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Fluctuation Patterns of Autonomic Arousal Predict Mental Arithmetic Performance

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LAKE FOREST COLLEGE

Senior Thesis

Fluctuation Patterns of Autonomic Arousal Predict Mental Arithmetic Performance

by

Krista A. Meuli

April 15, 2018

The report of the investigation undertaken as a
Senior Thesis, to carry two courses of credit in
the Neuroscience Program

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	Anne E. Houde
	Richard Fisher

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Pupil dilation, an autonomic arousal response, can measure attention because pupil dilation positively correlates with attention. This study investigated the predictability of mental arithmetic performance from pupil dilation fluctuation patterns of 11 college students. Arithmetic problems consisted of basic addition and varied in difficulty. The mental arithmetic task was administered while recording pupil dilation at 60 Hz with an ISCAN eye tracker. A pupil diameter baseline was measured before problems. Patterns of pupil diameter change from the baseline over time were analyzed by difficulty and performance. A marginal effect of Difficulty, marginal effect of Performance, and significant effect of Time on Pupil Dilation change were observed. Both Time by Difficulty and Time by Performance interacted significantly. However, Difficulty and Performance did not interact. These findings support the conclusion that attention increased over time during mental arithmetic problems. Furthermore, attention over time increased more on difficult problems and on correct problems.

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Introduction

Overview

Despite the crucial role that attention plays in basic cognitive functions and in conditions such as Attention Deficit/ Hyperactivity Disorder (ADHD), it remains poorly understood. Nevertheless, attention has been a major topic of research in neuroscience and psychology. First, previous studies on attention have established multiple components and models of attention. Theories of attention, such as the capacity theory proposed by Kahneman (1973), suggest voluntary attention can be selective and divided, though there is a limit on the total capacity. These theories are supported by research on the neuronal networks of attention. However, tasks used in attention research have often been designed to test specific components of attention, and as a result may not reflect attention tasks encountered in real life. Secondly, more recent studies have shown that mental arithmetic is a useful task for studying attention. Mental arithmetic is a common working memory task that requires attention to be successfully completed. Studies on attention that have administered mental arithmetic tasks have done so because solving mental arithmetic engages attention and performance can be clearly measured. Thirdly, a major barrier to better understanding attention has been the difficulty of developing accurate and tangible measures of attention. Previous research has found fluctuations in attention to correlate with measures of pupil dilation (i.e., pupillometry), which is an autonomic arousal response. The cognitive regulation of pupil dilation is thought to occur through Locus coeruleus norepinephrine pathways, which regulate arousal. Greater increases in pupil dilation have been associated with engagement in more difficult tasks, while smaller increases in pupil dilation have been related to inattention during attention tasks.

The goal of this study was to provide insight to the mechanisms of attention and establish an effective tool for investigating attention and dysfunctions of attention. This study used pupillometry to investigate if fluctuation patterns in pupil dilation, thought to reflect changes in attention, over time can predict performance on mental arithmetic problems. To this end, a mental arithmetic task was developed based on tasks used in previous studies and fourth grade education standards to ensure the 12 college students recruited would be able to solve all problems. The time-constrained task contained 40 basic addition problems. Problems were designed with varying levels of difficulty, in which more difficult problems involved carrying. The mental arithmetic task was administered while recording pupil dilation at 60 Hz with an ISCAN eye tracker and recording response latency. Between each problem, a baseline pupil dilation was recorded. Patterns of pupil diameter change over time from the baseline were compared based on problem difficulty and problem performance.

Attention

The elusive concept of attention has long been studied by scientists, who have attempted to define it in various ways. In his book *Principles of Psychology* (1890), William James, an early psychologist who is attributed with establishing psychological research on attention, described attention as “the taking possession of the mind, in clear and vivid form, of one out of what seem several simultaneously possible objects or trains of thought” (as cited in Sternberg, 2008, p. 188). Today, scientists still lack a clearer, more concrete, scientific definition of attention than William James provided, despite the abundance of research on the topic in psychology and neuroscience (Sternberg, 2008). However, scientists have identified and defined many subtypes of attention that describe ways attention can be utilized. Many of these subtypes are operational definitions that describe the tests used to measure them.

Selective attention. Selective attention refers to the ability of subjects to consciously perceive or attend to a small subset of stimuli, or aspects of simulation, over the many other stimuli exciting the sensory nervous system at any moment (Kahneman, 1973; Pinel & Barnes, 2014). This means that certain individual stimuli are receiving attention over others, which is essentially the core definition William James proposed in his 1890 book, *Principles of Psychology* (as cited in Sternberg, 2008, p. 188). Therefore, the way scientists define selective attention has not changed significantly for over a century. This selection of attention can be involuntary or voluntary. Involuntary selective attention refers to a selective process that results in an involuntary surge of effort to process the stimulus (Kahneman, 1973). This type of attention is called exogenous attention because something external drives us to attend to a specific stimulus (Pinel & Barnes, 2014). Voluntary selective attention, also known as endogenous attention, is an intentional exertion of effort to process selected stimuli because they are relevant to a task that the subject chose to complete (Kahneman, 1973). According to Breedlove, Watson, and Rosenzweig (2010), voluntary selective attention originates from within and under conscious control. Therefore, voluntary selective attention is considered a top-down process. A top-down process is one in which higher-order cognitive processes, which often involve conscious control, are in control of lower-order processes (Breedlove et al., 2010). Evidence of the top-down process of voluntary attention is presented later when discussing the neuroanatomy of attention. Voluntary and involuntary selective attention behaviors relate to two different pathways of attentional control. Voluntary selective attention describes a top-down pathway where cognitive mechanisms control attention; involuntary selective attention describes a bottom-up pathway where external factors control attention.

Tasks that have been developed to evaluate voluntary selective attention often support this top-down process (Goldstein & Brockmole, 2014; Kahneman, 1973). For example, Goldstein and Brockmole (2014) described common selective attention tasks that measure reaction time to the onset of a stimulus as an indicator of selective attention to the task. Reaction time is the measure of time from the onset of a stimulus to a response to a task. Reaction time tasks are often a lower-order process, in which the response involves simple behavior, such as a push of a button, an eye-movement toward the stimulus, or verbal indication. However, these tasks have been thought to reflect voluntary attention as this is the higher-order process thought to regulate the lower-order response processes (Goldstein & Brockmole, 2014). This means that the higher-order process of selecting to attend to the stimulus is necessary for the initiation of a response to occur. Voluntary selective attention is an abstract construct that is difficult to measure directly. Therefore, concrete measures of behaviors, like reaction time, that cannot occur without voluntary selective attention preceding the behavior are important measures that provide an indication of voluntary selective attention.

Models of selective attention. Several models for how selective attention works have been debated, some of which have been more widely accepted than others. Most models of selective attention have involved a bottleneck stage, which is a stage in processing where the many available stimuli are eliminated and only a few stimuli continue to be processed at a higher level. However, the various models with a bottleneck stage differ in the exact locus of the bottleneck within the processing stages. Debate still continues as to what type of model most accurately pinpoints the correct stage where a bottleneck occurs. Two bottleneck models that have been proposed are the Filter Theory bottleneck model and another, which can be thought of as the perceptual analysis bottleneck model (Kahneman, 1973). Other phenomenon of selective attention, such as the cocktail party effect and inattentional blindness refer to the heightening of attentional selectivity and the failure to notice unattended stimuli, respectively.

The general concept proposed in bottleneck models is that attention to stimuli as they flow through the processing pathway mirrors water being poured out of a long-necked bottle. In this analogy, all the present stimuli are comparable to the water at the bottom of the bottle, where the bottle is largest. However, as the water, or stimuli, begins to be poured out it enters the bottleneck, where only a small fraction of the water in the bottle can enter at a time. The small fraction of water entering the bottleneck at any given time represents the select stimuli important enough to pass on sensory messages to the brain for complex processing. As the water moves up the bottleneck the diameter of the bottleneck narrows, allowing less water to pass through, until ultimately only a very small amount, with respect to the entire volume of water, is able to be poured out of the bottle at a time. The narrowing of the bottleneck simulates the increasingly strict selection of stimuli to move to the next stage for higher-level processing. Finally, the few stimuli important enough to be poured out of the metaphorical bottle are those that enter conscious awareness. Though the bottleneck model is one of the most widely assumed models of attention in modern research, as Kahneman (1973) stated, much controversy exists over the precise step at which stimuli are weeded out and the number of stimuli able to progress through the elimination process (Kahneman, 1973).

