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Lapses in sustained attention and their relation to executive control and fluid abilities: An individual differences investigation

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ABSTRACT

A latent variable analysis was conducted to examine the nature of individual differences in lapses of attention and their relation to executive and fluid abilities. Participants performed a sustained attention task along with multiple measures of executive control and fluid abilities. Lapses of attention were indexed based on the slowest reaction times in terms of both quintiles and the τ parameter from the ex-Gaussian distribution. It was found that the slowest, but not the fastest, RTs in the sustained attention task were related to a broad based executive control factor and a fluid intelligence factor. The results further suggested that only the working memory capacity and response inhibition sub-executive control factors were related to the slowest RTs, with the fluency measures not being related to any of the RT variables. The results are consistent with the idea that fluctuations or lapses in sustained attention, as indexed by the slowest responses, are related to executive control and fluid abilities.

1. Introduction

The ability to sustain attention has long interested researchers concerned with attentional processes in both basic and applied fields (Parasuraman & Davies, 1984). In particular, researchers have been interested in what happens when one cannot continuously sustain attention on a task leading to periodic lapses of attention (Reason, 1984). For instance, assume you are a baggage screener at a large international airport. Your job is to examine the contents of thousands of bags for the possible presence of illicit and dangerous materials. Clearly this task requires a great deal of attentional resources in order to sustain attention and detect possibly dangerous materials. Any momentary lapse in attention due to external stimuli (such as a crying baby) or internal thoughts (such as ruminating about a prior fight with your spouse) can lead to a failure to detect illicit materials with potentially hazardous consequences. Understanding these lapses of attention, whereby attention is disengaged from the current task and focused on other external distracting stimuli or internal thoughts (e.g., day-dreaming), is important for understanding how and when attentional processes falter in both the laboratory and in real world situations. Therefore, in order to better understand lapses of attention in the present study we examined how lapses are related to a number of executive control and fluid ability measures.

1.1. Executive control and lapses in attention

Much recent work has been concerned with examining executive control requirements in a number of laboratory tasks and real world situations. Executive control refers to the set of general purpose control processes that regulate thought and action in a wide variety of situations. Executive control processes are of critical importance when novel responses have to be carried out in the presence of more habitual dominant responses (Roberts & Pennington, 1996). It is assumed that it is difficult to maintain attention on a task goal and therefore sustain attention on the task at hand when internal and external interferences and distraction are high (Engle &

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Kane, 2004). In situations when attention is tightly focused on the task goal, performance will be both fast and accurate. However, if attention is not tightly focused on the task goal, lapses of attention can occur which will lead to overall slower responses or to very fast errors that are guided by prepotent tendencies. For instance, consider the antisaccade task in which participants are required to fixate on a central cue and after a variable amount of time, a flashing cue appears either to the right or left of fixation (Hallet, 1978; see Everling & Fischer, 1998 for a review). With the onset of the flashing cue the participant's task is to shift their attention and gaze to the opposite side of the screen as quickly and accurately as possible. According to executive control views, it is critically important to maintain the task goal ("if flash on the left — look right") in order to successfully perform the task given that the required response is directly opposite of the habitual response (i.e., looking at the flashing cue). Thus, any lapses in attention (or intention) will result in the prepotent response guiding behavior and hence the occurrence of a fast reflexive error (i.e., looking at the flashing cue; Unsworth, Schrock, & Engle, 2004).

A similar argument applies to the Stroop task. In this task participants are required to name the color in which color names are printed. When the color and the word match (e.g., Red presented in red ink), the task is quite easy. However, when the color and the word conflict (e.g., Blue presented in red ink), both reaction time and error rates increase. According to an executive control view, because the prepotent response conflicts with the task goal (e.g., "Say the color not the word"), a loss of goal maintenance (perhaps due to a lapse in attention) should result in the prepotent response guiding behavior and hence the occurrence of fast word naming errors or slower overall response times. Work by De Jong, Berendsen, and Cools (1999) supports this general argument. In this study, De Jong et al. had participants perform congruent and incongruent Stroop trials with either a long (2000 ms) or a short (200 ms) response-stimulus interval (RSI). De Jong et al. reasoned that the fast pace of the short RSI would keep attention tightly focused on the task goal, thereby preventing lapses. The long RSI, however, should induce more lapses as participants would have ample time between trials to think about things unrelated to the task at hand. Thus, De Jong et al. hypothesized that at the long RSI there would be a large Stroop effect, but the effect would be greatly attenuated with a short RSI. Interestingly, this is precisely what they found. With a short RSI the Stroop effect was a non-significant 11 ms. With a long RSI the Stroop effect was 47 ms. Furthermore, after rank ordering the reaction times (RTs) from fastest to slowest for each of the conditions and forming 10 separate bins, De Jong et al. found that the difference in the magnitude of the Stroop effect between the two RSI conditions was localized primarily in the slowest RTs. Specifically, in the fast paced condition, there were no differences between congruent and incongruent RTs at any of the bins. In the slow paced condition there were no differences between congruent and incongruent conditions in the fastest bins, but large differences in the slowest bins. De Jong et al. suggested that these results provide evidence for fluctuations in attention that occur on a trial-by-trial basis and lead to goal neglect (see also Kane & Engle, 2003; West, 1999).

Overall, this work suggests that if attention is not tightly focused on the task goal, lapses of attention can occur which will lead to overall slower responses. In terms of RT distributions this would lead to a large number of slow responses and an increase in the tail of the upper end of the distribution. Research consistent with this has examined overall RT distributions by either rank ordering RTs and placing them into separate bins (De Jong et al., 1999; Larson & Alderton, 1990) or by fitting an ex-Gaussian function to the overall RT distributions (West, 2001). The ex-Gaussian function is a convolution of an exponential and a Gaussian distribution which has been found to provide an accurate description of RT distributions and has been used as a tool in examining group and experimental differences in RT distributions (Ratcliff, 1979; Spieler, Balota, & Faust, 1996). The ex-Gaussian has three parameters that describe the distribution: μ (the mean of the Gaussian), σ (the standard deviation of the Gaussian), and τ (the mean and standard deviation of the exponential). Although none of these parameters reflect an underlying cognitive process, research has shown that certain parameters are affected more by some manipulations than others and that group differences can be localized to specific parameters (e.g., aging, West, 2001; ADHD, Leth-Steensen, Elbaz King, & Douglas, 2000). Importantly, regardless of the method used for characterizing RT distributions, this work has suggested that there is something special about the slowest responses that seem especially vulnerable to manipulations of executive control and to deficits in executive control. In particular, this work has suggested that when demands for EC processes are high, there is an increase in the proportion of the slowest responses, but little change with the fastest responses (e.g. De Jong et al., 1999). Additionally, participants thought to have deficits in executive control also tend to differ from control participants primarily on the slowest responses (e.g., Leth-Steensen et al., 2000; West, 2001). Furthermore, work by Dinges et al. (Dinges & Powell, 1985; Dorrian, Rogers, & Dinges, 2005) has found that sleep deprivation primarily impacts the slowest RTs with greater sleep deprivation leading to a large increase in the slowest RTs. As such this work suggests that these slow responses can be seen as providing an index of periodic lapses of attention which result from an inability of executive control processes to maintain or sustain attention on task goals.

