Effort Allocation and Error Monitoring in Individuals with Varying Levels of ADHD

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Abstract

Problems with effort allocation have been observed in individuals with ADHD in recent research and appear to influence their performance. Furthermore, impairments in error monitoring may be another contributing factor to the lower performance of this population. More specifically, people with ADHD seem to slow down less than typically developing people upon committing a mistake (PES). The present study investigated how cognitive performance was affected by both effort allocation and error monitoring in university students with differing levels of ADHD. To operationalize this, a task-switching paradigm based on Sidlauskaite et al.'s (2020) task was used. With 46 participants, this online study also included the CAARS self-report measure for ADHD symptoms in order to quantify symptom severity. The results found no evidence to connect ADHD levels to differences in error monitoring and effort allocation when it comes to performance. However they did identify a relation between error monitoring and effort allocation. Further research on this topic with more representative samples is recommended.

Keywords: Effort allocation, attention deficit and hyperactivity/impulsivity disorder (ADHD), state regulation model, error monitoring, post-error slowing

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ADHD

Attention Deficit/Hyperactivity Disorder, ADHD, is one of the most common neurodevelopmental disturbances. Affecting an estimated 3 to 9.4% of school-aged children, it is characterized by impairments in attention, activity and/or impulsivity (American Psychiatric Assocation [APA], 1994; 2013; Danielson et al., 2018; Kessler et al., 2006; Szatmari, 1992). With an estimated 2.5 to 4.4% of the adult population suffering from ADHD, a myriad of research has emphasized the possibility for persistence of this disorder into adulthood (Searight et al., 2000; Seidman et al.,1998; Wender et al., 2001). The difficulties associated with the disorder affect several domains of functioning including, but not limited to the academic, social and occupational domains (Farone & Biederman, 2005). A similarity has been noted between the performance issues of children and that of adults suffering from ADHD. This is to be expected as adult-ADHD is the continuation of a developmental disorder, also known as syndromatic continuity (Hervey et al., 2004; Woods et al., 2002).

An effort to understand the aetiology of ADHD has been exuded by the scientific community. The current agreement upon this disorder regards its complex and multidimensional nature involving several genetic, environmental, and neurobiological factors (Nigg, 2005). This is especially due to varying symptom presentation depending on the setting as well as a function of motivation or even energetic state (including stress, fatigue, noise, punishment, time of day, supervision, presentation rate of stimuli, temperature, among others) (Douglas, 1999; Sonuga-Barke et al., 2010). Multiple studies have been conducted on the apparent weak cognitive performance of children with ADHD on tasks related to vigilance, motor inhibition, as well as verbal learning and memory (Barkley, Grodzinsky, & DuPaul, 1992; Boonstra et al., 2005; Hervey et al., 2004; Pennington &

Ozonoff, 1996; Sergeant et al., 2003). One key conclusion is that both children and adults with ADHD appear to commit more errors and variability in their responses than the neurotypical individuals (Balogh & Czobor, 2014; Kofler et al., 2013; Rabbit, 1966). However, the mechanisms underlying these performance issues are still unclear with multiple theoretical frameworks attempting to explain ADHD symptoms' relation to performance impairments. These include neurochemical deficit theories (for the Dynamic Developmental Theory, see Sagvolden et al., 2005; for the Dopamine Transfer Deficit Model, see meta-analysis by Tripp and Wickens, 2008) as well as neurobiological models (for the behavioural neuro-energetics model, see Killeen, 2013; for evidence supporting the executive dysfunction theory, see Baroni and Castellanos, 2014; for the delay aversion theory with a dual and tripartite pathway model variations, see Sonuga-Barke et al., 1992; 2010; Sonuga-Barke, 2003).

ADHD and Effort Allocation

Within the neurobiological models, a particular contribution for the understanding of individual performance impairments came from Sanders' (1983) proposal of the cognitive-energetic model. According to this model, four basic steps are involved when processing stimuli (encoding, feature extraction, response selection and response execution). Processing stimuli in any task requires effort allocation both to stay psycho-physiologically alert for upcoming stimuli (arousal), as well as to prepare and execute desired motor responses (activation). Non-optimal levels of arousal and activation dependent on task demands, affect the efficiency at which these steps are performed. From the assumption that individuals' effort (energetic resource) is limited, the energy/effort must be shared between arousal and activation. According to the State Regulation hypothesis, energy mobilization is assumed to be problematic in ADHD (Sergeant et al., 1999; van der Meere, 2002; 2005). As such when a task requires extra effort allocation to regulate motor responses (activation), the hypothesis assumes that individuals with ADHD will not allocate sufficient effort (due to energy mobilization problem) leading to poor task performance. The same holds when a task requires extra effort allocation for arousal. Furthermore, it also implies that when the context provides optimal levels of stimulation, similar performance can be expected between people with ADHD and typically developing populations (Finke et al., 2011; Sonuga-Barke et al., 2010; Wiegand et al., 2016). Nonetheless, most of literature and empirical evidence pinpointed that ADHD individuals have problems in regulating motor activation.

A significant body of research has grown in support of this hypothesis (Johnson et al., 2009; Metin et al., 2012; Sergeant, 2000). In fact, a particular emphasis on difficulties with understimulating tasks has gained special attention. In van der Meere's (2005) research on state regulation of children with ADHD, it was concluded that more pronounced performance issues surfaced when ADHD children were under-aroused, revealing problems with regulating their motor activation to match the task demands. The same problems were also found in adults with ADHD (Wiersema et al., 2006). This was operationalized by manipulating the length interstimulus presentation and the response (event rate) of the trials. The longer/slower stimulus condition proved itself to be the hardest for the participants as they committed more errors than their typically developing peers. This effect was found and corroborated in follow-up papers which looked into the effect of varying levels of stimuli presentation rate (slow, moderate, or fast) in order to test for effort allocation in the activation level of individuals with ADHD (Chee et al., 1989; Conte et al., 1986; Metin et al., 2012; Scheres et al., 2001; van der Meere et al., 1995). Thus, it appears that ADHD performance deficits are in part due to an effort allocation problem which manifests itself in tasks that are seemingly less stimulating.

