall baseline levels) predicted off-task thinking, which in turn was related to individual differences in attention control and WMC. The indirect effect from baseline *SD* to attention control was significant (indirect effect = −.14, $p <$ .05), and the indirect effect of baseline *SD* to WMC did not quite reach significance (indirect effect = −.07, $p = .06$). The indirect effect from off-task thoughts to WMC was significant (indirect effect = −.30, $p < .01$). Thus, this model supports the notion that trial-to-trial variability in arousal is related to variability in task disengagement (off-task thinking), which predicts individual differences in attention control and WMC. That is, low WMC individuals are more likely to experience moment-to-moment fluctuations in tonic arousal levels than high WMC individuals.

Another way of testing the notion that trial-to-trial variability in arousal is related to individual differences in task disengagement and individual differences in attention control is to test a model in which the attention control and WMC tasks are allowed to load on the same factor. That is, according to attention control and executive attention theories of WMC (Engle & Kane, 2004; Kane & Engle, 2002; Unsworth & Spillers, 2010) it is the shared variance between WMC and attention control that is important. Thus, the shared variance between WMC and attention control should be related to off-task thinking and variability in baseline pupil diameter. To test this, we specified a measurement model similar to that

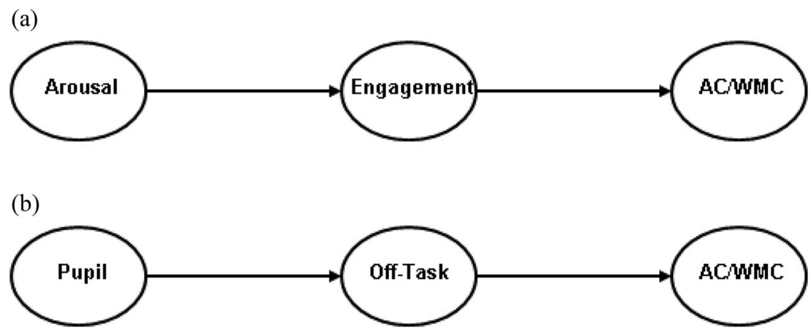

Figure 2. (a) Hypothetical structural equation model suggesting that variation in arousal predicts overall task-engagement, which in turn is related to individual differences in attention control (AC) and working memory capacity (WMC). (b) Operationalized structural equation model in which variation in pupil diameter predicts self-reports of off-task thinking, which in turn is related to individual differences in AC and WMC.

shown in Figure 3, but instead of having separate WMC and attention control factors; we allowed the WMC and attention control tasks to load on the same executive attention factor (see also McVay & Kane, 2012a). This executive attention factor was then allowed to correlate with off-task thinking, mean baseline pupil diameter, and *SD* of baseline pupil diameter. The fit of the model was acceptable, $\chi^2(58) = 139.41$, $p < .01$, RMSEA = .09, NNFI = .90, CFI = .92, SRMR = .07. Note we allowed the error variances for operation and reading span to correlate given overall similarities in task design and given the fact that they share the same stimulus set of to-be-remembered items. Shown in Figure 4a is the resulting model which suggests that executive attention was strongly related to off-task thinking and was related to trial-to-trial variability in baseline pupil diameter, but not to overall baseline pupil levels. We also tested the structural model to better examine the relations. The fit of the model was acceptable, $\chi^2(60) = 142.18$, $p < .01$, RMSEA = .09, NNFI = .90, CFI = .92, SRMR = .07. Shown in Figure 4b is the resulting model suggesting that trial-to-trial variability in baseline pupil diameter (but not overall baseline pupil levels) predicted individual differences in off-task thinking, which in turn was associated with individual differences in executive attention. The indirect effect from baseline *SD* to executive attention was significant (indirect effect = −.14, $p < .05$). Thus, moment-to moment variability in tonic arousal levels predicted susceptibility to task disengagement that was associated with the shared variance between attention control and WMC.

Next we examined TEPRs and their relation with the other individual-differences variables. Recall that when tonic arousal levels are too high or too low, phasic responding to task relevant stimuli should be reduced. Thus, when disengaged from the current task phasic pupillary responses should be lower than when engaged in a task. As shown above, off-task thinking was associated with smaller TEPRs than with on-task thinking. Similarly, individuals who experience more task disengagement (off-task thinking) should exhibit more variability in phasic responding (more variability in TEPRs) given that sometimes they will be on task leading to a strong phasic response, and other times they will be off task leading to a reduced phasic response. Thus, similar to examining pretrial baselines, here we should see that trial-to-trial variability in TEPRs should be related to off-task thinking, WMC, and attention control. To examine this we first specified a measurement model with WMC, attention control, and off-task thoughts similar to before. For the TEPRs we specified two latent factors. One represented mean TEPRs (based on TEPRs from the Stroop and psychomotor vigilance tasks) and the other represented variability in TEPRs based on the *SD* of TEPRs from the same two tasks). All factors were allowed to correlate. The fit of the model was acceptable, $\chi^2(55) = 120.51$, $p < .01$, RMSEA = .09, NNFI = .90, CFI = .91, SRMR = .08. Shown in Figure 5a is the resulting model that suggests that WMC, attention control, and off-task thinking were all associated with trial-to-trial variability in TEPRs, but not in overall levels of TEPRs. Although it should be noted that the relations with mean TEPRs were in the predicted direction, but the relations were likely not significant because of large *SE*s associated with the TEPR factor. Examining the structural model revealed similar overall results. The overall fit of the structural model was good, $\chi^2(60) = 130.52$, $p < .01$, RMSEA = .09, NNFI = .90, CFI = .91, SRMR = .08, and as shown in Figure 5b, trial-to-trial variability in TEPRs predicted susceptibility to off-task thinking that was associated with individual differences in attention control and WMC. The indirect from effect TEPR *SD* to attention control was significant (indirect effect = −.43, $p < .05$), and the indirect effect of TEPR *SD* to WMC was significant (indirect effect = −.22, $p < .05$). The indirect effect from off-task thoughts to WMC was significant (indirect effect = −.31, $p < .01$). This suggests that low WMC individuals are more likely to experience fluctuations in task engagement leading to mind-wandering and more overall variability in their TEPRs (i.e., a greater mix of high and low TEPRs) than high WMC individuals.

We also tested the relations with the executive attention factor as was done when examining the pretrial baselines. Shown in Figure 6a is the resulting measurement model which had an acceptable fit, $\chi^2(58) = 137.55$, $p < .01$, RMSEA = .09, NNFI = .90, CFI = .91, SRMR = .08. Similar to the prior models, the executive attention factor was strongly related to both off-task thinking and to variability in TEPRs, but not to overall levels of TEPRs. Examining the structural model, which had a reasonable fit, $\chi^2(60) = 145.64$, $p < .01$, RMSEA = .09, NNFI = .88, CFI = .90, SRMR = .09, suggested that variability in TEPRs predicted the propensity for off-task thinking which predicted individual differences in executive attention.