Current neuroimaging work bolsters these notions by suggesting that lapses of attention, as indexed by the slowest RTs on various tasks, are linked to several brain areas typically associated with executive control. For example, a recent study by Weissman, Roberts, Visscher, and Woldorff (2006; see also Chee et al., 2008) examined fast and slow responses in a variant of a global–local task and found that the slowest responses were associated with lower activation in several areas thought to be associated with executive control. Specifically, Weissman et al. found that the slowest RTs were associated with reduced activity in the inferior frontal gyrus, middle frontal gyrus, and the anterior cingulate cortex prior to the onset of the stimulus. Weissman et al. argued that this reduced activity reflected a lapse of attention whereby participants were focusing on internal thoughts rather than the external stimulus prior to the onset of the trial. Like the De Jong et al. (1999) study this suggests that lapses of attention that occur in between trials can lead to performance decrements on the subsequent trial.

Weissman et al. (2006) also found that the slowest RTs were associated with reduced activity in sensory processing areas of the occipital cortex suggesting that lapses of attention can lead to potentially lower quality perceptual representations. Finally, Weissman et al. (2006) found that the slowest RTs were related to increased activity in areas of the "default-mode" network (Raichle et al., 2001) which consists of brain regions that remain active between trials and during rest periods and are thought to be related to task irrelevant thoughts. Weissman et al. (2006) argued that this increased activity reflected task irrelevant thoughts (such as daydreaming) which lead to a lapse of the task goal and a subsequent decrement in goal directed behavior.

Additional neuroimaging work supports this. Mason et al. (2007) found that greater self-reports of mind wandering (i.e., lapses of attention) were related to greater activity in the "default-mode" network. Furthermore, Mason et al. (2007) found that activity in the "default-mode" network was positively correlated with a daydream frequency scale. Similarly, using the same sustained attention task as Dinges and Powell (1985) Drummond et al. (2005) found that the slowest RTs were associated with areas of the "default-mode" network and suggested that this increased activity in the "default-mode" network reflected instances of task disengagement and lapses of attention. Collectively these results suggest that the slowest responses seem to provide an index of lapses of attention which are related to reduced activity in executive control regions and increased activity in the "default-mode" network which lead to decrements in goal directed behavior.

1.2. Individual differences in lapses of attention

Lapses of attention (as partially indexed by the slowest RTs) are not only important for understanding executive control more broadly, but are also important for understanding individual differences in executive control and their relation to other cognitive constructs. Specifically, one prominent view of executive control is the executive attention view of Engle, Kane, and colleagues (Engle & Kane, 2004; Kane & Engle, 2002; Kane, Conway, Hambrick & Engle, 2007). This view primarily focuses on working memory capacity (WMC) as a construct responsible for the active maintenance of task goals in the face of interference. As such Engle, Kane, and colleagues have argued that measures of WMC such as Operation and Reading span tasks (Daneman & Carpenter, 1980; Turner & Engle, 1989) index individual variation in executive control (or executive attention). This view suggests that individuals low in WMC, and hence low in executive control, should be more prone to lapses of attention which should lead to poorer performance (increased errors and RTs) on a number of attention tasks. Support for this view comes from a number of studies which have demonstrated links between measures of WMC and other measures of executive control such as the antisaccade (Kane, Bleckley, Conway, & Engle, 2001; Unsworth et al., 2004), Stroop (Kane & Engle, 2003; Long & Prat, 2002), and flanker (Heitz & Engle, 2007; Redick & Engle, 2006) tasks.

Accordingly, by this view one would expect that measures of WMC and other cognitive abilities should be related to the slowest, but not the fastest, RTs. In fact, work in intelligence has suggested that the slowest RTs typically correlate higher with measures of intelligence than the fastest RTs leading to a *worst performance rule* (see Coyle, 2003 for a review). In an early and classic study of the worst performance rule, Larson and Alderton (1990) found that the correlations between RTs on a choice RT task and composites of WMC and intelligence increased from the fastest to the slowest RTs. Thus, the slowest and the worst trials correlated the best with composites of WMC and intelligence. Very much in line with the work discussed above, Larson and Alderton (1990) suggested that the slowest trials represented momentary lapses in working memory, and those individuals who tended to have the most lapses also tended to perform poorly on the measures of WMC and intelligence. Further support for the notion that the slowest trials are more related to measures of WMC and intelligence than the fastest trials comes from a recent study by Schmiedek, Oberauer, Wilhelm, Süß and Wittmann (2007). In this study, RT distributions from multiple choice RT tasks were desribed with the ex-Gaussian function and it was found that the τ parameter (which characterizes the slowest RTs) was substantially related to both WMC and measures of fluid intelligence (gF). Like the Larson and Alderton (1990) study, these results suggest that the slowest and worst trials are related to both WMC and intelligence.

Based on an executive control and lapses of attention view these results suggest that individuals differ in their ability to maintain task goals in working memory in order to sustain their attention on a task. Any momentary lapse of attention due to a strong external stimulus or due to distracting internal ruminations will lead to a delayed response in very simple RT tasks. Additionally, Kane et al. (2007), Kane, Conway, Hambrick and Engle (2007) recently suggested that individual differences in mind wandering based on self-reports in an experience-sampling study were strongly related with measures of WMC, especially during challenging tasks. Furthermore, McVay and Kane (2009) recently demonstrated that rates of mind wandering partially mediated the relation between WMC and sustained attention. Thus, individual differences in lapses of attention or mind wandering (see Smallwood & Schooler, 2006 for a review) as indexed by either the slowest RTs in basic RT tasks or self-report measures seem to be strongly related to measures of WMC and intelligence. As such, this suggests that the ability to actively maintain task goals and prevent lapses of attention or mind wandering is an important cognitive construct which should be related to other measures of executive control and cognitive abilities.