Effort Allocation and Error Monitoring

Another assumed factor that may explain poor task performance in ADHD is error monitoring. Error monitoring can be understood as the surveillance of errors and subsequent evaluation of those for the determination of a potential behavioral adjustment (Gehring & Fencsik, 2001; Ridderinkhof et al., 2004; Taylor et al., 2007). Furthermore, it can be considered an essential process in any cognitive task as it reflects proactive adaptation in the service of cognitive goals. Research on typically developing populations has shown that cognitively demanding tasks require additional effort to monitor errors. A recent study (Araujo et al., 2015) investigated error monitoring abilities in typically developing populations in tasks with differing difficulty levels. They found that both adolescents and young adults demonstrated increased error monitoring processes in more demanding tasks in comparison to less demanding ones. In this way, error-monitoring can reflect a cognitive mechanism used to identify the level of task demands in the light of own mistakes in performance and to estimate the amount of effort needed to either correct these mistakes (activation) or pay more attention to the characteristics of task stimuli (arousal) to avoid future mistakes. Therefore, displaying problem in this cognitive mechanism can lead to unsuccessful energy mobilization to reach the target performance (Sergeant et al., 1999). Hence, it can be seen in the State regulation model as an “evaluation mechanism” to “effort” (see Appendix A for visualization of the model retrieved from Wiersema & Godefroid, 2018).

ADHD, Effort Allocation Error Monitoring

From a different perspective, error monitoring can be considered an effortful process especially during demanding and complex tasks. Consequently, individuals who encounter difficulties in effort allocation (such as people with ADHD), are expected to show poor error-monitoring. Tasks like the go/no-go task, the choice reaction time task and stop sign tasks (Balogh and Czobor 2016, Meere 1999) have shown a link between successful performance on top-down tasks and error monitoring processes. According to an early study on the cognitive processes behind errors, conducted by Sergeant & van der Meere (1988), ADHD patients committed a higher number of errors and response variability than neurotypical participants. These results are illustrative of an impairment of error monitoring on people with ADHD. Well-functioning error monitoring is evident in performance when upon making a mistake, an individual tries to avoid repeating it by slowing down in their responses, also known as post-error slowing (PES) (Rabbitt, 1966). In this way, evidence has piled on the relatively reduced PES in the performance of children and adults with ADHD (see meta-analysis by Balogh & Czobor, 2014). A study conducted by Schachar et al. (2004) used go/no go tasks to assess error monitoring and response inhibition of individuals with and without ADHD. They reported an error monitoring deficit, indicated by a higher PES in healthy controls. One other relevant study by Payne (2016) investigated PES of individuals with ADHD and controls through a modified Flanker task. Lower post error adjustment and accuracy were reported as evidence for an error monitoring deficit.

The Present Study

Most of the studies abovementioned used solely clinically diagnosed ADHD patients and control groups. This approach to ADHD is called “categorical approach” in which people either have a diagnosis of ADHD or not (using clear cut divisions). This separation holds some limitations. From the reduced clinical sample sizes to the strict assessment criteria, which in turn leads to extreme expressions of the disorder, several studies have argued for a dimensional approach to ADHD (Haslam et al., 2006; Levy et al., 1997; Loughran, 2003; Lubke et al., 2009). This alternative takes ADHD as a continuum in which individuals experience different levels of ADHD symptoms. In practice, it also entails that a random sample of undiagnosed participants is collected, and the participants are tested for ADHD symptoms. Then, the performance of those with higher levels of ADHD symptoms is compared to that of those with lower levels. Furthermore, little to no research has been conducted on error monitoring deficits in typically developing populations with varying levels of ADHD (Mohamed et al., 2016). Thus, this paper will focus on this approach.

This paper holds three main goals. Firstly, it investigates how effort allocation in people with varying levels of ADHD symptoms affects their performance. Secondly, it explores how effort allocation impacts on individual error monitoring explain performance. Lastly, it investigates the interplay between error monitoring, effort allocation and ADHD symptom severity.

To investigate the abovementioned goals, participants are to perform a task-switching paradigm (Sidlauskaite et al., 2020). This measure is divided into three conditions (slow, medium, and fast). These are aimed to evaluate effort allocation by manipulating the length of the intervals between stimulus and response (with the people with higher levels of ADHD demonstrating difficulties with the longer interval than people with lower levels). Furthermore, this measure includes mixed and unmixed trials. The unmixed trials have been designed to isolate error monitoring from other cognitive adaptation mechanisms (such as set shifting; see Luna-Rodriguez et al., 2018). Additionally, this measure is deemed more appropriate for this research than the commonly used “Go/No-go” task (Epstein et al., 2010; Groom et al., 2010; Spinelli et al., 2011; Van De Voorde et al., 2010; Wiersema et al., 2005; 2009). Especially since it has been argued to be more cognitively demanding and thus showing clearer performance differences between typically developing populations and people with ADHD (Braver et al., 2003; King et al., 2007; Monsell, 2003).

H1. People with higher ADHD indexes will show poorer performance in the slow condition of the task than those with lower ADHD indexes (as shown in Borger & van der Meere, 2000; Mohamed et al., 2016; Wiersema, 2005; Wiersema et al., 2016). This hypothesis will look into the interaction between ADHD and Event rate as operationalized by higher MRTS and errors than those with lower ADHD indexes.

H2. Participants should display higher error monitoring processes in the most demanding condition (fast) when compared to the other conditions (medium and slow), regardless of their ADHD indexes. This hypothesis looks into the main effects of Event rate without ADHD indexes. The expected effect is based on the Cognitive Energetics Model assumptions (Sanders, 1983) as well as findings by Araujo et al. (2015).

H3. People with higher levels of ADHD should display impaired error monitoring in the slow condition in comparison with the other conditions and to people with lower levels of ADHD (see metanalysis by Balogh & Czorbor, 2014). This hypothesis concerns the interaction between ADHD, Correctness and Event rate.

Methods

Participants

For the following study, all data was collected from an archive from the Department of Clinical and Developmental Psychology from the University of Groningen. Of a total of 50 participants, 20 males, 29 females and 1 unknown, three were excluded due to lack of participation on one of the measures (Conners' Adult ADHD Rating Scales, CAARS) and one was excluded due to lack of participation on all questionnaires.