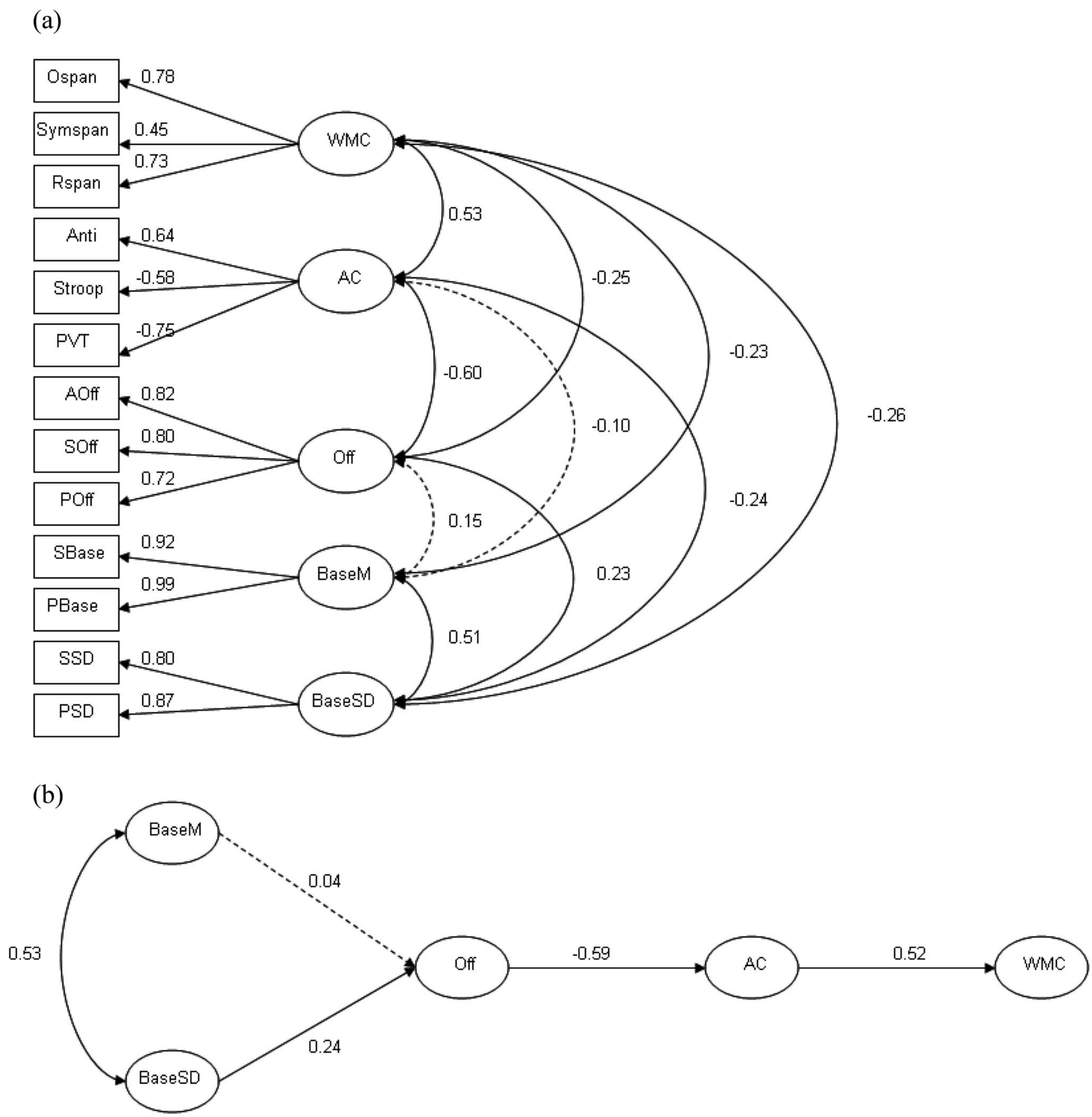

Figure 3. (a) Confirmatory factor analysis model for working memory capacity (WMC), attention control (AC), off-task thinking (Off), mean baseline pupil diameter (BaseM), and *SD* of baseline pupil diameter (BaseSD). Paths connecting latent variables (circles) to each other represent the correlations between the constructs and the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable. (b) Structural equation model in which both mean and *SD* of baseline pupil diameter predict off-task thinking, which predicts attention control, and attention control predicts working memory capacity. Solid paths are significant at the $p < .05$ level, whereas dashed paths are not significant. Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; Stroop = color word Stroop task; PVT = psychomotor vigilance task; Aoff = off-task thoughts Antisaccade; Soff = off-task thoughts Stroop; Poff = off-task thoughts psychomotor vigilance task; PBaseM = mean baseline pupil diameter psychomotor vigilance task; PBaseSD = *SD* of baseline pupil diameter psychomotor vigilance task; SBaseM = mean baseline pupil diameter Stroop; SBaseSD = *SD* of baseline pupil diameter Stroop.

(a)