Kahneman (1973) reviewed two common bottleneck models, the Filter Theory bottleneck and another, which can be considered the perceptual analysis bottleneck, which provide a deeper explanation of how bottlenecks work. The Filter Theory bottleneck, according to Kahneman (1973), proposed that multiple stimuli reach sensory registration but only a single stimulus can enter perceptual analysis at a time. However, the Filter Theory bottleneck has not been supported by research on divided attention. Despite divided attention generally lowering performance on tasks, previous research has established that parallel processing of simultaneous stimuli can sometimes occur with minimal interference and, in other instances, with significant interference that impairs efficiency (Kahneman, 1973). Parallel processing refers to two or more stimuli being processed at the same time through the same processing pathway. The Filter Theory proposes that parallel processing cannot occur, which contradicts the evidence of divided attention. The second common bottleneck structure that Kahneman (1973) described, the perceptual analysis bottleneck, suggests multiple stimuli can enter the perceptual analysis stage, but only a few stimuli can enter higher-level processing, like response selection. The perceptual analysis bottleneck proposes parallel processing does occur. The previous divided attention research that Kahneman (1973) used to discount the Filter Theory, supported a process more similar to the perceptual analysis bottleneck structure, due to the evidence for parallel processing. Though previous findings suggested a perceptual system with more than a single channel for processing, attention was also found to be more unified with higher-level tasks as more effort was required. Furthermore, parallel response selection to simultaneous stimuli on divided attention judgment tasks has been impaired in previous studies that Kahneman (1973) presented. This impairment of parallel response selection on judgment tasks, a higher-level processing task, supports more unified processing of tasks that require complex cognitive functions.

A common result of selective attention, known as the cocktail party effect, describes a phenomenon in which the intensity of selective attention can vary to compensate for distracting stimuli. The cocktail party effect should be thought of as a phenomenon that adds on to the bottleneck model because it still assumes a bottleneck model but is intended to describe how some stimuli are selected over others. Breedlove et al. (2010) refer to the cocktail party effect as the enhancement of selective attention in circumstances with a multitude of distracting stimuli in order to filter out the distractors. This effect is named the cocktail party effect because it can occur in a noisy environment such as a cocktail party. The cocktail party effect describes situations where attention to a single auditory stimulus, a person talking, is enhanced in order to ignore a multitude of other auditory stimuli, noises at a cocktail party (Breedlove et al., 2010). As explained by Kahneman (1973), the cocktail party effect phenomenon appears to result from the tendency to categorize stimuli. In the case of a noisy cocktail party, stimuli may be categorized by the tone of people's voices. In this case, the cocktail party effect allows the selection of stimuli matching one individual's voice, while other voices are filtered out. Similar exclusion of categorized stimuli can be observed in search tasks, such as in visual search tasks where the target object has a specific color, as described in Sternberg (2008). For example, if the target stimulus of a visual search task is green, an enhancement of selective attention for green stimuli can occur. This means distractor stimuli of a different color are filtered out easily, while distractor stimuli of the same green color pose a greater distraction. A larger number of green distractor stimuli would increase the difficulty of the task because the cocktail party effect does not apply. The cocktail party effect is important because it allows attention to be targeted toward stimuli of a particular category to best serve people's needs.

However, increased selective attention to one stimulus, such as with the cocktail party effect, means other stimuli receive less attention. This causes a greater chance for inattentional blindness. Inattentional blindness refers to the phenomenon of failing to perceive a stimulus because it was not attended to, that would otherwise easily be noticed (Breedlove et al., 2010). Previous studies described by Kahneman (1973) have suggested that increased difficulty and complexity of tasks, such as visual search tasks with more stimuli, result in greater inattentional blindness of other non-attended simultaneous stimuli.

Divided attention and mental effort. As suggested by supported bottleneck models of selective attention, described above, multiple stimuli are often simultaneously selected for attention. This causes attention to be divided across all the selected stimuli, which is referred to as divided attention. Divided attention, as defined by Goldstein and Brockmole (2014) is the ability to have conscious awareness of multiple stimuli at the same time. Research on divided attention often utilizes tasks that require subjects to process various stimuli concurrently (Goldstein & Brockmole, 2014).

However, divided attention tasks have been found to have very low performance, as Kahneman (1973) concluded in his review of previous divided attention studies. These findings support divided attention having a limited capacity. Goldstein and Brockmole (2014) described Nili Levi's load theory of attention, which can account for low performance on divided attention tasks. According to Goldstein and Brockmole (2014), the two key concepts of the load theory were cognitive capacity and cognitive load. Cognitive capacity suggests there exists a limit to the number or difficulty of cognitive tasks a person can engage in (Goldstein & Brockmole, 2014). This means that cognitive capacity can be reached when attention is divided among too many stimuli or when even a single selected stimulus is too difficult. Cognitive load is the amount of the cognitive capacity that a particular task requires (Goldstein & Brockmole, 2014). This means that tasks requiring little cognitive load can be completed by individuals who are engaging in other tasks without impairing performance. However, tasks that require a large amount of cognitive load cannot be completed while individuals engage in other tasks because cognitive capacity would be exceeded. In divided attention research, described by Kahneman (1973), that supported a perceptual analysis bottleneck model, cognitive load was a likely mediating factor for tasks where parallel processing interfered with performance versus tasks where parallel processing had minimal interference. When tasks required greater cognitive load, exceeding the cognitive capacity available, at least one if not both stimuli being processed would suffer. However, tasks where cognitive capacity was not reached, both stimuli could be processed with minimal disruption.

Egeth and Kahneman (1975) explained that their capacity theory is comparably more complex than previously mentioned theories of attention. The capacity theory builds off the basic bottleneck idea that there is a limitation on the number of stimuli that can be processed and that can enter conscious awareness. However, the capacity theory allows for more variation in how the maximum is reached. Bottleneck theories only account for the quantity of stimuli that can be processed. In the capacity theory, different stimuli can require varying amounts of cognitive load. The capacity theory also helps explain findings on divided attention, not accounted for in previous models. Several divided attention studies that Kahneman (1973) described found that the task difficulty of one task significantly impacted the performance of the other task. Kahneman (1973) proposed that these findings were a result of difficult tasks requiring greater cognitive load. Therefore, more difficult tasks leave less left-over capacity for other tasks. The number of tasks a person can engage in simultaneously significantly relies on the cognitive load each task requires and how much of the total cognitive capacity is taken up by the combined cognitive loads of all tasks. Therefore, task difficulty and the number of tasks, combined, control performance on tasks.

Egeth and Kahneman (1975) compared their capacity model, illustrated in Figure 1.1, to the well-established process of single stimulus recognition, in which a specific brain structure activates to the onset of the specific stimulus. The role of attention in single stimulus recognition is that attention increases the firing of neurons responsible for recognizing the specific stimulus when presented. Egeth and Kahneman (1975) claimed their capacity model is a larger scale of this process. When presented with a task, the "possible activities" in Figure 1.1, the brain structures involved in processing the task can be activated based on the allocation policy, which can lead to a response activity occurring (Figure 1.1). However, in order for the relevant brain structure to be activated and lead to a response activity, an additional input must come to the brain structure from an attentional network (Figure 1.1). The attentional inputs are limited based on the available capacity determined both by the number of inputs that can be sent and by the amount of attentional input needed for a task (Egeth & Kahneman, 1975).

Maintenance of attention. Many attention tasks require attention to a stimulus to be maintained over a period of time, which is not addressed in the selective and divided attention models described above. According to Breedlove et al. (2010), tasks in which a single stimulus source must be attended and the elevated level of attention to the stimulus must be held for a prolonged period of time, engage sustained attention. Sustained attention is attention that is maintained over time. The term sustained attention is sometimes used interchangeably with vigilance. According to Sternberg (2008), vigilance involves an individual's ability to attend to a field of stimulation over an extended period of time, which is sustained attention. However, Sternberg (2008) also stated that vigilance suggests an individual must also actively try to detect a stimulus. Sustained attention does not denote actively trying to detect a stimulus, which is how the two terms differ. Sternberg (2008) described previous neurological research that has demonstrated that successful signal detection of visual stimuli is most likely when a signal is expected. Greater signal detection performance when a signal is expected suggests that when a stimulus was expected, people would try to detect it. By trying to detect the stimulus people increased their vigilance. Sustained attention, on the other hand, can occur regardless of whether a signal is expected.