1.3. The present study

The aim of the present study was to examine the relation between measures of executive control, fluid abilities (gF), and lapses of attention. As noted above, previous work has shown that the slowest RTs in several basic RT tasks are related to both WMC and gF. However, no study has examined the extent to which these slow responses are related to executive control more broadly. In particular, although measures of WMC provide a good index of executive control, they are not the only measures of executive control. As such, it is important to examine how the slowest RTs are related to other measures of executive control. In particular, based on the preceding discussion of the importance of goal maintenance and the prevention of lapses in response inhibition tasks like the antisaccade, flankers, and Stroop, one would expect that the slowest RTs should be related to performance on these tasks. Thus, the goal of the present study was to examine how executive control processes indexed by a variety of tasks (including measures of WMC, response inhibition, and fluency) would be related to lapses of attention in a sustained attention task. To do so, we utilized the psychomotor vigilance task (PVT; Dinges & Powell, 1985) that has been used previously to examine sustained attention. Previous research has shown that RT increases with time on task as does the number of lapses (Dinges & Powell, 1985). Additionally, as noted previously, factors such as sleep deprivation tend to amplify these effects (Dorrian et al., 2005) and the slowest RTs in this task have been found to be linked to greater activity in the "default-mode" network (Drummond et al., 2005). Thus, there is good evidence that the slowest RTs in this task provide an index of lapses of attention as discussed throughout. In order to examine the fastest and slowest RTs we utilized two different methods that have been used previously. First, each individual's RTs were ranked from fastest to slowest and placed into quintiles and the mean of the quintiles were correlated with the executive control and gF measures. Next, each individual's RT distributions were fit with the ex-Gaussian function and the resulting parameter estimates (μ, σ, and τ) were correlated with executive control and gF measures.

Using this sustained attention task and these methods for characterizing RT distributions, a latent variable analysis was conducted examining the relation between the slowest RTs and measures of executive control and gF. Specifically, examining the three separate executive control factors, it was expected that only the WMC and response inhibition factors should be related to the slowest RTs, while the Fluency factor would not. This is because both the WMC and response inhibition factors are represented by tasks that have a high demand for active maintenance whereby any lapse in attention could be detrimental to performance. The fluency tasks, however, primarily rely on controlled retrieval from long-term memory and thus, should be hurt less by lapses of attention. This would provide both convergent and discriminant validity for the notion of lapses of attention. As such the current study provides a unique contribution to this field in that it examines lapses in attention in a well established sustained attention task and how these lapses are related to executive control abilities.

2. Method

2.1. Participants

Participants were 151 individuals recruited from the University of Georgia subject-pool. Participants were between the ages of 18 and 35 and received course credit for their participation. Participants were tested individually in a laboratory session lasting approximately two hours.

2.2. Procedure

All participants completed (in order) operation span, reading span, antisaccade, category fluency, the psychomotor vigilance task, letter fluency, arrow flanker, Raven, verbal analogies, and Number Series.

2.3. Psychomotor vigilance task (PVT)

The psychomotor vigilance task (Dinges & Powell, 1985) was used as the primary measure of sustained attention. Participants were presented with a row of zeros on screen and after a variable amount of time the zeros began to count up. 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. Interstimulus intervals were randomly distributed and ranged from 1 to 10 s. The entire task lasted for 10 min for each individual (roughly 75 total trials).

2.4. Executive control

2.4.1. WMC

2.4.1.1. Operation span (Ospan). Participants solved math problems while trying to remember an unrelated set of letters. Participants received three trials of each set-size, with the set-sizes ranging from 3 to 7. This made for a total of 75 letters and 75 math problems. Order of set-sizes was random for each participant. The score was the number of correct items recalled in the correct position. See Unsworth, Heitz, Schrock and Engle (2005) for full task details.

2.4.1.2. Reading span (Rspan). Participants read sentences while trying to remember an unrelated set of letters. Participants received three trials of each set-size, with the set-sizes ranging from 3 to 7. This made for a total of 75 letters and 75 sentences. Order of set-sizes was random for each participant. The score was the number of correct items recalled in the correct position.

2.4.2. Response inhibition

2.4.2.1. Antisaccade. In this task (Kane et al., 2001) participants were instructed to stare at a fixation point which was onscreen for a variable amount of time (200–2200 ms). A flashing white "=" was then flashed either to the left or right of fixation (11.33° of visual angle) for 100 ms. 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 and 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 1, 2, or 3) 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 10 practice trials to learn the response mapping, 15 trials of the prosaccade condition, and 60 trials of the antisaccade condition. The dependent variable was the number of errors made on the antisaccade trials.

2.4.2.2. Arrow flankers. Participants were presented with a fixation point for 400 ms. This was followed by an arrow directly above the fixation point for 1700 ms. The participants' task was to indicate the direction the arrow was pointing (pressing the F for left pointing arrows and pressing J for right pointing arrows) as quickly and accurately as possible. On 50 neutral trials the arrow was flanked by two horizontal lines on each side. On 50 congruent trials the arrow was flanked by two arrows pointing in the same direction as the target arrow on each side. Finally, on 50 incongruent trials the target arrow was flanked by two arrows pointing in the opposite direction as the target arrow on each side. These trial types were intermixed. The dependent variable was the reaction time difference between incongruent and congruent trials.

2.4.3. Fluency

2.4.3.1. Category fluency. Participants were given 1 min to type as many exemplars from the category of animals as possible. The dependent variable was the number of unique (i.e., not repeated) instances of a category. To assess alternate forms reliability, participants also completed a category fluency task in which supermarket items had to be generated.

2.4.3.2. Letter fluency. Participants were given 1 min to type as many words that began with the letter F as possible. The dependent variable was the number of unique instances. In order to assess alternate forms reliability, participants also completed a letter fluency task in which words beginning with the letter S had to be generated.

2.5. General fluid intelligence (gF)

2.5.1. Raven advanced progressive matrices

The Raven is a measure of abstract reasoning (Raven, Raven, & Court, 1998). The test consists of 36 items presented in ascending order of difficulty (i.e. easiest – hardest). Each item consists of a display of 3×3 matrices of geometric patterns with the bottom right pattern missing. The task for the participant is to select among eight alternatives, the one that correctly completes the overall series of patterns. Participants had 10 min to complete the 18 odd-numbered items. A participant's score was the total number of correct solutions. Participants received two practice problems.

2.5.2. Verbal analogies

In this task participants read an incomplete analogy and were required to select the one word out of five possible words that best completed the analogy. After one practice item, participants had 5 min to complete 18 test items. These items were originally selected from the Air Force Officer Qualifying Test (AFOQT; Berger, Gupta, Berger, & Skinner, 1990), and we used the same subset of items used in Kane et al. (2004). A participant's score was the total number of items solved correctly.

2.5.3. Number series (NS)

In this task participants saw a series of numbers and were required to determine what the next number in the series should be (Thurstone, 1962). That is, the series follows some unstated rule which participants are required to figure out in order to determine which the next number in the series should be. Participants selected their answer out of five possible numbers that were presented. Following five practice items, participants had 4.5 min to complete 15 test items. A participant's score was the total number of items solved correctly.