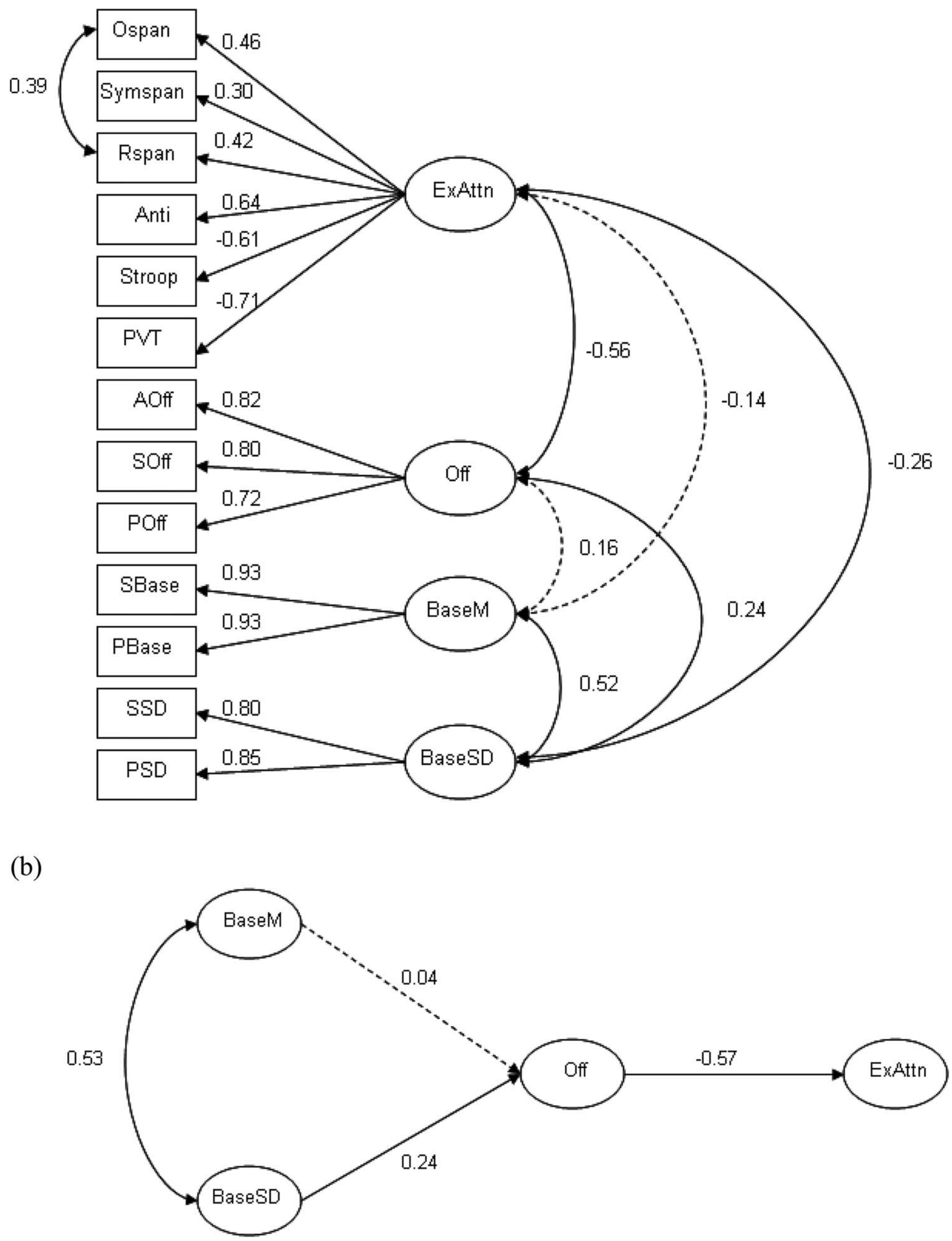

Figure 4. (a) Confirmatory factor analysis model for executive attention (ExAttn), off-task thinking (Off), mean baseline pupil diameter (BaseM), and *SD* of baseline pupil diameter (BaseSD). Paths connecting latent variables (circles) to each other represent the correlations between the constructs and the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable. (b) Structural equation model in which both mean and *SD* of baseline pupil diameter predict off-task thinking, which predicts executive attention. Solid paths are significant at the $p < .05$ level, whereas dashed paths are not significant. Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; Stroop = color word Stroop task; PVT = psychomotor vigilance task; Aoff = off-task thoughts Antisaccade; Soff = off-task thoughts Stroop; Poff = off-task thoughts psychomotor vigilance task; PBaseM = mean baseline pupil diameter psychomotor vigilance task; PBaseSD = *SD* of baseline pupil diameter psychomotor vigilance task; SBaseM = mean baseline pupil diameter Stroop; SBaseSD = *SD* of baseline pupil diameter Stroop.