The participants were recruited via a convenience sampling method operationalized by "SONA", the software, of first-year psychology students of the University of Groningen. With a mean age of 19.67 (1.85), the gender ratio was of 1.7 for females, with 37% males (17 in total) and 63% females (29 in total) (see table). The 46 remaining participants were further asked about relevant mental disorder diagnoses received prior to the research. Thirteen participants chose to refrain from providing information on this matter. Additionally, three participants stated having been diagnosed with ADHD and/or ADD prior to research. Furthermore, participants also reported whether they had been diagnosed with any comorbid disorder from a list of: (any form of) Depression disorder, (any form of) Anxiety disorder, (any form of) Stress disorder, Dyslexia and (any form of) Motor disorder. A total of 17 people reported holding at least one of the abovementioned diagnoses with 7 stating comorbidity of at least two disorders. With comparative performance deficits between people with ADHD and people with the abovementioned disorders (Kim et al., 2019; Mendl, 1999; Moores et al., 2003; Treadway et al., 2012; Yang et al., 2014) it could be relevant to understand how these disorders affect the research. However, due to inconsistencies in the participants statements regarding age related diagnosis as well as disorder expression, the abovementioned comorbidities can be suspect of invalidity. Thus, only those with a reported ADHD diagnosis will be further investigated.

Materials

CAARS

In order to measure the participants' symptom levels, the long form of CAARS questionnaire was used. The questionnaire was conducted online and operationalized through Qualtrics (Qualtrics, 2005), software which then stored the data. This consists of 66 items rated on a 4-point scale (0 = not at all, never; 1 = just a little, once in a while; 2 = pretty much, often; 3 = very much, very frequently). Each item is attributed to one or more of the 8 scales embedded: A, Inattention/Memory Problems; B, Hyperactivity/Restlessness; C, Impulsivity/Emotional Lability; D, Problems with Self-concept; E, DSM-IV Inattentive Symptoms; F, DSM-IV Hyperactive-Impulsive Symptoms; G, DSM-IV ADHD Symptoms Total; and H, ADHD Index). The E, F and G scales group similar symptom expressions in order to identify ADHD symptoms, in accordance with DSM-IV (APA, 2013). For this research, there will be a focus on scale H (ADHD Index) since this scale provides an overall ADHD symptom score that can be illustrative of individual symptom experience. This scale provides a t-score pertaining to how common a participant's symptom expression is in relation to their age and gender (4 categories of age for male and 4 categories of age for female). The CAARS has been deemed highly reliable with only few face validity concerns associated with self-report measures (see Erhardt et al., 1999; Macey, 2003, Suhr et al., 2017).

Task-Switching

The task-switching paradigm was created with OpenSesame (version 3.2) (Mathôt et al., 2011; see Figure 1 for illustration of the task) and then hosted by Jatos server (Lange et al., 2015). Then, this software further stored the collected data. It consisted of two blocks (unmixed and mixed block) in which the participants had to categorize objects in terms of color or shape. For the unmixed block, a sequence of trials requiring categorization according to color would only ask for shape or color at a time. For the mixed block, instructions would vary and ask randomly for categorization according to color or shape. The instructions were given in the following way

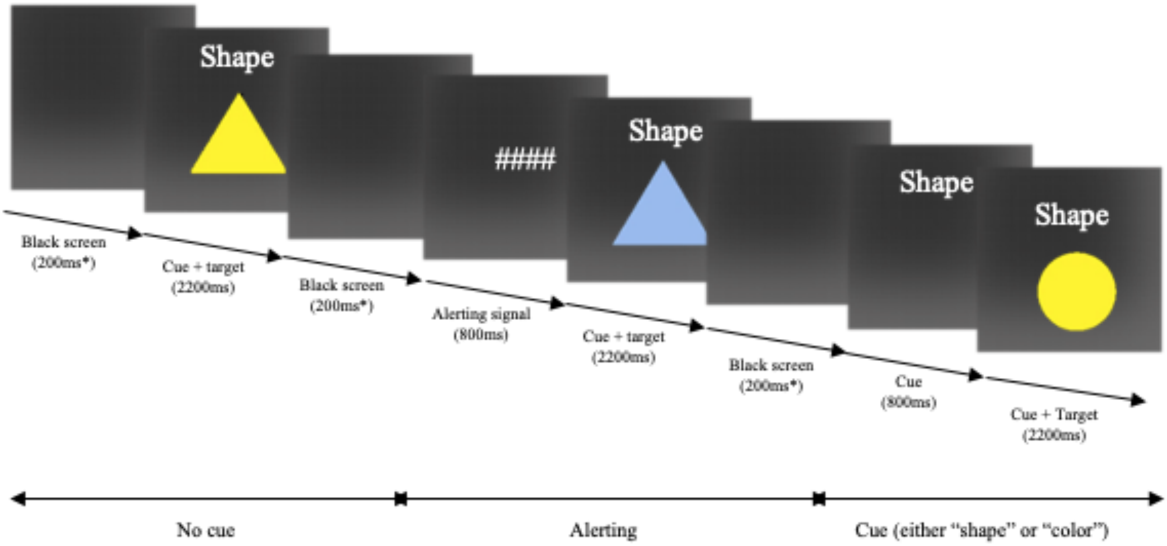
> You will see a geometric shape of circle or triangle in blue or yellow colour. Above the geometric shape,you will also see either the word “shape” or the word “colour”. If you see the word “shape”, press “m” = triangle shape, press “z” = circle shape. If you see the word “colour”, press “m” = blue colour, press “z” = yellow colour. Respond as fast and accurately as possible. Note. For some trials the word “shape” or “colour” will precede the presentation of the geometric shape. For other trials, no word or few hashtags “#####” will precede the presentation of the geometric shape. Press any key to see an example of stimulus presentation.

Hence, first the participants were given time to practice (14 trials). A cue was presented for 0.8 seconds per trial. Then, the stimulus (either shape or color) was presented for 2.2 seconds, along with feedback for 1 second, and an interval for 2 seconds. In the real experiment, the cue and stimulus were present the same amount of time as in the practice trials, though there was no feedback and the interval occurred for a varying amount of time. The interval depended on one of the three conditions (slow would have 2 seconds, medium would have 0.8 seconds and fast would have 0.2 seconds). In total, the fast condition included around 102 trials, the medium condition included 66 trials and the slow condition included 30 trials for each of the two blocks. To address the differing trial number, the “error rate” is calculated and explained in the data analysis. For this study, the focus was on the unmixed block with no particular distinction between the three different cue conditions as these were irrelevant for the hypotheses of this research. The event rate (slow, medium and fast) was the main aspect investigated in the task as this was the operationalized effort allocation.

Corresponding errors and mean reaction times in the performance on these tasks were used to analyse error monitoring.