Similar to the relationship between selective attention and inattentional blindness to unattended stimuli, vigilance affects detection of stimuli outside of the field of visual attention. Sternberg (2008) referenced previous research that has shown that accuracy decreases dramatically the farther the target stimulus is from the locus of visual attention. The locus of visual attention is the location where vigilance is maintained. Therefore, these findings suggest that stimuli outside of the range of vigilant attention, are significantly less likely to interfere with maintaining attention to the ongoing location. The concept Sternberg (2008) presented, that vigilance requires effort, converges with theories of mental effort, which are key in the intensity of attention.

Intensity of attention. While the types of attention and their models discussed above have established ways of categorizing attention or modeling its distribution, they have failed to consider attention on a scale of intensity. In contrast, when discussing attention colloquially the degree to which one attends to a stimulus is an inherent aspect of attention. Most people recognize they can be aware of stimuli in their environment, such as a conversation, without fully engaging and attending to it. Mental effort refers to the amount of cognitive work done. A greater amount of mental effort leads to more attention to a stimulus. Mental effort, or trying, as Sternberg (2008) described, is necessary for elevating attention through a top-down process, both momentarily and over a period of time. Kahneman (1973) used the term, mental effort, in his theory of attention, to help describe attention as a continuous scale.

Kahneman (1973) presented mental effort as voluntary parallel to the concept of involuntary arousal. The general term "arousal," referring merely to a level of wakefulness, has often been attributed to the fluctuating intensity of involuntary attention. Kahneman (1973) argued that the intensity of voluntary attention is not sufficiently explained by arousal. For voluntary attention, Kahneman (1973) explained, a subject must always be fully awake. Therefore, they suggest that the intensity of voluntary attention is a result of people expending their limited resources, in other words performing work. When people pay more attention, they do more work (Kahneman, 1973). The work being performed is analogous to the concept of cognitive load discussed previously (Sternberg, 2008). However, in order for work to be performed effort must be exerted. The mental effort exerted enables a varying degree of control over attention, Geva, Zivan, Warsha, and Olchik (2013) proposed, which can be observed by behaviors like orienting attention toward targeted stimuli. Kahneman (1973) argued that the amount of mental effort exerted has a physical effect. The physical effect of mental effort can be observed as physiological arousal, which is how cognitive work done can be observed.

Physiological arousal: an effect of attention. Physiological arousal can be observed by several autonomic nervous system responses, such as heart rate variability, skin conductivity, and pupil dilation. Sternberg (2008) described arousal, a physiological measure frequently used by psychologists, as the level of the body's physical excitation and readiness to respond. This means that arousal refers to the state of wakefulness and alertness. However, Kahneman (1973) stated that this readiness to respond to stimuli relates to the intensity of involuntary attention. On the other hand, Kahneman (1973) also described physiological arousal as an effect caused by mental effort. Previous research reviewed by Kahneman (1973) has repeatedly established that momentary variations in task difficulty correlate with levels of arousal. Therefore, both involuntary and voluntary attention result in physiological arousal, though the processes causing arousal may be different. Geva et al.

(2013) proposed one way to consider the differences of arousal from involuntary versus voluntary attention, in which arousal was described as a self-regulatory mechanism of alerting and activation. Alerting is the readiness to receive information and activation is the readiness to respond (Geva et al., 2013). This arousal mechanism is compared to a state of preparedness, activated by executing a conscious warning through a higher-order process.

One way to help distinguish the physiological effects of cognitive work and of involuntary arousal would be to compare baseline autonomic arousal measures to autonomic arousal during tasks that require cognitive work. Baseline measures of autonomic arousal would be taken while no activities engaging cognitive work are presented. While internal stimuli that influence involuntary arousal, such as stressful thoughts, cannot be controlled, external stimuli that might influence involuntary arousal can be controlled in laboratory settings. Taking multiple baseline measures throughout an experiment could help account for uncontrollable spikes in involuntary arousal due to internal stimuli.

Neuroscience of attention. ***Neurotransmitters involved in attention.*** There are three main neurotransmitters that have been particularly studied in association with attention: dopamine (DA), serotonin (5-HT), and norepinephrine (NE). Dopamine (DA) is one of the main neurotransmitters found in the brain and involved in the functioning of many different brain structures. However, most DA found in the brain is exclusively produced in either the substantia nigra (SN) or the ventral tegmental area (VTA), which are both structures in the midbrain. The many other brain regions receive DA from one of two major DA pathways. Figure 1.2 shows a diagram of the two main DA pathways. One is the mesostriatal pathway, beginning in the SN and projecting to the basal ganglia and the striatum. This DA pathway is primarily thought to be related to movement functions. The second main DA pathway, the mesolimbic pathway, begins in the VTA and projects to the frontal and prefrontal cortexes, parietal cortex, as well as other brain areas. The mesolimbic pathway is also frequently referred to as the "reward pathway" for its major role in motivation and pleasure. This is also the main DA pathway implicated in attention (Hawi et al., 2015).

Serotonin (5-HT) is a monoamine and another major central nervous system neurotransmitter. Figure 1.3 shows a diagram of the 5-HT pathways in the brain. The main source of 5-HT in the brain are the raphe nuclei, which are located around the reticular formation in the brainstem. 5-HT neurons originating from the lower raphe nuclei project axons to cerebellum and spinal cord, while ones originating from higher raphe nuclei project axons throughout the rest of the brain. The 5-HT pathway has been connected to cognition and low 5-HT levels have been found to impair the maintenance of attention (Cornish & Wilding, 2010).

The third important neurotransmitter involved in attention, norepinephrine (NE), is a catecholamine neurotransmitter, which is widespread throughout the brain (Figure 1.4). However, NE is synthesized in cell bodies of neurons only found in the Locus coeruleus, which is located in the pons of the brainstem. The NE network is primarily involved in arousal and alertness. Cornish and Wilding (2010) described previous research that has associated NE and the NE pathway with executive functioning and selective attention functioning. Executive functions are cognitive processes that are necessary for cognitive control of behavior, such as attentional control, cognitive inhibition, working memory, and planning. The frontal lobe is the primary brain region responsible for processing executive functions.

Neural networks of attention. As a complex, higher-order process, attention is more than a single function and is thought to manifest from the coordination of functions in multiple brain structures and neural pathways. This has led to many proposals of possible attentional networks. Breedlove et al. (2010) described the dorsal frontoparietal system, a cortical network for top-down control of voluntary attention. Breedlove et al. (2010) referenced previous studies that found elevated activity in the dorsolateral frontal cortex, associated with conscious direction of attention, and the intraparietal sulcus, involved in top-down attentional control, during presentation of a stimulus cue. Breedlove et al. (2010) described the different brain areas that these previous studies have found active during target stimulus processing, such as the pre- and postcentral gyrus and visual cortex. The brain areas found to be active during cueing related to higher-order processes, while the brain areas associated with target processing were areas involved with response initiation and stimulus processing, which are lower-order processes. Response initiation was considered lower order processes because responses involved simple motor movements, such as pressing a button. Stimulus processing was considered a lower-order process because stimulus processing simply involves recognizing the stimulus presentation and initiating the instructed response.

Cornish and Wilding (2010) described Posner's attentional network model, which proposes a model for how the different attention areas in the brain are integrated (Figure 1.5). Cornish and Wilding (2010) described three main attention systems of the model. First, a posterior system that regulates orienting was presented. This orienting system involved disengaging focus on a current target stimulus, controlled by the parietal lobe, shifting attention to a new location, controlled by the superior colliculus, and engaging attention to a novel stimulus, related to the pulvinar lobe in the thalamus. The posterior system controls orienting and involves brain areas shown in Figure 1.5 in yellow under orienting. The term "posterior system" may be misleading because structures, such as the frontal eye field, in the frontal lobe are part of the orienting system. The second system proposed was a vigilance network that regulates alerting. This alerting system controlled by the right parietal lobe, the frontal and prefrontal lobes, and the thalamus, which together regulate maintaining and varying alertness. The brain regions involved in the alerting system are shown in Figure 1.5 in red. Cornish and Wilding (2010), referred to the right parietal lobe area involved in alerting as the posterior area. Cornish and Wilding (2010) referred to the frontal and prefrontal lobe areas involved in alerting as the frontal area. Alertness plays a key role in attention, by enhancing efficiency of the posterior system and limiting input to the posterior system from the third system. Cornish and Wilding (2010) referred to the third, anterior system, as a general executing system, which involves the anterior cingulate gyrus, supplementary motor areas, Brodmann area 6, and basal ganglia. The brain regions involved in the executing system are shown in Figure 1.5 as green. According to Cornish and Wilding (2010), the executing system primarily resolves attentional conflict between multiple stimuli and directs other systems to attend to the most important stimuli based on present goals.