3. Results

3.1. Experimental effects

First, sustained attention effects in the psychomotor vigilance task were examined. RTs were grouped into eight blocks of ten trials each. Shown in Fig. 1 are the resulting RTs. Consistent with previous work (Parasuraman, 1986; Kribbs & Dinges, 1994), RTs increased as a function of time on task indicating a vigilance decrement, $F(7,\ 1050) = 51.44$, $MSE = 1580.62$, $p < .01$, partial $\eta^2 = .26$. Specifically, RTs increased on average by 64 ms from Block 1 to Block 8 and this increase was significantly different from zero, $t(150) = 10.62$, $p < .01$, partial $\eta^2 = .43$. Additionally, as might be expected the standard deviation of the RTs also increased across blocks suggesting that not only did participants get slower across blocks, but they also became more variable in their responding, $F(7,\ 1050) = 7.18$, $MSE = 3377.37$, $p < .01$, partial $\eta^2 = .05$. Specifically, SDs increased on average by 36 ms from Block 1 to Block 8 and this increase was significantly different from zero, $t(150) = 4.87$, $p < .01$, partial $\eta^2 = .14$. Thus, consistent with previous work in sustained attention and vigilance (Parasuraman, 1986; Kribbs & Dinges, 1994), the current results suggested that individuals became slower and more variable as time on the task increased.

3.2. Correlational effects

Next, correlational effects for the psychomotor vigilance task and the other measures were examined. Descriptive statistics for all measures are shown in Table 1. As can be seen there was a good deal of variability for most of the variables and most of the variables had adequate reliabilities. Shown in Table 2 are the correlations for all of the measures. A quick inspection of Table 2 suggests that tasks thought to tap the same latent construct were generally more highly correlated with each other than with tasks thought to tap different latent constructs.

Therefore, before examining the relations with the RT variables, two confirmatory factor analyses (CFAs) were

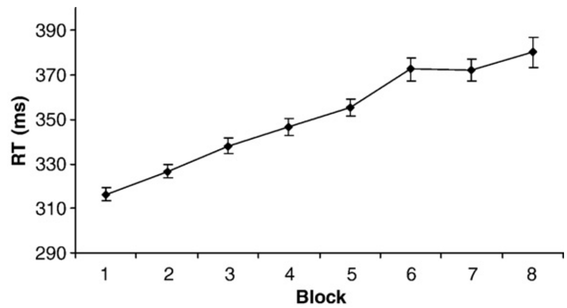

Fig. 1. Mean reaction time (RT) as a function of block. Error bars represent one standard error of the mean.

Table 1
Descriptive statistics and reliability estimates for all measures.

Measure	*M*	SD	Range	α
Ospan	64.01	7.25	36	.79
Rspan	60.55	9.19	66	.78
Antisaccade	.54	.12	.53	.84
Flanker INT	103	45	387	NA
Category	18.91	3.93	22	.71
Letter	18.49	3.76	21	.73
Raven	10.21	2.66	15	.64
Analogy	7.32	2.45	13	.60
Number series	9.65	2.54	10	.73
Q1	274	20	118	.91
Q2	304	25	167	.99
Q3	330	32	216	.99
Q4	363	41	301	.99
Q5	484	100	649	.92
μ	279	24	168	NA
σ	21	12	73	NA
τ	71	33	221	NA

Note. Q1–Q5 = quintiles for the ranked RTs; μ = mean of the Gaussian component; σ = standard deviation of the Gaussian component; τ = mean and standard deviation of the exponential component.

conducted to examine the factor structure of the executive control and gF tasks. In the first CFA (CFA1) a single executive control factor was constructed by allowing the six executive control tasks to load on it and this factor was allowed to correlate with a separate gF factor which consisted of the three gF tasks. Note that the residual variance between the two fluency tasks was allowed to correlate. As shown in Table 3 the fit of the model was good. Shown in Fig. 2A is the resulting model. As can be seen each of the tasks loaded significantly on their respective constructs and the correlation between the executive control and gF factors was quite high (r = .78). However, as can also be seen, the executive control factor was primarily influenced by the WMC measures which had strong loadings on the factor and was less influenced by the other executive control tasks which had much smaller loadings. This suggests that the executive control factor should be broken down into separate yet correlated factors (Miyake et al., 2000). Therefore, the second CFA (CFA2) specified three executive control factors including WMC (with Ospan and Rspan loading on it), response inhibition (with antisaccade and flanker loading on it), and fluency (with the two fluency tasks loading on it). The gF factor remained the same. As shown in Table 3, the fit of the model was good. In fact, CFA2 fit significantly better than CFA1, $\Delta\chi^2(4) = 14.59$, $p < .01$. Shown in Fig. 2B is the resulting model. As can be seen each of the tasks loaded significantly on their respective constructs and all of the constructs were correlated.

Next, in order to examine the relation between executive control and gF with the RT variables, separate models were analyzed with the overall executive control factor and with the separate executive control factors. The first model examined the relation between the overall executive control and gF factors with separate quintile factors. Each individual's RTs were ranked from fastest to slowest and placed into quintiles. Next, separate CFAs were run where either CFA1 or

Table 3
Fit indices for all models.

Model	χ^2	*df*	*p*	χ^2/df	RMSEA	NNFI	CFI	SRMR
CFA1	32.50	25	.14	1.30	.05	.94	.96	.06
CFA2	17.95	21	.65	.85	.00	1.0	1.0	.04
CFA1 quintiles	73.02	60	.12	1.22	.04	.98	.98	.07
CFA2 quintiles	51.02	46	.28	1.11	.03	.99	.99	.05
CFA1 speed	85.61	67	.06	1.28	.04	.97	.98	.07
CFA2 speed	68.66	59	.18	1.16	.03	.98	.99	.06
CFA1 ex-Gaussian	58.59	46	.10	1.27	.04	.92	.94	.07
CFA2 ex-Gaussian	39.55	36	.31	1.10	.03	.96	.98	.05

Note. RMSEA = root mean square error of approximation; NNFI = nonormed fit index; CFI = comparative fit index; SRMR = standardized root mean square residual.

Table 2
Correlations for all measures.