Figure 1

Schematic presentation of the task-switching paradigm



Note. The figure above intends to illustrate the order and time frame of each slide that was presented to the participants. However, it was adapted for readability purposes and so, the font and shape sizes are not accurate to the original task.
*Time frame attributed to the "Black Screen" slide is dependent on the Event Rate condition. In the figure above, this slide is presented for 200ms which corresponds to the fast condition. For the slow condition this slide appeared for 8000ms. For the medium condition the slide appeared for 3000ms.

Procedure

The study was approved by the Ethical Committee of Psychology of the University of Groningen. Due to ongoing external limitations, the study was fully conducted online. First, participants gave informed consent for participating. Then, the participants that decided to participate in the study, were asked to fill in two questionnaires: the CAARS and the Weiss Functional Impairment Rating Scale (WFIRS). They were also asked to indicate if they had any of the following disorders: ADHD, ADD, depressive disorder, anxiety disorder, stress, dyslexia or motor disorder and if they had it during childhood or adulthood. Furthermore, they were also asked about their age, gender and any use of medication. After filling out the questionnaires, they had to perform two online reaction time tasks: the task switching paradigm and the Stroop task. The order of these two was randomized. For each task (condition), participants first did several practice trials before starting the actual task. The participants were given the opportunity to take two 5-minute breaks to separate conditions within each task. If chosen to take these breaks, each task would have taken 44 minutes (either the Stroop task or the task-switching task). Due to the length of the experiment, the study was divided into two sessions. The WFIRS and Stroop task were part of a bigger study and will not be used in this specific study. After filling out the questionnaires, the participants were given a debriefing sheet regarding the true intentions of the study as well as emotional support.

Data analysis

Preparation of the data for error monitoring

First, the amount of correct and incorrect responses were counted per stimulus presentation rate per participant and per participant in general. Due to the differences in number of trials between the fast, medium and slow event rate the error rate was computed. This was done by dividing the amount of errors by the amount of trials. This gives a better picture of the accuracy of each participant. Mean Reaction Time was also calculated per event rate, participant and both together.

Traditional PES.

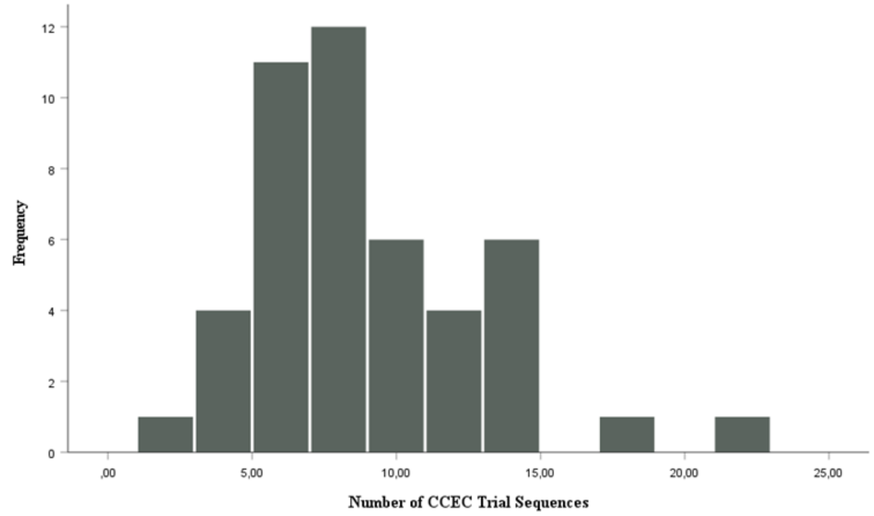
To analyse the participants' post-error slowing on the Task-Switching Task, two different approaches were taken. With these, the Traditional Post-Error Slowing (PES) and then Robust PES were calculated. For the prior mentioned, MRTs of correct answers following an error (EC) and MRTs of correct answers following a correct response (CC) were computed. This way the difference between the two should reveal whether a participant demonstrated PES in comparison to the speed at which they responded after having a correct response (see Dutilh et al., 2012 for thorough explanation of both calculations of PES).

Robust PES.

For the Robust PES, instances of CCEC trial sequences were counted when (1) the trial of focus had an incorrect response, (2) the two trials before had correct responses and (3) the trial after also had a correct response. Subsequently, the reaction time of the post error was subtracted from the reaction times of the pre-error. This was calculated for participant and per event rate. For robust in general, there is a mean of 8.41 trials with a standard deviation 3.89. The distribution of trials can be seen in Figure 2. Using Mohamed et al.'s (2016) 10-trial reference, the amount of trials were too little to be able to compute a trustworthy mean. Therefore, both the traditional and the robust method will be used in order to get a better understanding of post-error slowing.

Figure 2

CCEC Trial Sequences



Post-Error Accuracy and Post-Correct Accuracy.

A significant difference between Post-Error Accuracy (PEA) and Post-Correct Accuracy (PCA) would mean that the (possible) slowing down of a participant after making an error would lead to getting an accurate response on the next trial. PEA was calculated by dividing the amount of times an error was followed by a correct response (EC) by the total amount of errors. PCA was calculated by dividing the amount of times a correct response was followed by another correct response by the total number of correct responses. PCA and PEA were also computed for each participant on the different event rates.

Task manipulation

To validate whether the task manipulation was successful, a comparison of the mean reaction times (MRTs) per event rate was made through a Repeated Measures ANOVA. To check whether this measure was appropriate, assumptions were checked. For normality, a Shapiro Wilk test (Shapiro & Wilk, 1965) was conducted and it evidenced a violation in the distribution of the fast condition ($p = .01$). According to the Central Limit Theorem, when the sample size is large enough ($N > 30$, with the current sample being $N = 46$), sample means tend to be well-approximated by a normal distribution despite the data not being normally distributed (Kwak & Kim, 2017). For sphericity a Mauchly's sphericity test (Mauchly, J. W., 1940) was performed and revealed evidence for a violation of sphericity ($p = .033$) which was then corrected for with a Huynh-Feldt correction.

Hypothesis 1: ADHD and Effort Allocation

To look at the interaction between effort allocation and ADHD, a Repeated Measures ANCOVA was conducted. The within subjects variable consisted of the MRTs registered per person and further divided into the three levels (these were then attributed the event rate conditions: slow, medium and fast). Then, the ADHD index t-scores of the participants were added as a covariate (note that none of the assumptions changed substantially from the task validation ANOVA).