The regulation of different components of attention has been related to activation of specific brain regions. For instance, activation of frontal lobe areas has been related to controlling the direction of attention. Activating the right prefrontal cortex has been identified to be essential for sustained and phasic alertness, as well as attention to events and maintenance of information in working memory. Phasic alertness refers to the ability to increase readiness to respond to a stimulus based on external cues. The dorsolateral prefrontal cortex has been related to control of attentional selection and found to activate during changes and divisions in attention, such as when shifting attention from one stimulus to another or shifting attention from one stimulus to multiple stimuli. Selective attention has been found to increase activation in brain areas involved in processing a specific stimulus. For example, increased response activation in visual centers has been found when attention is directed at visual stimuli in comparison to when attention is directed to other sensory stimuli (Cornish & Wilding, 2010). Though these brain areas discussed have been associated with various components of attention, these brain areas have also been related to activities other than attention.

Neural networks related to visual attention. Humans rely most heavily on the sense of sight (Sternberg, 2008). This and the ease of developing tasks has lead the processing of visual stimuli to be studied extensively and be used frequently to investigate the effects of attention on stimulus processing. Research on visual attention typically addresses attention required for searching for, recognizing, and monitoring a visual stimulus. Though the attention task used in the present study mostly engages attention used for problem solving, the stimulus, the arithmetic problem, is presented as a visual stimulus. Therefore, it is important to understand the brain pathways involved in visual processing.

Cornish and Wilding (2010) provided an overview of the visual system and how visual stimuli are processed through two main pathways, the ventral and dorsal streams. The ventral visual stream, also known as the “what” stream, interprets stimuli in part by receiving significant input from parvocellular layers in the lateral geniculate nucleus (LGN), which processes high spatial and low temporal frequencies and distinguishes color wavelengths. This pathway includes the V4 visual area in the prestriate cortex that selectively processes information on color and form, the inferotemporal cortex, and the ventrolateral prefrontal cortex that helps process object features.

On the other hand, the dorsal visual stream, also known as the “where” or “how” stream, receives much of its input from magnocellular layers in the LGN, which are nonselective to wavelength and specifically activate to low spatial and high temporal frequencies. This means that the magnocellular layers of the LGN process information regarding the overall shape and movement of stimuli. The V5 visual area neurons in the extrastriate dorsal areas selectively process motion information and help interpret information on position via the pathway spanning from the posterior parietal cortex to the frontal eye fields and the prefrontal cortex dorsolateral areas. Visual information related to motor activity, and information on gaze direction and object positions relative to the body, have all been found to be processed in the parietal areas to prepare and control responses to objects, especially eye movements (Cornish & Wilding, 2010).

Research has also found attention to affect neural responses throughout the visual streams (Cornish & Wilding, 2010). Some studies have shown evidence that the effects of attentional focus become increasingly pertinent as information passes from the primary visual cortex up the system to the prefrontal areas. This means that these brain areas are more reactive and activate more to stimuli based on the level of attention. This narrowing upward stream of stimuli within the attentional field in the visual processing pathway supports a bottleneck model for selective attention, as discussed previously. The prefrontal areas, for instance, have been found to retain an attentional template of the nature of a target object, such as position, that is then passed on to the parietal and temporal areas that use this information to select targets and initiate actions (Cornish & Wilding, 2010, p. 97-99). This means that the component of the object attended to, in this case position, is passed on from lower level processing to higher level processes, while other components of the object are not processed further.

Several well-studied structures have been implicated in visual processes related to attention. Wolfe, Kluender, and Levi (2011) described observations of the role the superior colliculus has with eye movements between two attended objects. According to Wolfe et al. (2011), gaze pause neurons in the superior colliculus and collicular fixation neurons have been found to have increased firing during eye movements toward a stimulus that is the focus of attention. Wolfe et al. (2011) supported this by referring to findings of previous studies that showed monkeys with unilaterally inactivated superior colliculi lose the ability to utilize selective attention cues presented on the side corresponding with the inactivity.

The frontal eye field (FEF), in the premotor area of the frontal lobes, has many connections to the superior colliculus. Wolfe et al. (2011) associated the connection with the superior colliculus to the importance of the FEF for establishing gaze that is in accordance with one's cognitive goals. This is thought to occur through a top-down process. Wolfe et al. (2011) described the findings of previous studies showing that people with damage to the FEF have resulting difficulty suppressing unwanted reorientation of their eyes towards peripheral distractors. The parietal lobe has been largely associated with covert attentional control. Covert attention refers to attention to a stimulus that matches the visual direction of gaze (Breedlove et al., 2010). The intraparietal sulcus (IPS), which is found in the parietal lobe, has important functions in voluntary attention, through a top-down control mechanism (Breedlove et al., 2010).

Dysfunctions of attention. Since attention requires the coordination of many different brain regions, there are many mental disorders that involve attention deficits. Attention deficits are observed in several developmental disorders. Cornish and Wilding (2010) described the attentional deficits of conditions like Autism Spectrum Disorder (ASD), Fragile X Syndrome, Williams syndrome, and Attention Deficit/ Hyperactivity Disorder (ADHD). ASD is a neurological disorder that affects people's ability to interact with others and to learn. As a spectrum disorder, ASD can present with a variety of symptoms, though communication problems, repetitive behaviors, and intellectual disabilities are some of the most common characteristics (National Institute of Health (NIH), 2018). One of the less common symptoms of ASD is short attention span (Centers for Disease Control and Prevention (CDC), 2015). Fragile X syndrome is a genetic condition characterized by learning disabilities and cognitive deficits. Attention Deficit Disorder (ADD) and ASD are common comorbid diagnoses in people with Fragile X syndrome (National Institute of Health (NIH): U.S. National Library of Medicine, 2018). Williams syndrome is characterized by intellectual disability, distinct facial features, and cardiovascular problems. People with Williams syndrome tend to have advanced language abilities, but difficulty with visual-spatial tasks. ADD is frequently comorbid with Williams syndrome (National Institute of Health (NIH): U.S. National Library of Medicine, 2018). ADHD, which is characterized by attention deficits, hyperactivity, and impulsivity, is considered one of the most common neurodevelopmental disorders (Cornish & Wilding, 2010). Many estimates suggest the lifetime prevalence of ADHD is approximately 5-7% in the U.S. (Polanczyk, Willcutt, Salum, Kieling, & Rohde, 2014). While attention deficits are common in each of the disorders described in Cornish and Wilding (2010), attention deficits are one of the main features of ADHD. Therefore, this discussion on dysfunctions of attention will primarily focus on ADHD.

A history of attention deficits. Attention deficit conditions, the terminology of which has since evolved into what is now called ADHD, were reported already in the 1700's. The earliest reported cases of attention deficits date back to the late 1700's, according to Lange, Reichl, Lange, Tucha, and Tucha (2010). By the early 1900's, theories of the cause for attention deficits and hyperactivity generally pointed to defective moral control, as Lange et al. (2010) described. While modern scientists have largely abandoned these theories of moral deficiency contributing to ADHD, the persisting sentiment relating ADHD with laziness likely remains as a consequence of such early theories.

More recently, editions of the Diagnostic and Statistical Manual of Mental Disorders

(DSM) have been used to define attentional disorders, like ADHD. The DSM III, published in 1968, was the first DSM edition to include diagnostic criteria for "Attention Deficit Disorder" (ADD). In the DSM-III (1968), symptom criteria for ADD focused primarily on attentional deficits that could but were not necessarily accompanied by hyperactive or impulsive symptoms. Additionally, the DSM-III (1968) criteria restricted ADD as a disorder presenting exclusively in childhood, though earlier definitions of attention deficits typically targeted children as well. It was not until the early 1990's that brain imaging research helped debunk ADHD as a childhood disorder that subsided with age (Lange et al., 2010).