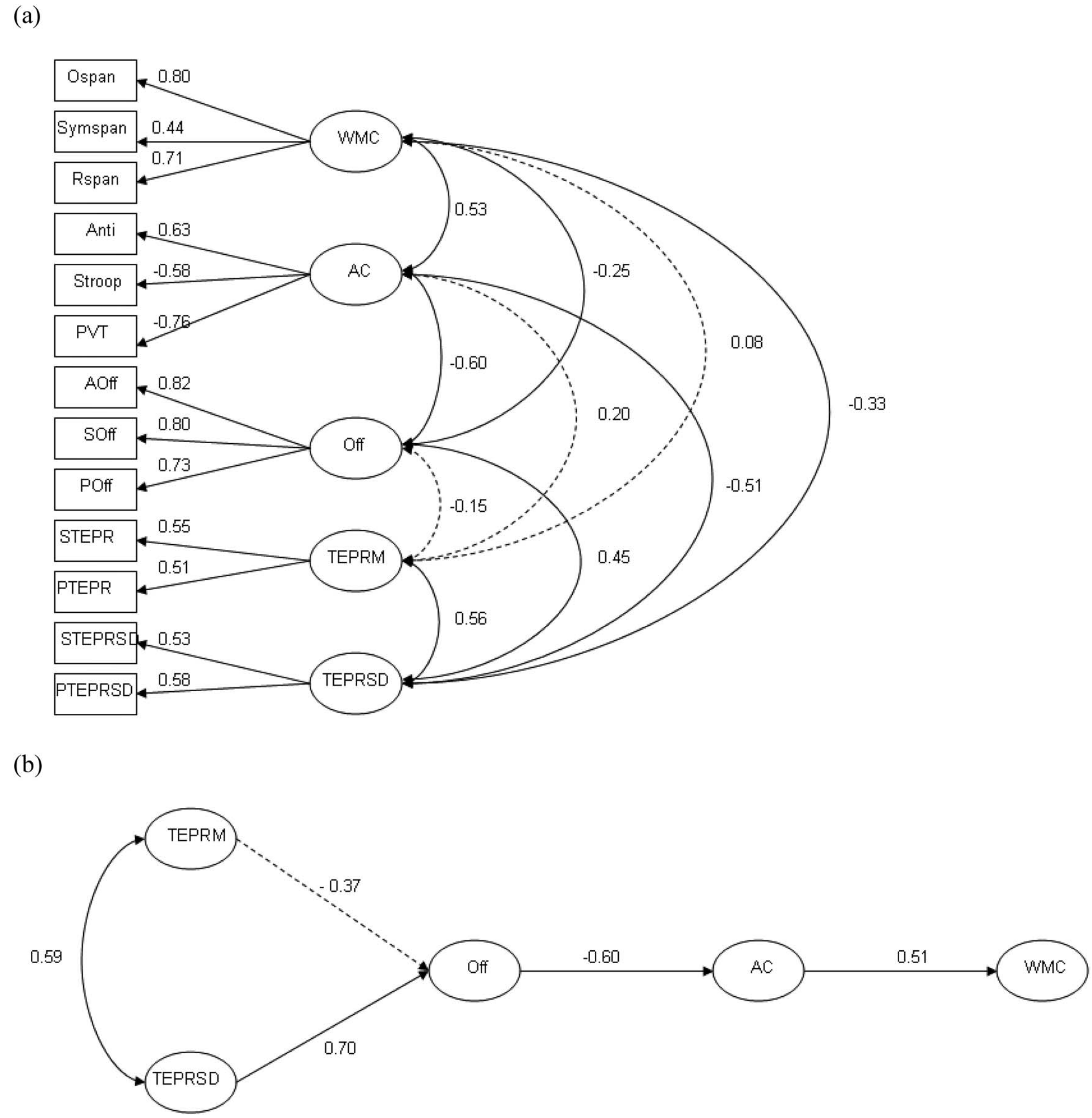

Figure 5. (a) Confirmatory factor analysis model for working memory capacity (WMC), attention control (AC), off-task thinking (Off), mean task-evoked pupillary response (TEPRM), and *SD* of the task-evoked pupillary response (TEPRSD). Paths connecting latent variables (circles) to each other represent the correlations between the constructs and the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable. (b) Structural equation model in which both mean and *SD* of the task-evoked pupillary response predict off-task thinking, which predicts attention control, and attention control predicts working memory capacity. Solid paths are significant at the $p < .05$ level, whereas dashed paths are not significant. Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; Stroop = color word Stroop task; PVT = psychomotor vigilance task; Aoff = off-task thoughts Antisaccade; Soff = off-task thoughts Stroop; Poff = off-task thoughts psychomotor vigilance task; PTEPR = mean task-evoked pupillary response psychomotor vigilance task; STEPR = mean task-evoked pupillary response Stroop; PTEPRSD *SD* task-evoked pupillary response psychomotor vigilance task; STEPRSD *SD* task-evoked pupillary response Stroop.

The indirect effect from baseline *SD* to executive attention was significant (indirect effect = $-.40$, $p < .05$). These results suggest that the variance shared by WMC and attention control is related to trial-to-trial variability in TEPRs which predicts susceptibility to task disengagement.

Collectively, the current models suggest that variability in pupillary responses (variability in both baseline levels and TEPRs) is related to task disengagement in the form of off-tasks thoughts, which in turn is related to individual differences in WMC and attention control. Furthermore, note that we examined an addi-

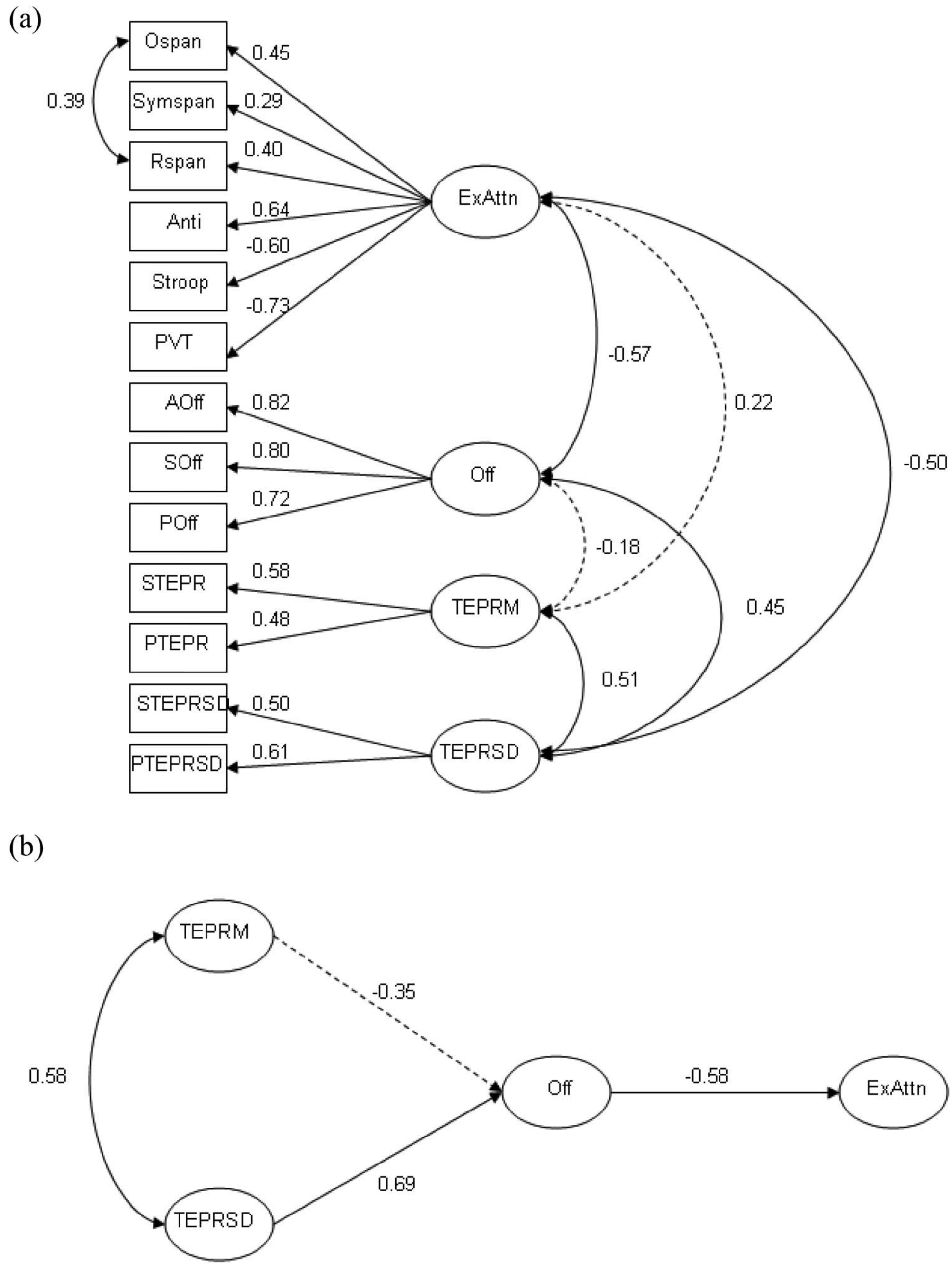

Figure 6. (a) Confirmatory factor analysis model for executive attention (ExAttn), off-task thinking (Off), mean task-evoked pupillary response (TEPRM), and *SD* of the task-evoked pupillary response (TEPRSD). Paths connecting latent variables (circles) to each other represent the correlations between the constructs and the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable. (b) Structural equation model in which both mean and *SD* of the task-evoked pupillary response predict off-task thinking, which predicts executive attention. Solid paths are significant at the $p < .05$ level, whereas dashed paths are not significant. Ospan = operation span; Rspan = reading span; Symspan = symmetry span; Anti = antisaccade; Stroop = color word Stroop task; PVT = psychomotor vigilance task; Aoff = off-task thoughts Antisaccade; Soff = off-task thoughts Stroop; Poff = off-task thoughts psychomotor vigilance task; PTEPR = mean task-evoked pupillary response psychomotor vigilance task; STEPR = mean task-evoked pupillary response Stroop; PTEPRSD *SD* task-evoked pupillary response psychomotor vigilance task; STEPRSD *SD* task-evoked pupillary response Stroop.

tional model with both *SD* of pretrial baseline and *SD* of TEPR. We found that these measures all loaded on the same factor and this factor was related to WMC, attention control, and off-task thinking, suggesting that individual differences in variability in baseline and phasic pupillary responses largely measure the same thing (see Unsworth & Robison, 2017). Overall, these results are consistent with the notion that low WMC individuals experience more moment-to-moment fluctuations in tonic arousal levels that results in fluctuations in phasic responses, increased off-task thinking, and lowered attention control. Thus, variability in arousal (here indexed by pupil variability) is a potent predictor of individual differences in attentional control and WMC.