Hypothesis 2: Effort Allocation and Error Monitoring

Firstly, a Repeated Measures ANOVA was conducted with PES (traditional) introduced for each event rate as within subjects variables. These variables consisted of correctness with two levels (EC and CC) and event rate with three levels (fast, medium and slow). When assumption checking, normality seemed to be violated for two conditions (see Appendix B). The sphericity check indicated evidence for a violation of such with a significant p-value ($p < .05$). This was corrected with Huynh-Feldt (Appendix B).

Secondly, a Repeated Measures ANOVA was conducted for PES (robust) which included event rate as a within subjects variable with levels fast, medium and slow (note the assumptions of normality did not differ from the previous ANOVA). Additionally, no evidence for a violation of sphericity was found (Appendix B).

Lastly, to investigate the PEA and PCA, a Friedman's Two-way Analysis of Variance by Ranks, was conducted. This was the most appropriate option for the variables of this research since they reported severe violations of both normality and sphericity (Appendix B).

Hypothesis 3: ADHD, Effort Allocation, Error Monitoring

For this hypothesis a similar analysis was conducted as the one for hypothesis 2. The reason for this lies in the addition of the covariate of ADHD indexes which affects all reported effects (see Thomas et al., 2009, for a detailed explanation). Hence, for traditional PES, a repeated measures ANCOVA was carried out with the unique addition of a covariate (CAARS ADHD index t-scores; note assumptions for this ANCOVA resembled the ones for the ANOVA previously conducted for traditional PES, see Appendix C).

Secondly, for the robust PES, each event rate condition was introduced as 1 within subjects variable with levels fast, medium and slow with the addition of a covariate (CAARS ADHD index t-scores). There was no evidence for a violation of sphericity ($p = .181$).

Lastly, for PEA and PCA a repeated measures ANCOVA was performed with the within subject variables being event rate (fast, medium and slow) and correctness (EC and CC). The covariate added was CAARS ADHD index t-scores. Significant violations of normality and sphericity were found with the latter being corrected for with a Greenhouse-Geisser correction (Appendix B).

Results

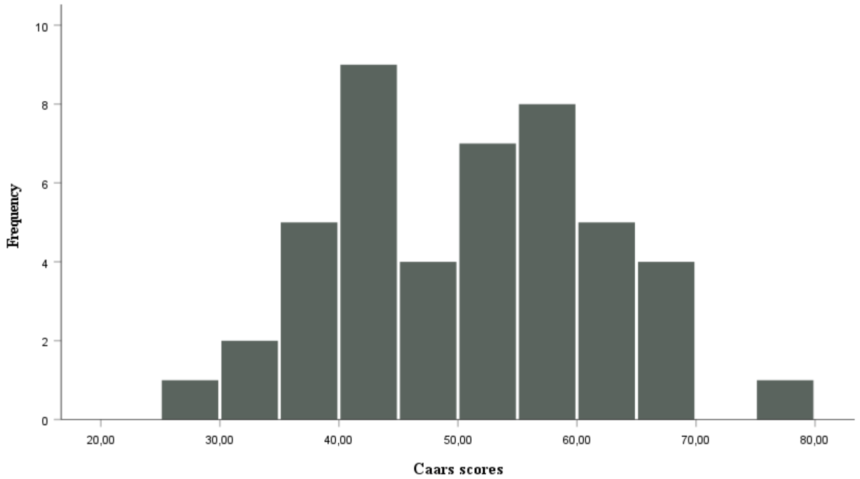
Descriptive Data

From the 46 participants, 3 mentioned having been diagnosed with ADHD. In order to see whether these extreme expressions of ADHD symptomatology impacted the data analyses two versions of all tests were conducted. With no significant differences, the people with ADHD were included in the data analysis. A visual analysis as well as statistical analysis of the ADHD score distribution (Figure 3) confirmed the CAARS data to be normally distributed (*p* = .62). Furthermore, the mean score on the CAARS was 49.27 (*SD* = 10.03) overall and specifically 48.10 (*SD* = 9.41) for females and 51.28 (*SD* = 11.01) for males.

With the number of errors per event rate condition (Table 1), the error rates were calculated. It is worth to mention that in the slow condition, unlike the other two, a total of 10 participants committed no errors. Implications of these numbers will later be addressed (find illustrative bar plot in Appendix A).

Figure 3

Frequency table of CAARS scores



Note. The maximum score registered was of 77.9 and lowest score of 29.8.

Table 1

Number of Correct and Incorrect Trials per condition

Event Rate	Correct Trials	Incorrect Trials	
		Omission	Commission
Slow	1131	44	159
Medium	2489	40	418
Fast	3759	65	683
Total	7379	149	1260

Note. Incorrect trials equate to errors.

Task Validation

To test how performance differs on the three conditions of effort allocation, a manipulation check was performed. The results of the Repeated Measures ANOVA were significant (Repeated Measures ANOVA: $F_{(1.81)} = 26.59, p = <.001, \eta^2p = .37$; see Table 2 for pairwise comparisons;). Significant results in the pairwise comparisons between MRTs of all three conditions, indicate a successful manipulation of all three conditions.

Table 2

Pairwise Comparisons MRT

Event rate	Mean difference	*SE*	*p* **
Fast-Medium	-131,76*	29.9	<.001
Medium-Slow	-83,11*	29.9	.018
Slow-Fast	214,87*	29.9	<.001

Note. Based on estimated marginal means
* The mean difference is significant at the .05 level.
**Adjusted for multiple comparisons: Tukey.

Effort Allocation x ADHD

The results of the Repeated measures ANCOVA showed insignificant differences between MRTs for both the main effect (event rate) as well as interaction effect (event rate * ADHD) (Event rate [$F_{(1.81)} = 2.54, p = .091$]; Event rate *ADHD [$F_{(1.81)} = 0.49, p = .593$]).