Today, the DSM-V recognizes the primary diagnostic criteria for ADHD as patterns of persistent inattention and/ or hyperactivity and impulsivity that interfere with functioning or development (APA, 2013). In contrast to the DSM III, the DSM-V recognizes hyperactivity and impulsivity as independent and equally important symptoms as attention that contribute to ADHD (APA, 2013). The chronic and persistent nature of these symptoms must be evident by presenting in multiple environments. These inattention and hyperactivity symptoms must arise prior to the age of 12 years old, though symptoms can persist into adulthood (APA, 2013). While there is evidence that ADHD symptoms often lessen in severity as patients age and learn to compensate, which could support the DSM-III notion that ADHD is a childhood disorder, Lange et al. assert that ADHD research points to the disorder being lifelong.

Types of attentional deficits in ADHD. Selective attention and maintenance of attention are two of the most prominent attention deficits reported in ADHD (Cornish & Wilding, 2010). Doehnert, Brandeis, Schneider, Drechsler, and Steinhausen (2013) found that children, ages 10-12 years old, with ADHD identified the target stimulus less often than age-matched controls on a continuous performance task, which measured maintenance of attention. Similarly, Koschack, Kunert, Derichs, Weniger, and Irle (2003) found participants with ADHD to have more false-negative responses (i.e. missed detection) on a visual scanning task that tested selective and sustained attention than age-matched controls. However, Cornish and Wilding (2010) noted that selective attention and maintenance of attention impairments are sometimes not observed in simple tasks. For example, Koschack et al. (2003) found no significant difference in error rates on a Go/No go selective attention task or a visual scanning sustained and selective attention task between children with and without ADHD. However, the low error rates in both groups could suggest that the task was too easy, causing a ceiling effect.

Deficits in components of attention, such as cognitive capacity and habituation, have also been associated with ADHD. Research on ADHD and cognitive capacity has found that people with ADHD typically perform poorly on tasks that demand a high cognitive load. Cornish and Wilding (2010) described previous review articles that concluded that all types of working memory were impaired in ADHD. Working memory refers to the mental information held in the conscious mind at one time, and therefore can be considered a component of cognitive load. ADHD has also been associated with decreased attentional habituation of stimuli (Sternberg, 2008). Habituation is the process of becoming accustomed to a continuous stimulus, where attentional processes progressively attend less to a stimulus until it continues unnoticed. This suggests that people with ADHD tend to continue to attend to continuous stimuli to a degree more similar to the degree of attention when the stimuli were novel than healthy individuals. If ADHD patients have a consistent deficit of habituation, it could be inferred that ADHD patients might to some extent constantly attend to environmental stimuli that healthy individuals can ignore through habituation.

Neuroscience of ADHD. The neural mechanisms that lead to ADHD remain relatively unknown. However, research reviewed by Hawi et al. (2015) suggested a consensus that reduced dopamine signaling plays a key role in the expression of ADHD symptoms, including impulsivity, inattention, and/ or hyperactivity. This dopaminergic circuitry, as reviewed earlier, consists of two major dopaminergic pathways, the mesolimbic and mesostriatal pathways. These dopaminergic circuits are commonly associated with attentiveness and impulse control, respectively. The mesostriatal pathway is composed of neurons whose cell bodies originate in the substantia nigra (SN) that project to regions like the striatum and are essential for motor movement. The mesolimbic pathway, consisting of neurons that originate in the ventral tegmental area (VTA), projects to regions like the nucleus accumbens and frontal cortex. Proper development of both the mesolimbic and mesostriatal circuits ensures that important environmental cues are paid attention to and that movements and behaviors are controlled appropriately.

Hawi et al. (2015) described the findings of previous studies that showed numerous ways in which the dopaminergic pathways can be disrupted by genetic abnormalities. These abnormalities result in reduced or altered dopamine throughout the mesolimbic and mesostriatal pathways. This is thought to lead to decreased function of the frontal cortex, causing inattentive and impulsive behavior and dysregulation of striatal dopamine, leading to the hyperactive symptoms of the disorder (Hawi et al., 2015).

Rivero, Sich, Popp, Schmitt, Franke, and Lesch (2013) investigated a potential ADHD risk gene, Cadherin-13, found in catecholaminergic cell clusters in the Ventral tegmental area (VTA) and Locus coeruleus (LC). As mentioned previously, the VTA is the origin of the mesolimbic dopamine pathway and the LC is the origin of the norepinephrine pathway in the brain. The norepinephrine pathway is primarily responsible for alerting and arousal. Dopamine neurons of the VTA and norepinephrine neurons of the LC project to many brain regions, influencing functions that are key in ADHD symptomology (Rivero et al., 2013). Not only did this provide support for Cadherin-13 being implicated in ADHD, but it further established the importance of the LC in ADHD. As discussed later (cf. "Pupillometry"), the LC is believed to have a major role in the regulation of pupil dilation in response to cognitive function. Therefore, pupil dilation patterns during cognitive tasks, such as mental arithmetic, may be affected in ADHD.

Mental Arithmetic

The ability to perform arithmetic computations performed in the head without aid from writing figures or using a calculator, mental arithmetic, is an important skill developed in modern education and utilized in various everyday situations. Mental arithmetic incorporates complex cognitive processes, such as working memory, executive functions, and attentional control (Iglesias-Sarmiento, Deaño, Alfonso, & Conde, 2017). Iglesias-Sarmiento et al. (2017) described the cognitive steps needed in mental arithmetic problem solving, which are understanding arithmetic operations, understanding and manipulating the numerical relations, understanding the type of arithmetic problem based on operations, and applying strategies to solve the problem. However, the exact mechanisms by which the cognitive steps of mental arithmetic problem solving are accomplished are not well understood.

Research on the cognitive mechanisms underlying mental arithmetic and mental arithmetic performance is important due to the significant role of mathematics in modern life and the high rates of learning difficulties in mathematics. Tosto, Momi, Asherson, and Malki (2015) described the importance of mathematical abilities in education, noting that mathematical training accounts for a significant part of modern education. Furthermore, mathematical ability is an important predictor of educational duration and socio-economic status (Tosto et al., 2015), which further emphasizes the importance of mathematical ability.

According to Iglesias-Sarmiento et al. (2017), approximately 3.6-9.8% of U.S. school children have difficulties in mathematics. Understanding the cognitive mechanisms involved in mental arithmetic and cognitive influences on mental arithmetic performance could provide insight on difficulties in comprehension and learning of mathematics.

Mental arithmetic tasks. Mental arithmetic tasks can be effective tasks for studying attention. Mental arithmetic tasks have frequently been utilized as working memory tasks in scientific investigations. However, working memory is a complex process that relies on several components of cognition, such as arousal and attention. Lang, Tulen, Kallen, Rosbergen, Dieleman, and Ferdinand (2006) supported the use of mental arithmetic tests in their study of attention because mental arithmetic tests have been established as a standard laboratory stress test in order to induce measurable physiological arousal changes. Therefore, mental arithmetic tests have been established to cause physiological arousal responses. Klingner et al. (2011) justified the use of mental arithmetic tasks to study attention because mental arithmetic tasks involve diverse types of cognitive processes and use simple stimuli for visual presentation. Studies showing that attentional deficits in conditions like ADHD account for mathematical impairments provide further evidence that attention is a key cognitive process influencing mental arithmetic performance. According to Iglesias-Sarmiento et al. (2017), the deficits in cognitive load and attention linked with ADHD have been directly implicated in mathematical difficulties, specifically arithmetic problem solving. Previous studies, according to Iglesias-Sarmiento et al. (2017), have found that children with ADHD are slower, struggle to maintain and manipulate numbers in their head, and fail to follow necessary steps when solving arithmetic problems. Furthermore, Iglesias-Sarmiento et al. (2017) found sustained and selective attention scales accounted for some of the variance in arithmetic performance.

Similarly, Benedetto-Nasho and Tannock (1999) observed that children with ADHD had less academic efficiency, more immature computation techniques, more trading errors, and more inattentive and disruptive behavior while completing a math task.

Applying mental arithmetic in the present study. The present study aimed to investigate how fluctuations in attention relate to performance on a mental arithmetic task. The arithmetic task developed incorporated the multiple subtypes of attention discussed above because this is more representative of tasks people encounter in real life. That is, the task demanded complex problem solving, which engaged higher-order processes necessitating the top-down regulation of selective voluntary attention. The task also involved working memory, executive control, and other high-level cognitive processes. The task was designed to provide just sufficient time to make solving the problem possible, while minimizing the likelihood of excess time. In creating this time constraint, participants needed to selectively attend solely on the presented task to solve the problem within the given time. In order to successfully attend to the task, participants engaged top-down cognitive control to select the task as the target of their attention and resist competing demands on attention. Response latency is a measure very similar to reaction time, which is a well-established measure related to selective attention, as mentioned above. Response latency measures the time from the onset of trial presentation to the response.