Exploratory Analyses of Nonlinear Relations and Sub-Group Variation

In the latent variable analyses it was shown that variability in pupil responses was related to individual differences in off-task thinking, WMC, and attention control. Interestingly, baseline pupil diameter was only found to be related to WMC. However, earlier we suggested that task disengagement (in the form of off-task thinking) should be related to baseline pupil diameter such that individuals who are too high or too low in tonic arousal levels should be more likely to disengage from the task at hand. Looking at the prior models there is a trend of a positive relation between baseline pupil diameter and off-task thinking ($r = .15$), but it's not quite significant, $t = 1.76$, $p = .08$. One potential reason for this is that the prior models assume linear relations among the factors, whereas earlier it was suggested that the relation might be nonlinear (quadratic) in nature. That is, prior research has suggested quadratic relations between pupil diameter and performance within participants. It is also possible that there are similar relations between participants. Thus, to explore this possibility we conducted a number of exploratory analyses in which we created factor composites for baseline pupil diameter, off-task thinking, WMC, and attention control. Next, we examined quadratic relations between baseline pupil diameter and the other factor composites. Note, these analyses are based on 137 individuals who had complete data for all the tasks. That is, individuals who had missing data from one task (such as missing antisaccade accuracy data or missing all data from the psychomotor vigilance task) were excluded from these analyses. In terms of the relation between baseline pupil diameter and off-task thinking, these analyses suggested that there was not a quadratic relation ($\beta = .021$, $p = .70$). Interestingly, in this subsample of the data the linear relation between pupil diameter and off-task thinking was significant ($\beta = .23$, $p = .01$) suggesting that individuals with higher tonic levels of arousal tend to experience more off-task thoughts than individuals with lower tonic levels of arousal. Although this relation is partially because of the strong relation between baseline pupil diameter and *SD* of baseline pupil diameter. When *SD* of baseline pupil diameter is partialed out, the relation is reduced and not quite significant ($\beta = .15$, $p = .08$) similar to the latent variable results. Similar nonsignificant quadratic relations were found between baseline pupil diameter and WMC ($\beta = -.004$, $p = .93$) and attention control ($\beta = -.031$, $p = .86$). There was still a linear relation between WMC and baseline pupil diameter ($\beta = -.17$, $p = .02$). Thus, these results suggest that there were linear, but not quadratic relations between baseline pupil diameter and some of the cognitive ability constructs.

Another potential reason for the lowered relations between baseline pupil diameter and off-task thinking is because there may be subgroups of participants who demonstrate different relations between the two variables. To examine this we submitted the baseline pupil diameter and off-task thinking factor composites to a two-step cluster analysis. Cluster analysis is a tool used to determine group membership by minimizing within group differences and maximizing between group differences (Everitt, Landau, & Leese, 2001; Kaufman & Rousseeuw, 2005). Groups are formed where individuals in the group are very similar to one another but unlike individuals in other groups. It should be noted that these methods are largely atheoretical and group membership is merely based on empirical similarities within a cluster and differences across clusters. In this analysis, performed in SPSS 22, cases were first grouped into preclusters at the first step by constructing a cluster feature tree (see Zhang, Ramakrishnan, & Livny, 1996). For each case the algorithm determined if the case should be included with a previously formed precluster or a new precluster should be created based on the cluster feature tree. In the second stage an agglomerative hierarchical clustering method was used on the preclusters and allowed for an exploration of different numbers of clusters. In this stage clusters were recursively merged until the desired number of clusters was determined by the algorithm. In these analyses, distance between clusters was based on a log-likelihood measure whereby distance was related to the decrease in log-likelihood as the clusters were formed into a single cluster. The algorithm automatically determines the number of clusters by taking into account the lowest information criterion (here AIC) and the highest ratio of distance measures (indicating the best separation of the clusters).

The cluster analysis suggested the presence of four groups consisting of 62, 27, 37, and 11 participants each. Shown in Figure 7 are the results. As can be seen, Group 1 consists of individuals who have intermediate baseline pupil diameters and relatively little off-task thinking. Group 2 is composed of individuals who are low in both baseline pupil diameter and off-task thinking. Group 3 consists of individuals who have relatively low baseline pupil diameters, but report a great deal of off-task thinking. Finally, Group 4 is composed of individuals who have the largest baseline pupil diameters and frequently report off-task thinking. These results suggest a complex and nuanced relation between propensity for off-task thoughts during attention control tasks and baseline pupil diameter.

To determine the overall characteristics of each of these groups, we next examined whether there were differences between the groups in WMC, attention control, *SD* of baseline pupil diameter, TEPRs, and *SD* of TEPRs. Shown in Table 4 are the results. As can be seen, the groups differed on nearly all of the measures (the effect for WMC did not quite reach conventional levels of significance). For example, Groups 3 and 4 not only reported the most off-task thinking, but these two groups also tended to have the lowest attention control, low WMC, small TEPRs, and large variability in TEPRs. More important, these two groups differed in overall baseline pupil diameter, with Group 3 having a small baseline pupil and Group 4 having a large baseline pupil. In comparison, Group 1 was composed of individuals with fairly average attention control, WMC, and variability in TEPR. How-

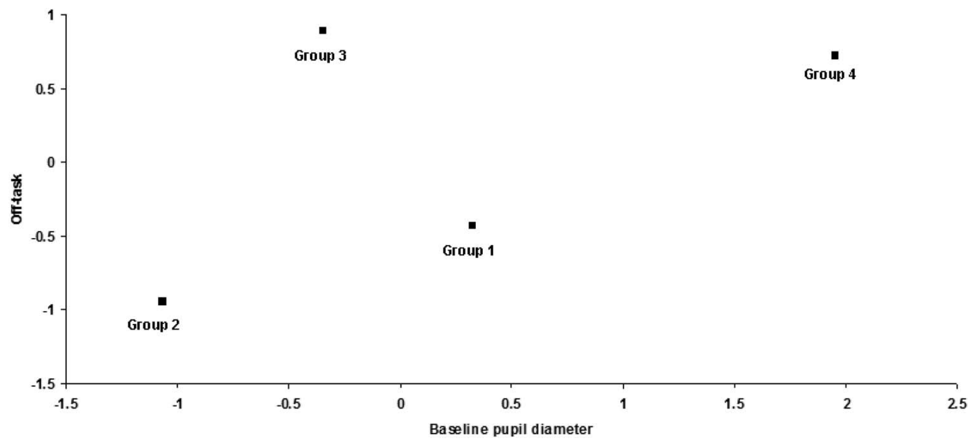

Figure 7. Subgroup variation in baseline pupil diameter and propensity for off-task thinking.

ever, this group demonstrated the largest TEPRs. Thus, these results are consistent with the notion that both high and low levels of tonic arousal are related to increased task-disengagement, lowered attention control, smaller TEPRs, and more variability in TEPRs. Examining Group 2 suggests that this group is composed of individuals who have the highest WMC and attention control scores, but have the lowest amount of variability (both baseline and TEPRs), and the smallest overall TEPRs. Thus, this group consists of those individuals who demonstrate the best overall performance, but also seem to have relatively low levels of arousal and attentional effort as indexed by small baseline pupil diameters and small TEPRs. As discussed below, it is possible that these participants find the current tasks unchallenging and, thus, can perform at relatively high levels when underaroused.