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Ospan	–	.70	.07	–	.21	.33	.24	.20	.25	−.02	−.15	−.20	−.26	−.21	–	–	–
2. Rspan	.55	–	.16	–	.23	.30	.34	.50	.25	−.09	−.26	−.32	−.34	−.35	–	–	–
3. Anti	.06	.13	–	–	.08	.15	.20	.01	.20	−.16	−.16	−.20	−.19	−.14	–	–	–
4. Flanker	−.16	−.13	−.26	–	–	–	–	–	–	–	–	–	–	–	–	–	–
5. Category	.16	.17	.06	−.12	–	.58	.27	.20	.25	−.04	−.04	−.07	−.05	−.06	–	–	–
6. Letter	.25	.23	.12	−.10	.42	–	.16	.11	.32	.02	−.01	−.04	−.04	−.12	–	–	–
7. Raven	.17	.24	.15	−.19	.18	.11	–	.36	.15	.07	−.03	−.10	−.15	−.18	–	–	–
8. Analogy	.14	.34	.01	−.12	.13	.07	.22	–	.26	.12	.06	.03	.00	.00	–	–	–
9. NS	.19	.20	.16	−.10	.18	.23	.10	.17	–	−.23	−.33	−.40	−.39	−.29	–	–	–
10. Q1	−.02	−.08	−.14	.08	−.03	.02	.05	.09	−.19	–	.96	.87	.77	.49	–	–	–
11. Q2	−.13	−.23	−.15	.11	−.04	−.01	−.02	.05	−.28	.91	–	.97	.90	.63	–	–	–
12. Q3	−.18	−.28	−.18	.12	−.06	−.03	−.08	.02	−.34	.83	.96	–	.97	.73	–	–	–
13. Q4	−.23	−.30	−.17	.14	−.04	−.03	−.12	.00	−.33	.73	.89	.96	–	.85	–	–	–
14. Q5	−.18	−.30	−.12	.17	−.05	−.10	−.14	.00	−.24	.45	.60	.70	.81	–	–	–	–
15. μ	−.03	−.10	−.15	.06	−.06	.04	.08	.07	−.20	.87	.88	.80	.65	.21	–	–	–
16. σ	−.14	−.24	−.10	.01	−.11	.00	−.02	−.02	−.17	.21	.47	.48	.40	.09	.59	–	–
17. τ	−.21	−.28	−.08	.15	−.02	−.11	−.17	−.03	−.22	.25	.41	.54	.69	.95	−.04	−.10	–

Note. Anti = antisaccade; NS = Number series; Q1–Q5 = quintiles for the ranked RTs; μ = mean of the Gaussian component; σ = standard deviation of the Gaussian component; τ = mean and standard deviation of the exponential component. Correlations below the diagonal are the raw correlations. Correlations above the diagonal have been corrected for unreliability where possible.

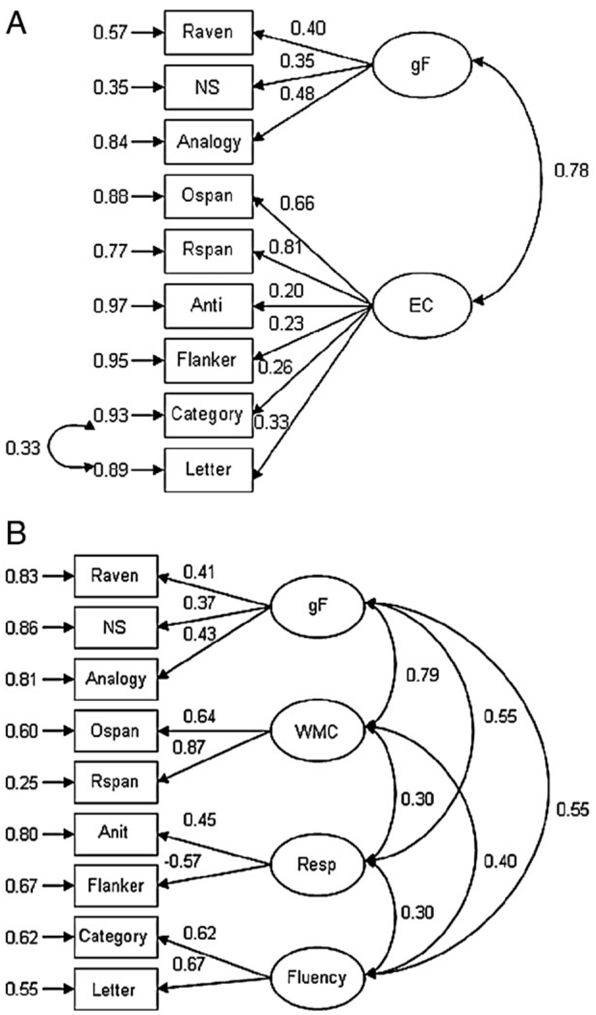

Fig. 2. (A) Confirmatory factor analysis for general fluid intelligence (gF) and executive control (EC). (B) Confirmatory factor analysis for gF, working memory capacity (WMC), response inhibition (Resp), and fluency. Paths connecting latent variables (circles) to each other represent the correlations between the constructs, the numbers from the latent variables to the manifest variables (squares) represent the loadings of each task onto the latent variable, and numbers appearing next to each manifest variable represent error variance associated with each task.

CFA2 was combined with latent factors for each of the quintiles. The loadings for the quintiles were set based on their respective reliabilities. Shown in Table 3 are the fits for the resulting models which were quite good. Shown in Table 4 are the interfactor correlations between the quintiles and shown in Table 5 are the correlations for the quintiles with the executive control total and separate factors, as well as the gF factor.

As can be seen, the correlations between executive control and gF with the quintiles tended to increase from the fastest to the slowest RTs. Specifically, the fastest RTs did not correlate with either executive control or gF, but the slowest RTs did. Furthermore, breaking executive control down into separate WMC, response inhibition (Resp), and Fluency factors suggested that both WMC and response inhibition demonstrated a similar pattern of correlations with non-significant correlations with the fastest RTs, but significant correlations with the slowest RTs. The fluency factor, however, did not correlate with any of the quintiles. The results suggest that some executive control processes are related to the slowest RTs, but none of the executive control factors were related to the fastest RTs. Thus, individuals low in executive control had substantially slower RTs at the tail of their distributions compared to individuals high in executive control. To get a sense of what this looks like on a trial-by-trial basis, plotted in Fig. 3A are time series plots for a typical low executive control participant (left panel) and a typical high executive control (right panel) participant. It is clear that the low executive control participant was more variable than the high executive control participant and this mainly occurred due to a large number of slow responses (lapses) that the low executive control participant exhibited. Indeed, shown in Fig. 3B is a plot of the two executive control participants from Fig. 3A with each of their RTs ranked from fastest to slowest. As can be seen the two individuals differ mainly in the slow end of the distribution.

Next, in order to disentangle basic differences in speed of processing abilities which should occur primarily on the fastest trials from lapses which should occur primarily on the slowest trials, two models were specified in which theoretical speed associated and lapse associated variance was extracted. Specifically, a Speed factor was specified as the common variance from the first four quintiles, while the Lapse factor was the common variance from the last four quintiles. Thus, for quintiles 2–4, two separate sources of variance were extracted. One source shared variance with the fastest trials, and the other source shared variance with the slowest trials. Separate models were run for both the broad executive control factor (CFA1 Speed) and for the specific executive

Table 4
Correlations for the quintiles.