The task used was a working memory task, even though working memory was not a major focus of the study. Working memory is a system of short-term memory with a limited capacity that temporarily holds information available for immediate conscious cognitive processing. However, attention is necessary for any working memory task, and therefore a working memory task can be useful for investigating attention. The task was designed so that solving it in one step would exceed working memory and cognitive capacity. Therefore, the task needed to be broken into parts, which involved attending to one part of the problem at a time. The cocktail party effect was likely engaged in this task because attention to one part of the task was enhanced at a time, while the other parts were ignored. This could cause inattentional blindness, where participants perform poorly because only one part of the problem was attended to without maintaining attention to a part of the problem already solved. Therefore, the task may have also engaged divided attention because multiple parts of the problem needed to be attended to simultaneously to varying degrees.

Pupillometry

History of pupillometry. For ages, eyes have been recognized as the key to the human mind. Sirois and Brisson (2014) noted the phrase 'the eyes are the window to the soul' is thought to have been keyed by the Roman politician, Cicero (106-47 BCE). Interest in pupils and their variation in size also date back to Roman times. The Roman physician Galen (129-216 CE) used medicinal plants to dilate pupils during eye surgery, according to Sirois and Brisson (2014). Attempts to measure pupil size, also known as pupillometry, have intrigued physicists dating back just as far. Sirois and Brisson (2014) described cylinders and rectangular paper tools for measuring pupil size developed by physicists Archimedes (287-212 BCE) and Galileo (1564-1642), respectively. These crude measures, however, were incomparable to the tools developed centuries later with image capturing technologies. Modern cinematographic technology and the use of infrared sensitive cameras allowed pupils to be measured in varying light settings and with increased temporal precision. The development of eye tracking machines helped to automate pupillometry (Sirois & Brisson, 2014).

Today, pupil size fluctuations are thought to arise from both cognitive and light factors (Sirois & Brisson, 2014). Regulating how much light enters the eye to reach the retina is the primary function of pupil size changes (Goldstein & Brockmole, 2014). For psychologists and neuroscientists, however, the cognitive control of pupil dilation (Figure 3.1) is far more interesting, as compared to light regulated pupil dilation, as a tool for studying higher-level brain processes. According to Knapen, Gee, Brascamp, Nuiten, Hoppenbrouwers, and Theeuwes (2016), cognitive modulation of pupil size (Figure 3.1) has allowed scientists to track mechanisms underlying important brain processes, such as attention. Geva et al. (2013), for example, described three constructs of attention: alerting, orienting, and executive control (Figure 1.5), that involve autonomic associations that result in pupil dilation responses (Figure 3.1).

Applying pupillometry as a tool in research. Based on previous research with pupillometry on cognitive processes, such as working memory, attention, and arithmetic processing, Querino et al. (2015) asserted, the advantages of using pupillometry in neuropsychological studies is that pupillometry provides accurate information of underlying processes in real time. Pupil dilation is an autonomic nervous system response of arousal that has been used in previous research investigating atypical development (Sirois & Brisson, 2014) and has been used to measure fluctuations of mental effort related to arousal, such as attention (Egeth & Kahneman, 1975). Pupil size has long been observed to correlate with states of arousal (Costa & Rudebeck, 2016; Sirois & Brisson, 2014). Costa and Rudebeck (2016) and Sirois and Brisson (2014) both explained that pupil dilation, as a measure of autonomic arousal, has been favorable due to its ability to change rapidly, about 200-250 milliseconds, in response to internal and external stimuli. Pupil diameter has been found to vary from 1.5 to 9 millimeters, according to Sirois and Brisson (2014). In standard light, pupil size is typically around 3 millimeters (Sirois & Brisson, 2014).

Increased task difficulty has been associated with greater pupillary diameter

(Steinhauer, Siegle, Condray, & Pless, 2004; Alnaes, Snerve, Espeseth, Endestad, Van De Pavert, & Laeng, 2014). Additionally, task engagement has been related to increased pupil dilation (Hopstaken, Linden, Bakker, & Kompier, 2015). According to Kahneman (1973), when people are exerting the maximum mental effort possible, their pupils dilate by about 50%. After this the task becomes too difficult and people will tend to give up (Kahneman, 2011). Furthermore, mental effort can be measured in manifestations of arousal, including pupil dilation (Kahneman, 1973). For example, pupillometry was used in coordination with the five-digit test (FDT) to assesses automatic mechanisms controlled through cognitive processes (Querino et al. 2015). The FDT is a type of Stroop test that uses numbers and quantities instead of colors and words. The first two parts of the test are easy and considered to be accomplished through automatic processes (Querino et al. 2015). The latter two parts of the test increase in difficulty and are therefore thought to be accomplished through controlled processes (Querino et al. 2015).

Anatomy of the eye. In order to understand the mechanisms of pupil dilation, it is important to understand the anatomy of the eye. The eyes are a structure (Figure 3.2) that provide us with a physiological mechanism for sensing light. The first tissue that light passes through is the cornea, which is a transparent (Wolfe et al., 2011). This means that almost all photons are able to pass through the cornea without being reflected or absorbed. Second, light passes through a chamber of water-like fluid, the aqueous humor, that supplies the cornea and lens with oxygen and nutrients and removes waste (Wolfe et al., 2011). Then, in order for light to reach the lens, it must first pass through a hole, called the pupil. The pupil is the hole that is formed by the surrounding iris, which is a muscular structure. The iris controls the size of the pupil by regulating the expansion and contraction of two muscles. This control of muscle contraction (Figure 3.2) allows the iris to regulate the amount of light entering the eye (Wolfe et al., 2011). Changes in pupil size are controlled by smooth muscles in the iris, the sphincter and the dilator pupillae (Sirois & Brisson, 2014). Contraction of the circular sphincter muscles causes pupil constriction, while the radial dilator muscles cause pupil dilation, according to Sirois and Brisson (2014).

Neuroscience of pupil dilation. Despite being a frequently used measure, the neural regulation of pupil size related to cognition is not well understood (Costa & Rudebeck, 2016). The sphincter pupillae has cholinergic fiber innervation from the Edinger-Westphal nucleus and is parasympathetically controlled, shown in Figure 3.1 (Sirois & Brisson, 2014). The dilator pupillae is controlled by adrenergic innervation from the superior sympathetic ganglion, shown in Figure 3.1 (Sirois & Brisson, 2014).

Aston-Jones and Cohen (2005) described the pathway of pupil dilation through comparison of the similarities between the Yerkes-Dodson curve and the empirically observed relationship between performance and Locus coeruleus- Norepinephrine pathway (Figure 1.4) activity (Figure 3.3). The Yerkes-Dodson relationship states that task performance is low with minimal attention when non-alert, peaks with increased attention while engaged in the task, and then decreases to the same level as during inattention, as arousal increases beyond optimal task engagement, leading to distractibility (Figure 3.3). Similarly, Aston-Jones and Cohen (2005) noted that task performance is low with low tonic LC activity, highest with intermediate LC activity, and low, again, with high LC activity (Figure 3.3). Aston-Jones and Cohen (2005) also described pupillometry as an indirect index of LC activity. They supported the ties between pupillometry and LC activity by referring to classic studies on monkeys, that found strong correlations between pupil diameter and LC tonic activity. These classic findings have been supported in human research as well, according to Aston-Jones and Cohen. Sara and Bouret (2012) reviewed several studies that supported the close association between the LC and pupil dilation (Figure 1.4 & Figure 3.3). According to Sara and Bouret (2012), the increased autonomic arousal related to complex working memory tasks that require pre-frontal cortex processes may be caused by an increased release of norepinephrine needed for effective task performance. Research has suggested that the Locus coeruleus (LC) has important functions with cognitive processes, such as attention (Geva et al. 2013). The LC is largely made up of noradrenergic neurons. The LC has been implicated in regulating arousal. Geva et al. (2013) described previous research that established a correlation between pupil dilation and norepinephrine (NE) neuron activity in the LC (Figure 1.4 & 3.3) through single cell recordings in monkeys (Geva et al. 2013).

Present study

The overall goal of the current study was to investigate how fluctuation patterns of pupil dilation, thought to indicate changes in attention, over time correlate with task performance, and task difficulty on a mental arithmetic task. This overall goal encompassed three sub-goals. The first aim was to determine whether attentional fluctuations, reflected by pupil dilation change measures, related to task difficulty. The second aim was to establish whether lower attentional fluctuations, as measured by pupil dilation changes, were correlated with decreased task performance. The third aim was to confirm that pupil dilation, a purported measure of attention, task engagement, and arousal, increased over time during the mental arithmetic task compared to baseline.