General Discussion

In the current study we examined the role of arousal in accounting for individual differences in WMC and attention control via pupillometry. Examining baseline pupil diameter and TEPRs for on- and off-task attentional states suggested that off-task states were associated with both lower pretrial baselines and lowered TEPRs compared with on-task states consistent with prior research (Grandchamp et al., 2014; Mittner et al., 2014; Unsworth & Robison, 2016a). Off-task states were also associated with slower RTs and lowered accuracy than on-task states. Similar results were found for both the psychomotor vigilance task and the Stroop task demonstrating the generality of these results to various measures of attention control. These results suggest that in attention demanding tasks where it is critically important to maintain and sustain attention to the task at hand, fluctuations in arousal (in particular fluctuations to a lowered arousal state) result in increases in lapses of attention (more off-task thinking) and reductions in performance (Kahneman, 1973; Lenartowicz et al., 2013; Unsworth & Robison, 2016a). Furthermore, these results lend further credence to the notion that pupillometry can be used as a means to track lapses of attention.

Using latent variable techniques we next tested possible ways in which arousal could influence individual differences in WMC and attention control as well as possibilities based on differences in attentional capacity and efficiency (see Table 1). Specifically, in terms of arousal low WMC and attention control individuals may have lower tonic arousal levels, greater tonic arousal levels, or more variability in arousal than high WMC and attention control individuals. In each case these differences in arousal could result in lowered attention control, decreased task performance, and more off-task thinking for low WMC individuals compared with high WMC individuals. In terms of differences in attentional capacity low WMC and attention control individuals may have fewer resources to allocate to the task at hand than high WMC and attention control individuals resulting in overall lower performance for low WMC individuals compared with high WMC individuals. In terms of effi-

Table 4
Descriptive Statistics for Each Group Defined by the Cluster Analysis on Measures of Working Memory Capacity, Attention Control, SD of Baseline Pupil Diameter, Task-Evoked Pupillary Responses, and SD of Task-Evoked Pupillary Responses

Measure	Group 1	Group 2	Group 3	Group 4	F	p	η^2
WMC	.07 (.09)	.26 (.11)	−.19 (.14)	−.19 (.19)	2.47	.065	.054
AC	.17 (.09)	.41 (.15)	−.49 (.15)	−.17 (.30)	8.17	.000	.156
BaseSD	.15 (.11)	−.73 (.13)	−.05 (.08)	.92 (.26)	12.56	.000	.221
TEPR	.21 (.08)	−.22 (.14)	−.11 (.09)	−.11 (.22)	3.97	.010	.083
TEPRSD	.01 (.07)	−.47 (.09)	.18 (.14)	.27 (.19)	6.40	.000	.127

Note. WMC = working memory capacity; AC = factor composite of three attention control measures; BaseSD = *SD* of baseline pupil diameter; TEPR = task-evoked pupillary responses; TEPRSD = *SD* of task-evoked pupillary responses. Numbers in parentheses are *SEM*.

ciency, high and low WMC and attention control individuals may have the same overall arousal levels and capacity, but low WMC individuals may not allocate their resources as efficiently as high WMC individuals, resulting in lowered performance and more potential lapses of attention for low WMC and attention control individuals compared with high WMC and attention control individuals.

To examine these possibilities we relied on both baseline pupil diameter (as a metric of tonic arousal) and TEPRs (as a metric of phasic arousal and attentional effort). The latent variable models demonstrated that the bulk of the evidence suggests that fluctuations in arousal are important predictors of individual differences in WMC and attention control. Specifically, variability in both baseline pupil diameter and TEPRs was related to WMC, attention control, and off-task thinking. Furthermore, structural equation models suggested that variability in both baseline pupil diameter and TEPRs predicted off-task thinking, which in turn predicted variation in WMC and attention control. These results are consistent with prior work by Daly (1966) who found that variability in pupil size decreased when participants were focused and suggested that variance in pupil size "could be used as an estimate of the amount of fluctuations, inattention, or concentration" (p. 55). The data did not match predictions from the other possibilities examined. In particular, the idea that low WMC individuals are hypoaroused or hyperaroused compared with high WMC individuals would predict that overall baseline pupil diameter would be correlated with individual differences in WMC, attention control, and off-task thinking. However, only WMC was significantly negatively related to baseline pupil diameter (suggesting that low WMC individuals were hyperaroused). Furthermore, these two possibilities predict that low WMC and attention control individuals should have smaller TEPRs responses than high WMC and attention control individuals. Likewise, both the attentional capacity and efficiency possibilities would predict no differences in overall baseline pupil diameter (that was the case), but both of these possibilities predict differences in mean TEPRs. However, mean TEPRs did not correlate with any of the cognitive ability measures, whereas variability in TEPRs correlated with WMC, attention control, and off-task thinking.

Collectively, the current results provide evidence for the notion that moment-to-moment fluctuations in arousal are an important determinant of individual differences in WMC and attention control. Most of the time when low WMC individuals are on-task their performance is similar to that of high WMC individuals (e.g., McVay & Kane, 2009). However, low WMC individuals experience more moment-to-moment fluctuations in arousal levels which are associated with an increase in lapses of attention compared with high WMC individuals. When this occurs, low WMC individuals are more susceptible to lapses of attention (including mind-wandering and external distraction) resulting in lowered phasic responding to task-relevant stimuli and lowered and more erratic performance than high WMC individuals. The current results go beyond prior work demonstrating relations among WMC, attention control, and off-task thinking (Kane et al., 2016; McVay & Kane, 2012a; Robison et al., 2017; Unsworth & Spillers, 2010) by demonstrating that individual differences in fluctuations of arousal are important predictors of these constructs. As such the current study extends prior influential theories of individual differences in WMC and attention control by highlighting the important role of arousal in determining fluctuations in attention during attention demanding tasks.[4]