Variable	1	2	3	4	5
1. Q1	–				
2. Q2	.96 [a]	–			
3. Q3	.88 [a]	.97 [a]	–		
4. Q4	.77 [a]	.90 [a]	.97 [a]	–	
5. Q5	.50 [a]	.65 [a]	.75 [a]	.86 [a]	–

[a] $p < .05$.

Table 5
Correlations for the RT measures from the psychomotor vigilance task with the executive control and fluid ability factors.

Measure	EC	WMC	Resp	Fluency	gF
Q1	−.09	−.08	−.22	.00	−.11
Q2	−.26 [a]	−.25 [a]	−.25 [a]	−.03	−.30 [a]
Q3	−.32 [a]	−.32 [a]	−.29 [a]	−.06	−.42 [a]
Q4	−.37 [a]	−.36 [a]	−.31 [a]	−.05	−.46 [a]
Q5	−.37 [a]	−.36 [a]	−.31 [a]	−.13	−.40 [a]
Speed	−.20 [a]	−.20 [a]	−.22	−.03	−.20
Lapse	−.39 [a]	−.38 [a]	−.30 [a]	−.06	−.47 [a]
μ	−.10	−.10	−.20	.00	−.04
σ	−.27 [a]	−.26 [a]	−.10	−.07	−.17
τ	−.34 [a]	−.32 [a]	−.25 [a]	−.04	−.35 [a]

[a] Significant at the $p < .05$ level.

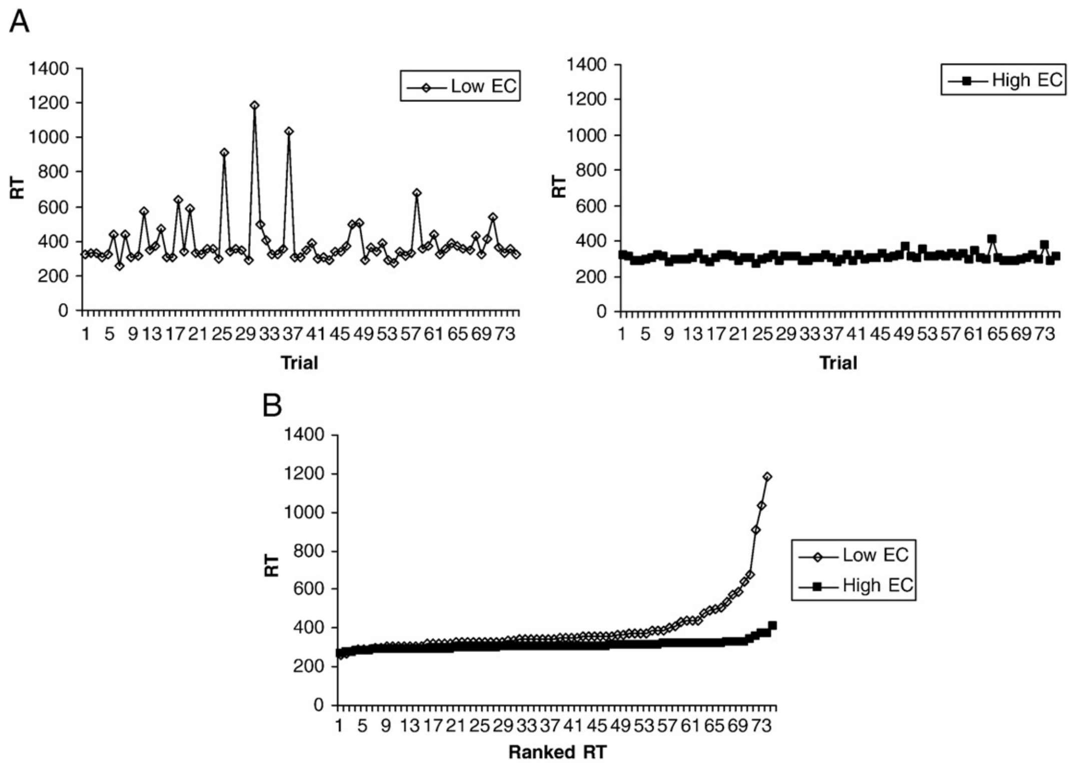

Fig. 3. (A) Trial-by-trial RT performance for a typical low executive control (EC) participant (left panel) and a typical high executive control participant (right panel). (B) Comparison of typical low and high EC participants after ranking RTs from fastest to slowest.

control factors (CFA2 Speed). The fit of both models was good as shown in Table 3. The loadings of the quintiles onto the separate factors are shown in Table 6. As can be seen, quintiles 2–4 cross-loaded onto the factors, as expected, and the magnitude of the loadings changed as a function of quintile number. Specifically, faster quintiles loaded more strongly on the Speed factor, while slower quintiles loaded more strongly on the Lapse factor. The two factors were also moderately correlated ($r = .57$). Shown in Table 5 are the resulting correlations with the executive control and fluid ability factors. As can be seen, the Speed factor correlated significantly only with the broad executive control factor and with WMC. The other factors did not quite reach statistical significance due to large standard errors (i.e., SEs > .13). The Lapse factor, however, was significantly related to all of the factors except for the Fluency factor. Furthermore, the broad executive control factor, the WMC factor, and the gF factor were more strongly correlated with the Lapse factor than with the Speed factor (all t's > 2.5). Thus, partialling the variance into Speed and Lapse components suggested that the variance associated with the Lapse component was more strongly related to executive control and gF than the Speed component.[1]

Finally, in order to examine distributional characteristics more fully we fit an ex-Gaussian function to each individual's RT distribution using QMLE (Brown & Heathcote, 2003). These parameter estimates were then used in combination with CFA1 and CFA2 to examine the correlations of the parameters with each other and with the executive control and gF factors. Although these analyses will be somewhat redundant with the preceding analyses, it is important to show that the different parameters extracted after fitting the ex-Gaussian are differentially related to the cognitive ability factors in line with previous findings by Schmiedek et al. (2007). Note the loadings of the parameters onto their respective latent variables were set equal to 1.0. Shown in

Table 6
Loadings for the quintiles onto the Speed and Lapse factors.

Variable	Speed	Lapse
1. Q1	92[a]	
2. Q2	.85[a]	.23[a]
3. Q3	.63[a]	.48[a]
4. Q4	.36[a]	.75[a]
5. Q5		.84[a]

[a] $p < .05$.