The mental arithmetic task was developed to minimize the likelihood of excess time. The time per trial was established based on fourth and fifth grade math education standards, as well as time given on similar tasks in previous research (Common Core: State Standards Initiative, 2018; Sirois & Brisson, 2014). All trials required some increased mental effort to perform well, by involving mental addition of three different two-digit numbers. Solving the problem correctly required participants to keep track of the sum of one part of the problem while adding together other parts of the problem. Mental effort was varied by having half of the 40 problems in the task, “difficult problems,” require carrying in both the one’s place and ten’s place. This meant that participants needed to attend to the sum of one part of the problem, while remembering the number being carried, and adding the other parts of the problem. As mentioned above, by increasing the number of stimuli participants attended to simultaneously, the mental effort necessary was increased. Based on the previous research discussed above, attention and mental effort have a physiological effect. The physiological arousal regulated by attention and mental effort (i.e. pupil dilation) was used as a measure of the degree of attention and mental effort participants engaged during the task.

Method

Participants

The target population was college students, recruited from Lake Forest College through recruitment flyers, classes and word-of-mouth. After potential participants responded to the recruitment flyer (Appendix A) or other form of recruitment, an email (Appendix B) was sent explaining the study and the requirements for participating in the study. The email also included an attached participant information questionnaire (Appendix C) to complete before the visit and listed available times to schedule an appointment.

Informed consent was obtained from participants prior to receiving the participant information questionnaire. Informed consent involved having participants read and sign an informed consent form that explained the voluntary nature of participation, as well as risks and compensation for participating. Participants were compensated for participating in the study with a lab t-shirt. In addition to having the opportunity to read the consent form, participants received a verbal explanation of the contents of the consent form and an opportunity to ask any questions. The full purpose and procedure of the study was provided in the consent form. Once informed consent was obtained, the participant information questionnaire was reviewed to confirm the participant's eligibility for the study.

Participants with other conditions that could affect attention or math ability, such as autism and dyslexia, were excluded from the study during recruitment. A total of 12 participants was recruited, though only 11 participated (3 males, 8 females) in the study due to difficulty calibrating the eye tracker. All participants were between ages 20-22 years and at least second-year students in college. No participants reported having taken math classes in college, though 6 participants reported taking calculus in high school. All participants reported passing at least regular high school math, also indicated by their status as college students. Only 1 participant reported having a diagnosis of ADHD. This study was approved by the Lake Forest College Human Subjects Review Committee.

Measures

Participant information questionnaire. Participants received a questionnaire (Appendix C) to complete prior to participating in the study. The questionnaire contained demographic questions to confirm the participant was within the age range to participate, as well as their year in college and sex, which was used to determine the diversity of the studied sample. The questionnaire also contained questions about one participant's medical diagnosis and treatment of ADHD and other conditions relevant to the study. Though this study did not investigate differences between people with and without ADHD, having ADHD could affect participants' attention and ADHD treatment, such as stimulants, could affect pupil dilation. Although treatment history of ADHD did not exclude participants from the study, this information could influence the results and was therefore necessary to report. The questionnaire also asked about ADHD medications taken the day of the experiment because certain medications (i.e. stimulants) could affect pupil dilation independent of attention and task-engagement. Participants with other attention-related disorders, poor vision, anxiety, or math-related conditions were excluded from the study based on the questionnaire responses. Only one recruited student was excluded for having poor vision because of difficulty calibrating the eye tracker through glasses. A copy of the questionnaire can be found in the appendix (Appendix C).

The mental arithmetic task. Before the task, instructions for the mental arithmetic task and two practice problems were given (Figure 4.1). The instructions appeared on the computer screen and were read aloud to the participant (Appendix D). Mental arithmetic responses were given verbally by the participant and recorded by the researcher. During piloting of the task, pilot subjects had many errors at the beginning of the task due to misunderstanding how to perform the task. Therefore, participants were given two practice problems, one which involved carrying numbers and one which did not involve carrying numbers. Before each problem a white screen with the words, “Are you ready?” appeared for 5 seconds (Figure 4.1a). Then, the problem appeared for 10 seconds (Figure 4.1b). After the 10 seconds the numbers disappeared, but the equals sign and question mark remained for an additional 2 seconds, during which the participant could provide his/her final answer, if they had not done so already (Figure 4.1c).

Task problems. The 40 mental addition problems consisted of 20 easy and 20 hard problems (Table 4.1), which occurred in one of two randomly assigned orders. Each possible order had the easy and hard problems distributed in a controlled random sequence, with no more than three easy or hard problems in a row. For each possible order, the first and last problems were easy. All problems, easy and hard, consisted of adding together 3 numbers that had 2 digits each. None of the numbers included 0's. The easy problems included numbers with digits 1, 2, 3, 4, 5, and 6 in the 1's place and some larger digits in the 10's place. The easy problems did not involve carrying, except sometimes in the 10's place yielding answers in the 200's and 100's. The hard problems included numbers with digits 2, 3, 4, 6, 7, 8, and 9, excluding digits 1 and 5. The hard problems involved carrying both in the 1's place and 10's place. The problems and the words "Are you ready?" appeared on the screen in a grey color to limit the contrast between the text and white background on the screen (Figure 4.1). Figure 4.1 shows example slides of the task and Table 4.1 shows a list of all of the arithmetic problems. This task was developed for this study, based on arithmetic tasks used in previous studies (Adams & Hitch, 1997; Clair-Thompson, Stevens, Hunt, & Bolder, 2010) and Common Core education standards for 4th and 5th graders (Common Core: State Standards Initiative, 2018). Since this was a novel task, the defined problem difficulty was adjusted based on performance results.

Equipment

ISCAN eye tracker system. Fluctuations of pupil dilation, thought to indicate changes in attention, were measured by tracking changes in participant's pupil dilation as a dependent measure, which were recorded using an ISCAN infrared corneal reflection eye tracker system. A schematic diagram of how pupil dilation was measured is depicted in Figure 4.2. In addition, a digital video camera recorded the eye tracker computer screen on which the participant's point of regard appeared superimposed on the screen that the person was viewing, as well as moment-to-moment pupil diameter measures. Video recording provided a video record of participant responses and of time-lapsed pupil diameters as the measures appeared on the screen.

Procedure

Once informed consent was obtained, the participant questionnaire was obtained and briefly reviewed by the researcher to confirm the participant met the requirements of the study (Appendix D). The participants were asked whether all answers were still true on the day of the experiment, specifically confirming the accuracy of responses to the participant's age and medication taken that day. The questionnaires were then placed in an envelope with only the participant code number on it. The participant was then seated in front of a display area and familiarized with the lab equipment before receiving instructions for the task and calibration of the ISCAN eye tracker. The ISCAN eye tracker was calibrated by setting the light threshold for the corneal reflection and the darkness threshold for the pupil in the eye tracker circuitry. Then, a frame of reference was set for the corneal reflection and pupil positions at five points on the screen. Precise calibration was important for accurate measures of pupil diameter. Setting the darkness threshold too low could result in darker facial features, such as eyelashes, being included in the pupil diameter measures. On the other hand, setting the darkness threshold too high would result in only partial measurement of the pupil.

After calibration, the researcher confirmed that the participant was comfortable and willing to remain still for the duration of the mental arithmetic task. Participants were also reminded that they could stop the task at any time. Then, the instructions for the mental arithmetic task were read aloud while being shown on the computer screen for the participant to follow along. When the participant was ready, the mental arithmetic task was started and lasted about 10 minutes. After the task was completed, the researcher provided the participant with a debriefing letter and provided a short verbal summary of the debriefing letter to the participant, as well as answers to any questions regarding the study.

Finally, the participants received a t-shirt as compensation for participating.

Data Analysis

Pupil diameter data were converted to Excel files and then formatted for analysis. All analyses were conducted using Microsoft Excel and IBM SPSS Statistics software. All graphs and tables were made in Excel.

Mental arithmetic task construct check. A paired samples *t*-test was conducted to analyze differences in average performance rates for the two levels of problem difficulty. Further analysis of problem difficulty, considering three levels of difficulty, was done with a repeated measures analysis of variance (ANOVA).