Error Monitoring x Effort Allocation

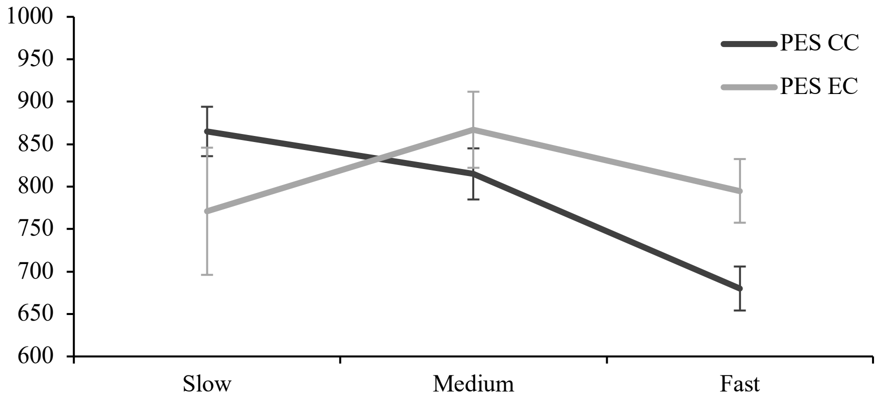
Traditional PES

The Repeated measures ANCOVA indicated a significant interaction effect (Correctness * Event rate [$F_{(1.47)} = 4.19, p = .029, \eta^2_p = .09$]) but insignificant main effects

(Correctness [$F_{(1)} = 0.91$, $p = .345$]; Event rate [$F_{(1.58)} = 3.19$, $p = .057$]). However, the main effect of event rate condition reported a p-value on the cusp of significance with a medium effect size ($\eta^2_p = .07$) (reference levels based on Cohen, 1988; in which small: $\eta^2_p = .01$, medium $\eta^2_p = .06$, large $\eta^2_p = .14$). Additionally, the interaction effect also reported a medium effect size drawn from the partial eta squared (see Figure 4).

Figure 4

Distribution of the MRTs of the Traditional PES per condition



Robust PES

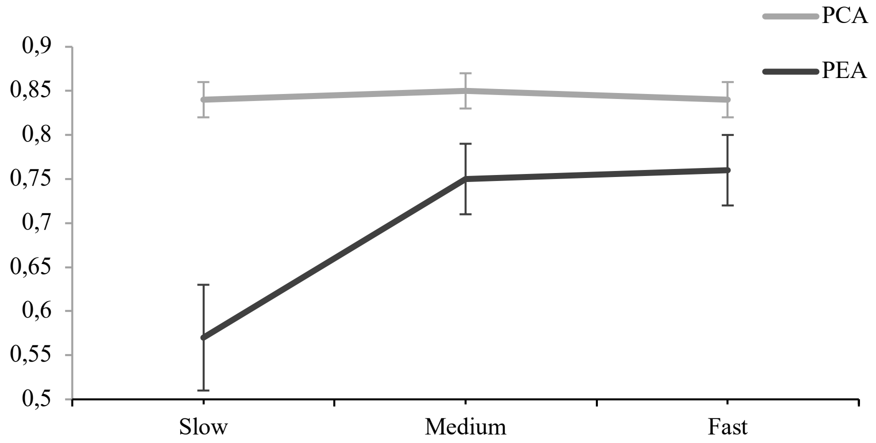
The ANCOVA reported insignificant differences between the different conditions for robust PES ($F_{(2)} = 0.24$, $p = .785$, $\eta^2_p < .001$). Thus, there is little evidence to support the presence of post-error slowing in the different conditions.

PEA and PCA

The results of Friedman's two-way analysis of variance by ranks were insignificant ($X^2_{(5)} = 2.56$, $p = .767$). However, a visual analysis of the mean distribution of PCA and PEA per condition, reveals a tendency towards increasing post-error accuracy as a function of increasing task condition interstimulus speed (Figure 5).

Figure 5

Distribution of PEA and PEA per condition



Effort Allocation x Error Monitoring x ADHD

Traditional PES

The Repeated Measures ANCOVA for the traditional PES with corrected *df* (Greenhouse-Geisser correction; see Abdi, 2010; and Greenhouse & Geisser, 1959) indicated insignificant results (Correctness*Event rate*ADHD [$F_{(1.47)} = 0.62$, $p = .492$, $\eta^2_p = .01$]).

Robust PES

The repeated measures ANCOVA (Event rate: $F_{(1.98)} = 0.15$, $p = .856$; Event rate * CAARS: $F_{(1.98)} = .795$) showed insignificant differences on robust PES between conditions with CAARS as a covariate.

PEA and PCA

The results of the Repeated Measures ANCOVA revealed insignificant results (Correctness*Event rate*ADHD [$F_{(1.38)} = 0.48$, $p = .553$, $\eta^2_p = .01$]).

Discussion

As evidence increases in support of the State Regulation Model to explain some of the deficits present in those with ADHD, so does the need to further understand its practical implications. Little research has been conducted to understand how impaired effort allocation in people with ADHD affects their performance. Moreover, the connection between tasks that require higher effort demands and error monitoring needs more investigating. The present paper attempted to understand this connection through the administration of a task-switching paradigm as well as a symptom severity questionnaire (CAARS). In addition, it added onto previous literature by utilizing a novel calculation method for the post-error slowing, as part of error-monitoring (Dutilh et al., 2012).

Hypothesis 1: ADHD and Effort Allocation

The first hypothesis stated that people with higher ADHD indexes would show poorer performance in the slow condition of the task than people with lower ADHD indexes. This effect was supported by evidence. In fact, the analysis revealed no evidence for a difference in performance on the different conditions as a function of ADHD symptom levels. These results were in line with the findings of Raymaekers et al., 2007, who also found no performance decline between conditions as a function of ADHD symptoms. Like the research mentioned, the present study classified ADHD symptoms according to the DSM-IV and not the DSM-III-R, which the State Regulation Model was derived upon. An influence regarding ADHD subtypes may have had an influence. Especially since most studies on the state regulation model used children and the inattentive symptoms of ADHD tend to persevere into adulthood in comparison to the hyperactivity/impulsivity symptoms (Biederman et al., 2000).

However, these results also contradict multiple research papers on the state regulation model and performance of people with ADHD in different event rate conditions (Borger & Meere, 2000; Metin et al., 2017; Van der Meere et al., 2009; 2010; Wiersema et al., 2005;

2006). Two potential explanations for this arise. Firstly, there is the possibility that the task demands of the slow condition were far too accessible to spark a need for increased effort. This can be argued as the number of participants who committed no errors was high (10 in 46, find in Appendix A corresponding figure). Shiels & Hawk (2010) illustrate how increasing task difficulty results in higher error rate and thus, lower performance. In this way, absence of any errors in the performance of 10 participants is in line with an insufficiently demanding task.