[1] At the risk of being further redundant, we also partialled out the variance associated with the first quintile from the fifth quintile and examined the correlations between the executive and fluid ability factors with the residuals. This provides an analysis of the correlation between the slowest responses and cognitive abilities after statistically removing variance from the fastest responses. As such it should provide a relatively pure estimate of lapse associated variance. The resulting correlations between the residuals and the executive and fluid ability factors were nearly identical to the correlations in Table 5. Specifically, the correlations were: Q5 − EC = −.37; Q5 − WMC = −.35; Q5 − Resp = −.23; Q5 − Fluency = −.14; Q5 − gF = −.36.

Table 3 is the fit of the models which were both quite good. The correlations among the parameters are shown in Table 2, and the correlations with the executive control and gF factors are shown in Table 5. As can be seen in Table 2, although μ and σ were significantly correlated, neither of these parameters was related to τ. As shown in Table 5, τ, was significantly related to the overall executive control and gF factors, as well as the WMC and response inhibition factors. Additionally, μ was not related to any of the factors, yet σ was significantly related to the overall executive control factor and the WMC factor. Once, again this suggests that that the slowest, but not the fastest, RTs are significantly related to executive control and gF. Furthermore, the results demonstrate that the slowest RTs are not related to all executive control factors, thereby providing both convergent and discriminant validity.

4. General discussion

The goal of the current study was to explore lapses in sustained attention and their relation to executive and fluid abilities. It was shown that indices of lapses of attention were related to both executive and fluid abilities. Specifically, it was shown that lapses of attention, indexed by the slowest quintiles and the τ parameter after fitting an ex-Gaussian function to the distributions, were related to overall executive control and gF factors. These results provide evidence that in the current sustained attention task, individuals differed in fluctuations or lapses in attention where on some trials attention was not tightly focused on the task goal leading to goal neglect. Indeed, these lapses were related not only to basic WMC tasks, but were also related to response inhibition tasks such as the antisaccade and flankers. This makes sense given that a lapse of attention on the antisaccade will likely result in attention being captured by the flashing cue leading to a faster reflexive saccade in the wrong direction and hence an error (Unsworth et al., 2004). Thus, despite claims to the contrary (Schmiedek et al., 2007) the current results are quite in line with executive control models that suggest that individual differences in executive control are partially due to differences in the ability to maintain task goals in the face of external and internal distraction (Engle & Kane, 2004). Furthermore, these results suggest that these individual differences are apparent even in relatively simple sustained attention tasks, where there is little need to set up and maintain temporary bindings between stimulus and response categories (Schmiedek et al., 2007) because in the current task only a single response had to be maintained (i.e., press the space bar when the numbers start counting up).

The results from the current study are also consistent with previous neuroimaging work which has examined lapses of attention. As noted previously, research with the current sustained attention task as well as other tasks, has shown that lapses of attention are associated with increased activation in the "default-mode" network suggesting that attention is focused on internal ruminations instead of being focused on external stimuli (Drummond et al., 2005; Weissman et al., 2006). That is, participants are essentially zoning out, or allowing their minds to wander rather than being focused on the task at hand. With the onset of the external stimulus attention must be redirected from internal thoughts to the external stimulus in order for the correct response to occur. This process tasks time, leading to much slower than normal RTs. Combined with the current individual difference work, this suggests that individuals low in executive control are more likely to zone out leading to greater activity in the "default-mode" network and a greater proportion of slow responses.

Furthermore, the results suggest that the worst performance rule whereby the slowest RTs are related to intelligence also seems to hold for some executive abilities. That is, the worst performance rule works not only for intelligence measures, but also for broad based measures of executive control, as well specific measures of executive control such as measures of WMC (Larson & Alderton, 1990) and measures of response inhibition. However, the worst performance rule does not seem to hold for measures of Fluency. That is, measures of Fluency did not correlate with any of the RT measures, yet they did moderately correlate with measures of WMC, response inhibition, and gF. Thus, it is not simply the case that the Fluency measures were poor indicators, but rather that these measures simply were not related to the RT variables in the current study. This is interesting given that the Fluency measures are rate-limited in that participants have to generate as many exemplars as possible in a fixed amount of time (usually 60 s). Thus, the worst performance rule found with RT measures seems to index something other than just a general timing variable. Rather, it seems to provide an index of periodic lapses of attention. As such, not all executive control processes are related to the worst performance rule, but rather it seems that only those processes that are especially susceptible to periodic lapses of attention are (such as active goal maintenance). Fluency measures rely more on controlled/strategic retrieval than active maintenance, and thus lapses of attention are less likely to impair performance. This provides both convergent and discriminant validity for the notion of lapses of attention as a distinct individual differences construct.

Overall these results are consistent with prior work suggesting that certain groups are more likely to experience lapses of attention and that certain variables can lead to breakdowns in sustained attention and increases in lapses (e.g., sleep deprivation, Dorrian et al., 2005). Furthermore, the results provide support for the notion that variability in the slow end of RT distributions is an important index of an individual's ability to consistently maintain and sustain attention on a task which is related to other important executive and fluid abilities. As noted previously this ability is likely related to executive deficits seen in a number of populations (e.g., Stuss, Murphy, Binns & Alexander, 2003), and may be related to variation in the efficiency of dopamine (Li, Lindenberger, & Sikstrom, 2001) or norepinephrine (Aston-Jones & Cohen, 2005) neuromodulation. Furthermore, this ability may be important for real world phenomena such as mind wandering (e.g., Kane et al., 2007; Kane, Conway, Hambrick & Engle, 2007b). The current work (along with previous research) suggests a promising field of inquiry examining how fluctuations in basic cognitive processes determine overall task performance and how these fluctuations are related to other important processes.

4.1. Limitations, alternative explanations, and future directions

One of the biggest limitations of the current study is the lack of additional measures of RT and lapses of attention. Specifically, only a single sustained attention task (the psychomotor vigilance task) was used to get an index of lapses of attention based on the slow end of the distribution. Clearly, more evidence for the notion of broad lapses of attention construct would come from having multiple tasks. This would include several RT tasks such as sustained attention tasks, choice RT tasks, as well as RTs in other selective attention tasks where lapses would like lead to delayed responses. Recently, Schmiedek et al. (2007) examined eight choice RT tasks and found that the ex-Gaussian parameter estimates were correlated across the tasks, and a latent τ variable (formed based on the τ estimates from the eight individual tasks) was highly related to both WMC and gF. Multiple RT measures were not collected in the current study, because we decided to focus on a particular sustained attention task that has been linked with lapses of attention in a number of studies thereby providing fairly specific evidence for the notion of individual differences in executive control and lapses of attention. Like the Schmiedek et al. (2007) study, however, it would be optimal to examine multiple RT measures in the future.