Arousal, Attention Control, and LC-NE Functioning

The current results are consistent with prior work suggesting the important role of arousal in attention control (Kahneman, 1973; Lenartowicz et al., 2013; Robbins, 1997). In attention demanding tasks, like those used in the current study, it is critically important to maintain arousal levels at an optimal level to ensure attention is properly focused and sustained on the current task to prevent attentional capture from internal or external sources. When arousal levels are too high or too low, involuntary attention is more likely to determine the allocation of attention to irrelevant salient stimuli, resulting in a lowered intensity of attention to the current task. With this lowered intensity of attention to the current task, lapses of attention are more likely to derail the train of thought resulting in errors and erratic performance. Thus, moment-to-moment fluctuations in arousal and attention are an important contributor to task performance within and between individuals. One wrinkle to this line of reasoning is the fact that baseline pupil diameter did not consistently predict off-task thinking. That is, those individuals who on average have too low (or too high) arousal levels should be susceptible to off-task thinking. In the latent variable analyses baseline pupil diameter was positively related to off-task thinking (r = .16), but this relation was not quite significant (p = .08). In the exploratory analyses, the relation was somewhat stronger and significant, r = .23, p = .01, but this relation seemed largely because of shared variance with *SD* of baseline pupil diameter. Thus, there was weak evidence in the current data that having too low (or too high) arousal levels is associated with a greater propensity for off-task thinking. This could be because of possible heterogeneity in arousal (see below) or because of heterogeneity in off-task thinking that is associated with different arousal states. Specifically, it is possible that some mind-wandering is associated with lowered arousal levels (similar to mind-blanking), some mind-wandering is associated with increased arousal levels (related to anxiety and stress), and some mind-wandering is associated with optimal arousal levels, but with attention being focused

[4] A possible alternative explanation for the results is that perhaps fluctuations in pupillary responses are because of making many errors. Prior research has shown that errors lead to larger TEPRs than correct trials (e.g., Braem et al., 2015; Critchley, Tang, Glaser, Butterworth, & Dolan, 2005; Wessel, Danielmeier, & Ullsperger, 2011). Thus, those individuals who make many errors will likely also have greater trial-to-trial variability in pupillary responses as some pupillary responses will be associated with correct responses and some will be associated with error responses. We do not think the current results are because of differences in error pupillary responses for two reasons. (a) The only possible errors in the psychomotor vigilance task are false alarms where the participant hits the space bar before the numbers begin counting. These tend to be quite rare. In the current data there were only nine false alarms (less than .1% of all responses), and most of these came from two participants (one participant had three false alarms and another had four false alarms). Thus, relations between variability in pupillary responses across all participants in this task are not likely because of error responses. (b) Overall accuracy on the Stroop task was high for both congruent (M = .97, SD = .04) and incongruent trials (M = .93, SD = .06). Furthermore, accuracy on the Stroop task did not correlate with either WMC (r = .06) or variability in pupil responses (r = .01). Thus, it does not seem likely that the current results are because of differences in pupillary responses associated with errors.

internally rather than to the external attention demanding task (i.e., active mind-wandering; Lenartowicz et al., 2013; Mittner et al., 2016). Thus, depending on the type of mind-wandering that one is engaging in, we might expect a negative correlation, a positive correlation, or a null correlation with off-task thinking. Future research is needed to better examine how different types of mind-wandering are associated with different arousal states indicated by baseline pupil diameter.

The current results also have important implications for the potential role of the LC-NE system in individual differences in WMC and attention control. That is, given the role of the LC-NE in modulating arousal and attentional state (Aston-Jones & Cohen, 2005; Berridge & Waterhouse, 2003; Samuels & Szabadi, 2008b), and prior work demonstrating a link between the LC-NE and pupil dilation (Aston-Jones & Cohen, 2005; Gilzenrat et al., 2010; Joshi et al., 2016; Samuels & Szabadi, 2008b; Varazzani et al., 2015), the current results suggest that individual differences in WMC and attention control might be linked to variation in LC-NE functioning (Unsworth & Robison, 2017). Specifically, it is possible that differential LC-NE functioning results in differential attention control and WMC due differences in the LC to properly and consistently modulate arousal levels and attentional effort to the task at hand. That is, low WMC and attention control individuals experience more moment-to-moment fluctuations in LC-NE functioning than high WMC individuals resulting in fluctuations in arousal, increased susceptibility to lapses of attention, and overall lowered task performance in a variety of situations where attention control needs to be allocated consistently to maintain task goals in an active state and prevent irrelevant stimuli from hijacking attention away from the task at hand. In contrast, the LC-NE system for high WMC and attention control individuals consistently modulates arousal levels contingent on task demands resulting in more optimal levels of arousal and attention control. Thus, individual differences in WMC and attention control may be due, in part, to differences in LC-NE functioning that result in differences in arousal and task-engagement. At the same time, it is important to note that given widespread connections of the LC-NE system throughout the cortex, it is also possible that fluctuations in arousal and attention seen in low WMC and attention control individuals is because of differential functioning of frontal-parietal regions important for vigilant attention (Langner & Eickhoff, 2013), which send abnormal signals to the LC-NE system, which in turn then forward them on. Thus, the LC-NE system may be a mediator, rather than root cause, of fluctuations in arousal and attention seen in low WMC and attention control individuals. Given the correlational nature of the current data, this would suggest that the links between arousal and individual differences in WMC and attention control may be because of the fact that low WMC and attention control individuals are less able to regulate their arousal levels than high WMC and attention control individuals. Future research is needed to better examine the potential link between LC-NE and frontal-parietal functioning and individual differences in WMC and attention control.

Potential Heterogeneity of Arousal and Attention Control

The current results suggest that fluctuations in arousal are important contributor to individual differences in WMC and attention control. At the same time, variation in tonic arousal levels may also be critical. Specifically, the exploratory subgroup analyses suggested that both high and low levels of tonic arousal (based on baseline pupil diameter) are associated with greater off-task thinking, lowered attention control, lowered WMC, and lowered phasic responses (smaller TEPRs). Thus, there is potential heterogeneity in the relation between tonic arousal levels and WMC and attention control. Some individuals may be hypoaroused resulting in lowered attention control and alertness. These individuals may not be adequately increasing arousal and attentional effort to meet task demands resulting in overall lowered task performance. Additionally, some individuals may be hyperaroused resulting in lowered attention control potentially because of anxiety and stress. Indeed, the current results suggested a negative correlation between baseline pupil diameter and WMC. A possible reason for the negative relation between baseline pupil diameter and WMC could be due anxiety and stress linked with neuroticism. As noted previously, 119 participants of the current study were also part of Robison et al. (2017) where we examined relations among neuroticism, WMC, attention control, and mind-wandering. Examining the shared participants across studies suggests that neuroticism was related to WMC ($r = -.34$) and to baseline pupil diameter ($r = .22$). More important, partialing out neuroticism from the WMC-baseline pupil diameter relation resulted in a significantly weaker correlation between WMC and baseline pupil diameter ($r = -.16$). Additionally, this relation could be because of the strong correlation between baseline and *SD* of baseline pupil diameter. In fact, when partialing *SD* of baseline pupil diameter out, the correlation between baseline pupil diameter and WMC was no longer significant, $r = -.12$, $p = .13$. Partialing out both neuroticism and *SD* of baseline pupil diameter resulted in a correlation near zero ($r = -.06$).