Secondly, ADHD levels may not have been high enough to impair the participants' performance. According to the State Regulation model, people with ADHD should perform similarly to neurotypical populations in the medium condition with differences mostly on the slow condition (Sergeant et al., 1999; van der Meere, 2002; 2005). However, as this study utilizes a dimensional approach to ADHD, only three participants displayed levels of ADHD symptoms that would be classified as "at risk of receiving an ADHD diagnosis". In this way, the severity of the ADHD symptoms in the participants with higher levels, was still below clinically significant levels and may not have affected their performance significantly (Drescher et al., 2021).

Hypothesis 2: Effort Allocation and Error Monitoring

The second hypothesis, which states that there should be a higher use of error monitoring (as evidenced by increased PES) in cognitive demanding conditions (fast) was partly supported by the results. As evidenced by the significant interaction effect, the traditional form of calculating PES indicated that error monitoring appeared to be absent in more accessible condition (slow) than more demanding ones (fast). In this way, as cognitive demands increase, the individuals need to evaluate their performance and consequently change it. Nevertheless, the same significance was not found for the other form of PES calculation (robust). In addition, despite a tendency towards the predicted effect, the analysis of PEA and PCA was insignificant. Additionally, limitations of both PES measures must be taken into consideration.

The traditional form of computing PES gives way to confounding variables (spurious post-error slowing and spurious post-error speeding, see Dutilh et al., 2012) which reduce its validity. Nevertheless, although Dutilh et al.'s (2012) solution (robust PES) is overall a better and more viable option, this particular research included a reduced number of trial sequences. This is due to the limited sample size and sample characteristics (university students). That leads to a reduced validity just like the traditional measure. Very little research is available on the connection between the state regulation model and error monitoring. Despite multiple comparisons between ADHD participants and typically developing participants, only Araujo et al. (2015) has seemingly investigated a solely neurotypical population on error monitoring abilities over event rate conditions. Their findings were in line with the ones of the traditional PES measure in this paper. Thus, with shortcomings on both measures, this hypothesis can only be partly supported. For future replications it is advised to increase number of trials per condition as to maximize the occurrence of robust PES, as it is argued to provide the study higher internal validity.

Hypothesis 3: ADHD, Effort Allocation, Error Monitoring

The third hypothesis stated that individuals with higher levels of ADHD should display impaired error monitoring in the slow condition in comparison to the medium condition. The evidence collected did not support the expected effect. The ADHD levels of the participants did not explain the differences in performance throughout conditions nor the correctness of their answers. A multitude of studies have shown a significant impact of ADHD on both error monitoring and effort allocation (see Balogh & Czobor, 2014, for metanalysis). Thus, the main possible explanation for the opposing results regards the insufficiently high levels of ADHD displayed by the participants. Furthermore, the current sample consisted solely of University students. This particular population may not be representative of the general adult population. This is due to their high academic achievements which demand adaptive mechanisms that allow them to be high functioning (Suhr et al., 2011). Thus, the reported results cannot draw implications for clinical settings. Regarding future research on this connection, it is advised that general adult populations be researched. Furthermore, a bigger sample may also result in significant interactions.

Limitations

This study was not without limitations. Firstly, the relatively small sample size reduced the study's power. Recruiting more participants may solve this problem. Furthermore, the evaluation of ADHD symptoms relied solely on self-report measures. These types of measures tend to have problems regarding face validity (Suhr et al., 2017), especially when participants are asked to report symptoms in retrospect (Harrison, 2007; Murphy et al., 2000). Moreover, as mentioned in hypothesis 2, the relatively reduced number of CCEC trial occurrences, as a result of a limited number of overall trials, originated concerns regarding validity of the robust PES. This problem can be solved by increasing the total number of trials particularly in the slow condition. With an understanding that such solution will also increase the task duration, financial compensation may be added as a form of motivation booster.

Conclusion

In sum, this study did not collect sufficient evidence supporting an impact of ADHD symptoms on error monitoring or effort allocation. However, it supported in part an effect of effort allocation on error monitoring abilities. Hence, this paper contributes to the understanding of how varying levels of ADHD experienced by the unique population of university students impact their effort allocation and error monitoring abilities. Lastly, it adds to the growing view of ADHD as a dimensional construct rather than categorical.

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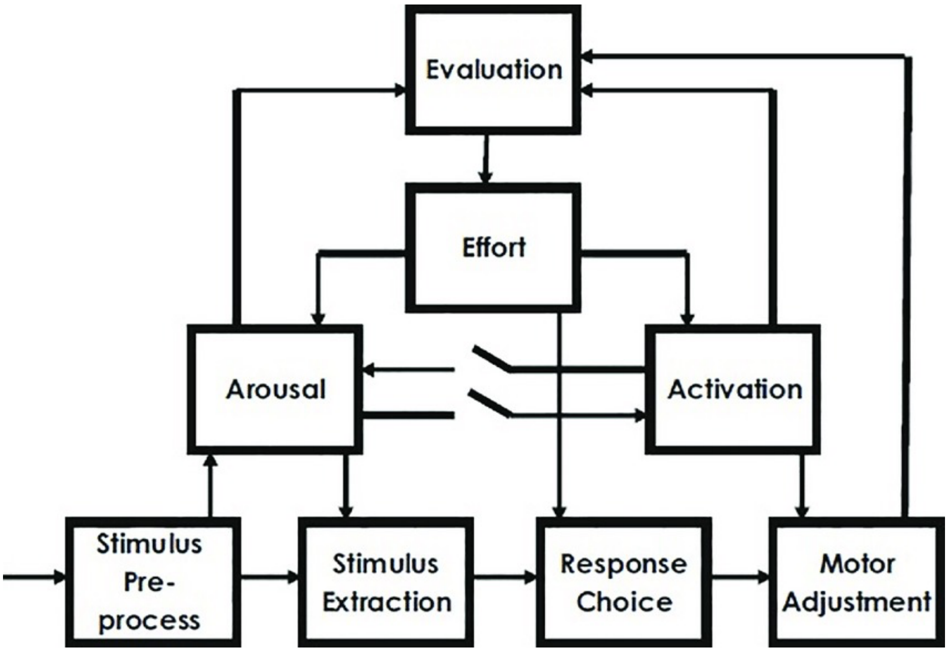
Appendix A

Figure A1

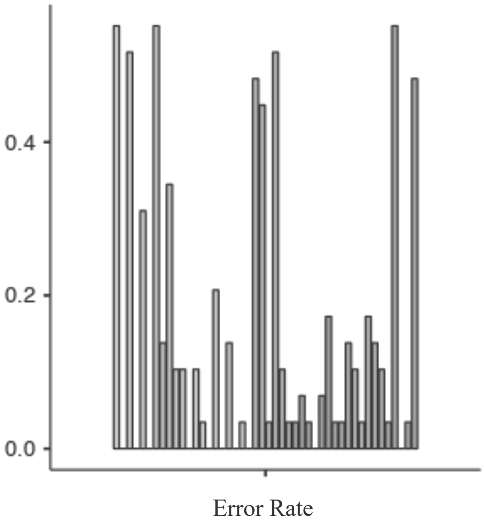
State Regulation Model



Note. This figure was retrieved from Wiersema & Godefroid (2018) as an illustration of the State Regulation Model.