Further evidence for broad lapses of attention construct would also come from the inclusion of multiple self-report measures of lapses of attention and mind wandering. This would serve to bring together work that has exclusively focused on the slowest RTs and work that has focused on self-reports of lapses. To the extent that these two areas are in fact measuring the same underlying construct, we would expect that these measures would be correlated and would load on the same common factor which should be related to various executive control factors. In line with this, another limitation of the current study is the use of only three executive control factors to examine the differential relation of lapses to other executive control functions. Given that other executive control functions have been examined in the literature (e.g., task switching) future work should include additional executive control measures and executive control functions to get a better idea of how multiple executive control functions are related to one another and related to lapses of attention.

Another potential limitation of the current study is the fact that several of the zero-order correlations were fairly weak. Because the zero-order correlations were weak, there is little shared variance among the measures leading to low communalities for the latent factors. As noted by Friedman and Miyake (2004) the result is that the parameter estimates in the subsequent models will be less precise than when stronger inter-correlations are examined. Thus, there is certainly some imprecision within the current models. However, it should be noted, that despite this imprecision, all of the measures loaded significantly on their respective latent variables and the latent variables were related in a theoretically meaningful manner with each other replicating prior work. Furthermore, several of the endorsed models fit significantly better than alternative models. Thus, despite low zero-order correlations, the current results demonstrated that separate executive control factors were present in the data and these factors were related to one another and to other important cognitive abilities.

In terms of alternative explanations to our data, there are likely several, but here we will focus on two. The first alternative explanation is that our results can be handled by a version of the diffusion model (e.g., Ratcliff & Rouder, 1998; Schmiedek et al., 2007). This model provides an excellent account of RT distributions in a wide variety of tasks. In a two-choice version of this model, it is assumed that information is continuously accumulated until a boundary condition is reached. In full versions there are a number of parameters that index different aspects of the diffusion process. For instance, there are separate parameters for the point at which information accumulation begins, the rate of information accumulation (drift rate), as well the separation between the two boundaries (response criterion). According to a diffusion model explanation of the current results, individual differences in the slow end of the distribution would be due to differences in drift rate (Ratcliff, Schmiedek, & McKoon, 2008; Schmiedek et al., 2007). High executive control individuals extract higher quality stimulus information, which leads them to reach the correct boundary quicker than low executive control individuals. Thus, this view suggests that lapses of attention are not necessary to explain differences in the slow end of the distribution; rather these differences are nicely accounted for by differences in drift rate. In fact, Schmiedek et al. (2007) specifically argued for a diffusion model explanation rather than lapses of attention explanation, suggesting that the diffusion model explanation offered a simpler account of the data.[2] However, it is not clear how this account would account for self-report differences of lapses of attention and mind wandering that have been found to be related to individual differences variables such as WMC (Kane et al., 2007; Kane, Conway, Hambrick & Engle, 2007b). By a lapses-of-attention of account both the slowest RTs and self-reports of lapses should be measuring aspects of the same underlying construct which is related to other cognitive abilities like WMC and gF. Furthermore, it is not clear how a diffusion model account would handle the fact that brain areas associated with executive control show reduced activity prior to stimulus onset (Weissman et al., 2006; Chee et al., 2008) which is related to the slowest RTs. If drift rate provides an index of the rate of accumulation of stimulus information that is already present, then why would activity levels prior to the onset of a stimulus predict RTs? Rather, it would seem that prior activity would likely have more of an effect on the starting point than drift rate. Thus, it is not immediately clear that a diffusion model explanation provides a simpler account of the data than a lapses-of-attention view. Furthermore, it is not clear that these two views are necessarily mutually

[2] Note that we did not fit a diffusion model to the data in the current study for two reasons. 1) A typical diffusion model requires both RT and accuracy data. However, because there are no errors in the psychomotor vigilance task and only a single response is required a modified version of the diffusion model would be needed. Specifically, a reflecting boundary (e.g., Diederich & Busemeyer, 2003) would be needed to ensure that all responses drifted to the same criterion. 2) Given that a modification to the typical diffusion model would be needed, we would have to fit a full modified version of the model to each participant's data which would be very time consuming (e.g., Ratcliff et al., 2008, pp.16–17) given the large sample size.

exclusive. It is possible that the reduced activity prior to stimulus onset is due to a lapse of attention whereby individuals are more focused internally than on the presence of external stimuli. Once the stimulus appears, its perceptual representation is weaker than what would be expected if full attention were paid to the stimulus (e.g., Weissman et al., 2006). More time would then be required to extract information from this weakened percept leading to overall slower drift rate. Thus, it is possible that these two concepts in conjunction provide a better account of the data than either alone. Cleary future work in multiple areas is needed to better understand these concepts.

The second alternative explanation is that differences in RT actually reflect differences in basic speed of processing rather than differences in lapses of attention. According to this view high ability individuals (high executive control, high WMC, high gF) are faster at processing information leading to faster overall RTs in a number tasks (e.g., Jensen, 1998). A similar view has been advocated in the developmental (Hale, 1990) and aging (Salthouse, 1996) literatures to explain age differences in cognitive processes. In these views it is the ability to rapidly process information that accounts for the shared variability amongst these measures rather than differences in lapses of attention or drift rate. Accordingly, in these speed of processing views, high and low ability individuals should differ at nearly all RTs including both the fastest and the slowest RTs. However, as shown in the current study the fastest RTs indexed by the first quintile did not correlate with any of the cognitive ability. Additionally, partialling the variance into Speed and Lapse components suggested that the Lapse component was more strongly related with the executive control and gF factors. Furthermore, μ, which is an index of the leading edge of the RT distribution, did not correlate with any of the cognitive ability measures either. Thus, the slowest, but not the fastest, RTs were correlated with the various cognitive ability measures which is inconsistent with a speed of processing view. These differences in correlations cannot be due to the fact that the fastest RTs are simply unreliable measures as the reliability of the first quintile was .91 and the first quintile was highly correlated with the other quintiles. Likewise, μ was substantially correlated with σ ($r = .59$) suggesting that it too was somewhat reliable and had adequate systematic variance. Collectively, these results are inconsistent with a speed of processing view, and suggest that the slowest, but not the fastest. RTs provide an index of an important cognitive ability.

5. Conclusion

The current findings suggest that individual differences in lapses of attention were related to both executive and fluid abilities. It was demonstrated that the slowest, but not the fastest, RTs indexed by both the slowest quintiles and the τ parameter from the ex-Gaussian distribution were related to executive control and fluid abilities consistent with the worst performance rule. Furthermore it was shown that not all executive control functions were related to the slowest RTs. Specifically, of the three executive control functions examined (WMC, response inhibition, and Fluency) only WMC and response inhibition were related to the slowest RTs consistent with the worst performance rule. Overall, the current work suggests that variation in fluctuations or lapses in sustained attention are related to a number of important cognitive constructs which are needed in a number of real world situations.

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