Furthermore, this negative relation could be because of a subset of particularly high ability participants who were able to perform well on the tasks even when underaroused. Specifically, the exploratory subgroup analyses also suggested the presence of a group of high functioning participants who had the lowest levels of arousal and the lowest phasic responses, but also tended to report little off-task thinking and performed very well on the WMC and attention control measures. One possibility is that this group is composed of very high ability individuals who simply find the tasks too easy and, thus, are underaroused while performing these tasks. That is, these individuals are bored by the tasks, but can still perform at a very high level without putting in too much effort. As noted previously, this is consistent with prior work by Ahern and Beatty (1979) who found that individuals with high SAT scores had higher accuracy and lower TEPRs than individuals with low SAT scores while solving mental multiplication problems. Ahern and Beatty (1979) suggested that high ability individuals were more efficient in their ability to perform the tasks, thus expending less overall effort to achieve a higher score. Similarly, Unsworth and Robison (2015; see also Heitz et al., 2008) found that high WMC individuals had smaller TEPRs than low WMC individuals when working memory load was small, but that as load increased up to and beyond capacity levels, high WMC individuals had larger TEPRs than low WMC individuals. Thus, although these participants are performing better than other participants, it is possible that we are underestimating their true abilities and that if we increase task difficulty, these participants will increase their arousal levels and attentional effort to meet task demands. That is, by increasing task difficulty and demands on attention, these participants may increase their arousal to more optimal levels resulting increased task performance. This suggests that an important aspect for future research will be to examine how these relations change as a function of task difficulty.

It is also possible that this group is composed of individuals who simply have smaller pupils overall. That is, as noted previously there are individual differences in pupil diameter that are independent of arousal levels or attentional effort. One problem with this account is that it does not explain why this group has the smallest TEPRs. Because the TEPR are baseline corrected, one might expect this group to have small baseline pupil diameters, but still have relatively large TEPRs if they are applying more attentional effort to the tasks. Because both pupil diameter and TEPRs were small, it is unlikely that these differences are simply because of differences in the absolute physical size of the pupil. For now, these exploratory analyses suggest that there are subtle and nuanced relations between baseline pupil diameter and off-task thinking with subgroups of participants demonstrating different profiles across a number of variables. More work is needed to better examine these important relations. In particular, an important aspect of future research will be examining the nature of each individual's profile of arousal and attention control to determine what may be causing lowered task performance in a variety of situations.

The notion of possible heterogeneity of arousal could also explain differences between the current study and prior research examining pupil diameter and individual differences in WMC. As mentioned previously, Heitz et al. (2008) found that low WMC individuals had smaller pre-experimental baseline pupil diameters than high WMC individuals in three separate experiments. This suggests that these low WMC individuals were hypoaroused compared with high WMC individuals. More recently Tsukahara et al. (2016) replicated these findings in similar sample of participants (a combination of university students and community volunteers). In their third experiment, Tsukahara et al. extended these results and found that not only was baseline pupil diameter positively related to WMC, but it was also positively related to a fluid intelligence composite. Furthermore, Tsukahara et al. found that fluid intelligence mediated the relation between WMC and baseline pupil diameter. Thus, it is possible that the relation between WMC and baseline pupil diameter in the current study was obscured by shared variance with fluid intelligence. As noted in the Methods, all participants also completed three fluid intelligence tasks as part of another study. Therefore, to examine this possibility we examined the correlations among WMC, fluid intelligence, and baseline pupil diameter. Consistent with prior research WMC and fluid intelligence were correlated (r = .50), but fluid intelligence was not related to baseline pupil diameter (r = −.08). Thus, these results do not replicate Tsukahara et al. (2016). There are a number of possible reasons for differences in results including differences in the tasks used and importantly differences in the sample used. As noted, previously, the current results are from university students, whereas Tsukahara et al. (2016) relied on a combination of university students (from Georgia Tech and surrounding universities) as well as community volunteers. It is possible that the positive correlation is driven by a specific subset of individuals. Future research is needed to be better examine possible relations between individual differences in cognitive abilities (WMC, AC, and fluid intelligence) and tonic arousal indexed by baseline pupil diameter.

Limitations

Finally, we would be remiss not to address several limitations of the current study. For example, given the nuanced relation between baseline pupil diameter and off-task thinking and performance in the current study, one limitation is that we only examined baseline pupil diameter during the attention control tasks. Although this was done to examine trial-to-trial changes in baseline pupil diameter (and arousal) and the relation with off-task thinking, WMC, and attention control, it would have also have been good to measure pre-experimental baseline pupil diameter for each individual. That is, similar to Heitz et al. (2008; see also Tsukahara et al., 2016) it will be important for future research to not only measure baseline pupil diameter before every trial, but also before the experiment has begun to get a better sense of tonic arousal before any attentional engagement by the task. Examining pre-experimental baseline pupil diameter and variability in pre-experimental baseline pupil diameter should allow for a better assessment of pre-experimental arousal levels as well as an assessment of possible individual differences in how arousal changes once participant begin performing an attention demanding task. As noted above, most individuals should demonstrate an increase in arousal as attentional demands increase, but it is also possible that some individuals do not sufficiently increase their overall arousal levels. Additionally, it is possible that some individuals will become hyperaroused because of the task being too difficult, resulting in anxiety and worry. Future research should examine individual differences in pre-experimental and task-related baseline pupil diameter to get a better sense of how various task demands influence arousal levels and individual differences in changing arousal levels. Another limitation is that we only measured off-task thinking in the attention control tasks. In hindsight it would have been desirable to measure off-task thinking in all tasks including the WMC tasks as has been done previously (Mrazek et al., 2012; Unsworth & Robison, 2016b). Doing so would have allowed us to examine much broader off-task thinking factor and better examine how off-task thinking directly influence performance not only on the attention control tasks, but also on the WMC tasks. Future research should include thought probes in a variety of tasks (likely varying difficulty) to examine a broader off-task thinking factor and examine relations with this broader factor.

Conclusions

Collectively the current results suggest that fluctuations in arousal are an important piece of the WMC-attention control puzzle. Low WMC and attention control individuals experience more moment-to-moment fluctuations in arousal than high WMC and attention control individuals resulting in increased off-task thinking, increased inconsistency in attention control, and lowered behavioral performance. Future research combining experimental, differential, and physiological methods will be important for elucidating the critical role of arousal for individual differences in WMC and attention control.

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