Figure A2

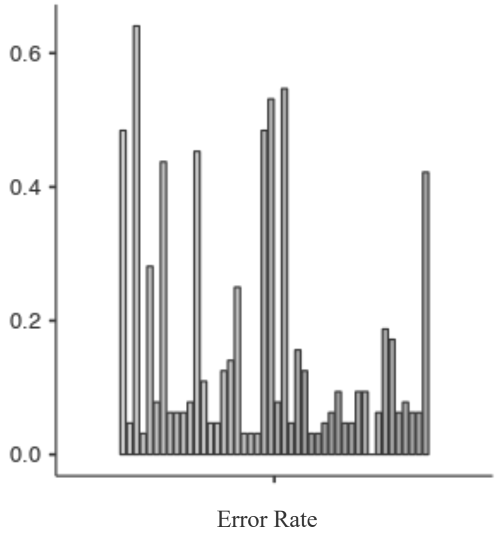
Bar plot of Error rates per participant on the slow condition



Note. Each bar accounts for the error rate of a participant.

Figure A3

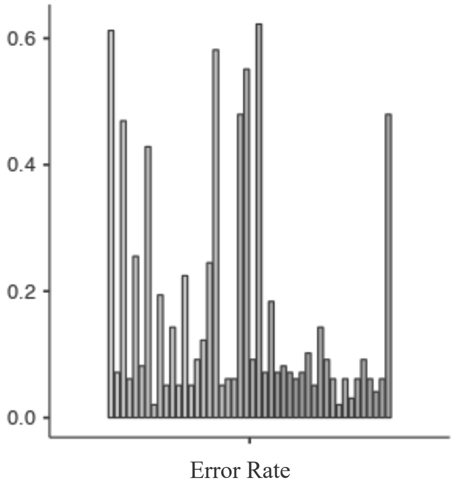
Bar plot of Error rates per participant on the medium condition



Note. Each bar accounts for the error rate of a participant.

Figure A4

Bar plot of Error rates per participant on the fast condition



Note. Each bar accounts for the error rate of a participant.

Table A1

Test for sphericity for MRT

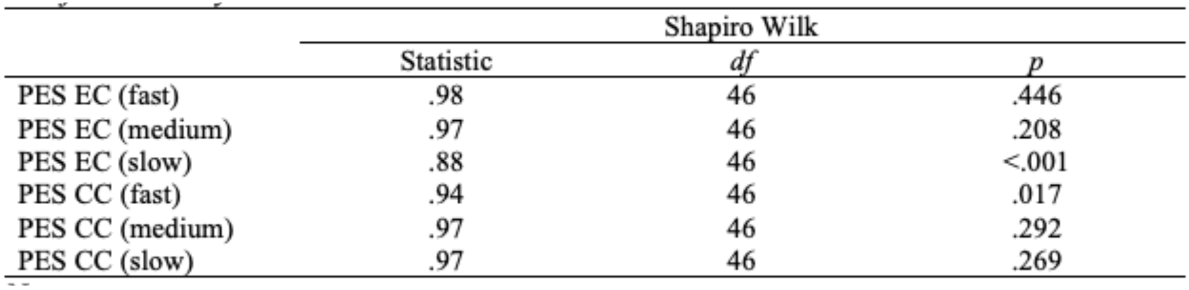
	Mauchly's *W*	*p*	Greenhouse-Geisser *ε*	Huynh-Feldt *ε*
Event rate	.86	.033	.87	.91

Note. With an ε > .75, the correction of Huynh-Feldt (ε = .91) was deemed most appropriate as it has been argued to provide more efficient and powerful approximations (Abdi, 2010; Field, 2013; Howell, 2002).

Appendix B

Table B1

Test for normality of PES traditional measure



	Shapiro Wilk		
	Statistic	*df*	*p*
PES EC (fast)	.98	46	.446
PES EC (medium)	.97	46	.208
PES EC (slow)	.88	46	<.001
PES CC (fast)	.94	46	.017
PES CC (medium)	.97	46	.292
PES CC (slow)	.97	46	.269

Table B2

Sphericity test for Repeated Measures ANCOVA for MRT and ADHD index

	Mauchly's W	*p*	Greenhouse-Geisser *ε*	Huynh-Feldt *ε*
Event rate	0.85	.004	.87	.9

Table B3

Sphericity test for traditional PES

	Mauchly's W	*p*	Greenhouse-Geisser *ε*	Huynh-Feldt *ε*
Correctness	1	-*	1	1
Event rate	.73	.001	.79	.81
Correctness * Event rate	.64	<.001	.74	.75

Note. * The repeated measures has only two levels. The assumption of sphericity is always met when the repeated measures has only two levels.

Table B4

Test for normality of robust PES

	Shapiro Wilk		
	Statistic	*df*	*p*
PES Robust (fast)	.98	46	.522
PES Robust (medium)	.97	46	.171
PES Robust (slow)	.88	46	<.001

Table B5

Sphericity test for robust PES

	Mauchly's W	*p*	Greenhouse-Geisser *ε*	Huynh-Feldt *ε*
Event rate	0.924	.177	.93	.97

Table B6

Test for normality of PEA and PCA per condition

	Shapiro Wilk's *p*
PCA (slow)	<.001
PCA (medium)	<.001
PCA (fast)	<.001
PEA (slow)	<.001
PEA (medium)	<.001
PEA (fast)	<.001

Appendix C

Table C1

Test for sphericity for Robust PES with CAARS index

	Mauchly's *W*	*p*	Greenhouse-Geisser ε	Huynh-Feldt ε
Event rate	.92	.181	.93	.99

Table C2

Test for sphericity for the traditional PES with CAARS index

	Mauchly's *W*	*p*	Greenhouse-Geisser ε	Huynh-Feldt ε
Event rate	.725	<.001	.78	.81
Event rate * Correctness	.636	<.001	.73	.75