Pupil dilation analysis. Video recordings of the eye tracker computer screen were used to time-lock pupil diameter recordings and the start of the mental arithmetic task. Pupil diameter measures were corrected for blinks by replacing pupil diameter samples in the bottom 10% of the trial (i.e. sections indicating a blink had occurred) with the average pupil diameter on each trial. Abnormally high pupil diameter samples were also considered errors and replaced with the average pupil diameter on each trial. In order to smooth data noise, a moving average with an interval of 30 data points was taken of pupil diameter samples. The moving average was also taken because pupil dilation has been shown to change at a rate between 200-250 milliseconds (Costa & Rudebeck, 2016; Sirois & Brisson, 2014), which is slower than the sampling rate. Averages were taken for every 500 milliseconds because the shape of data curves did not change significantly by having smaller averaging rates. Since baseline pupil diameters differ among individuals, pupil dilation data were calculated as baseline average pupil diameters subtracted from pupil diameter samples during mental arithmetic problems. A repeated measure ANOVA was conducted to analyze the effects of performance, difficulty, and time bin on pupil dilation changes from baseline. Due to the exploratory nature of this study, *p*-values less than 0.05 were considered significant and *p*-values between 0.05-0.1 were considered marginally significant.

Results

Problem Performance Rates

The problem difficulty construct was checked for validity. Validity was checked by analyzing participants' performance rates on problems based on the defined difficulty. A paired-samples *t*-test was conducted to compare average Performance Rates on Easy and Hard Problems. The mean percent correct on Hard Problems ($M = 0.20$, $SD = 0.18$) was significantly lower than on Easy Problems ($M = 0.69$, $SD = 0.10$); $t(10) = 8.0$, $p < 0.001$ (Table 5.1). The lower mean Performance Rate of Easy problems and higher mean Performance Rate of Hard problems is shown in Figure 5.1.

Although the mean Performance Rates on Easy and Hard problems differed significantly, a frequency analysis of percent correct ranges (Figure 5.2) revealed that some problems, initially defined as easy, had performance rates similar to those of hard problems. That is, participants had significantly lower average performance rates on some easy problems compared to other easy problems. Closer consideration of the "easy" problems with lower performance rates showed these problems all had answers in the 200's. Other easy problems with higher performance rates only had answers under 200. The easy problems with answers in the 200's had performance rates similar to some difficult problems. These difficult problems that had similar performance rates as the easy problems had no consistent difference from difficult problems with lower performance rates.

In order to determine if a third (i.e. medium) difficulty level had significantly different performance rates from easy and hard problems (Figure 5.3), a repeated measures analysis of variance (ANOVA) was conducted to compare the effect of Difficulty with three levels on Performance Rate. Mauchly's test of sphericity (Table 5.4) was not significant (p = 0.71), which meant sphericity could be assumed. There was a significant effect of Difficulty on Performance Rates at the $p<0.05$ level for the three Difficulty conditions, [$F(2, 20) = 50.78$, $p < 0.001$] (Table 5.5). Post hoc comparisons using the Bonferroni correction (Table 5.6) indicated that the Performance Rates of Easy Problems (M = 0.85, SD = 0.13) (Table 5.3) were significantly higher ($p<0.001$) than of Hard Problems (M = 0.20, SD = 0.18) (Table 5.3) and significantly higher ($p<0.001$) than on Medium Problems (M = 0.39, SD = 0.18) (Table 5.3). Additionally, the Bonferroni pairwise comparisons indicated that the Performance Rates of Medium Problems were significantly higher ($p<0.01$) than of Hard Problems. All later analyses were completed accounting for three levels of Difficulty by excluding Medium level problems from analysis.

Pupillometry Analysis

Pupil dilation fluctuation patterns were analyzed as a reflection of attention changes during the mental arithmetic task. A repeated measures ANOVA was conducted to determine the effects of time, problem difficulty, and problem performance on pupil dilation fluctuation. The ANOVA had a 2 (2 levels of Difficulty: Easy and Hard) x 2 (2 levels of Performance: Correct and Incorrect) x 20 (20 levels of Time: 0.5s intervals) factor design. The mean Pupil Dilation Fluctuations from baseline by Time, Performance, and Difficulty are shown in Table 5.7.

The ANOVA revealed a marginally significant effect of Difficulty on Pupil Dilation Fluctuations at the $p<0.1$ level for Easy and Hard Problems, [$F(124.05, 296.76) = 3.76$, p = 0.084] (Table 5.8). This meant that pupil dilation fluctuations from baseline tended to differ for easy and hard problems (Figure 5.4), but not significantly. As shown in Figure 5.4, the marginal effect of Difficulty presented a trend of greater Pupil Dilation Fluctuation on Hard

Problems than on Easy Problems.

The ANOVA also revealed a marginally significant effect of Performance on Pupil Dilation Fluctuations at the $p<0.1$ level for Correct and Incorrect Problems, [$F(30.49, 62.33) = 4.40$, $p = 0.065$] was observed (Table 5.8). This meant that a trend of differing pupil dilation fluctuations based on task performance was observed, but not significantly (Figure 5.5). As shown in Figure 5.5, the marginal effect of Performance showed a trend of greater Pupil Dilation Fluctuation on Incorrect Problems than on Correct Problems.

Additionally, the ANOVA revealed a significant effect of Time on Pupil Dilation Fluctuations at the $p<0.05$ level for the twenty-0.5 second Time Intervals of problems, [$F(256.11, 116.09) = 19.86$, $p < 0.001$] (Table 5.8). This meant pupil dilation fluctuated from the baseline over the time of trials (Figure 5.6). As shown in Figure 5.6, pupil dilation fluctuations increased over time. The trend of increasing pupil dilation fluctuation over time best fit the linear curve, $y = 0.0106x + 0.0597$ ($R^2 = 0.9618$) (Figure 5.6).

The ANOVA showed two significant two-way interactions. Pupil dilation fluctuations over time interacted with difficulty and with performance, significantly. Since Pupil Dilation Fluctuation increased significantly by Time, influence of Difficulty and Performance on Pupil Dilation Fluctuation was more clearly expressed by the interaction of Time by Difficulty and Time by Performance. The interaction of Difficulty by Time and Performance by Time described the patterns of Pupil Dilation Fluctuation.

The ANOVA revealed a significant two-way interaction of Difficulty by Time on Pupil Dilation Fluctuations at the $p<0.05$ level for Easy and Hard Problems, [$F(32.51, 126.11) = 2.32$, $p = 0.002$] (Table 5.8). This meant that pupil dilation fluctuation patterns over time differed based on difficulty (Figure 5.7). As shown in Figure 5.7, pupil dilation fluctuation increased over time for both easy and hard problem. The trend of pupil dilation fluctuation increase over time for easy problems best fit the quadratic curve, $y = -0.0483x^2 + 0.603x - 0.6402$ ($R^2 = 0.9364$) (Figure 5.7). The trend of increasing pupil dilation fluctuation over time for hard problems best fit the linear curve, $y = 0.251x + 0.2566$ ($R^2 = 0.9453$) (Figure 5.7).

The ANOVA also showed a significant two-way interaction of performance by time on pupil dilation fluctuations at the $p<0.05$ level for correct and incorrect problems by time of trials, [$F(10.14, 51.92) = 1.757$, $p = 0.031$] (Table 5.8). This meant that the observed patterns of pupil dilation fluctuations over time differed based on performance (Figure 5.8). As shown in Figure 5.8, pupil dilation fluctuation increased over time for both correct and incorrect problems. The trend of increasing pupil dilation fluctuation over time for correct problems best fit the curve, $y = -0.0048x^3 + 0.0453x^2 + 0.1643x + 0.2537$ ($R^2 = 0.9575$) (Figure 5.8). The trend of pupil dilation fluctuation increase over time for incorrect problems best fit the curve, $y = -0.0167x^2 + 0.3665x - 0.3295$ ($R^2 = 0.9682$) (Figure 5.8).

However, the 2 x 2 x 20 ANOVA did not reveal a significant two-way interaction of Difficulty by Performance on Pupil Dilation Fluctuations at the $p<0.05$ level. This meant that pupil dilation fluctuations on easy and hard problems did not differ by problem performance. Additionally, there was no significant three-way interaction of Difficulty by Performance by Time on Pupil Dilation Fluctuations.

Individual biological and cognitive differences can produce temporal jitter, which refers to small differences in pupil dilation fluctuations over time among participants. These differences in pupil dilation fluctuation can include variations, such as different rates of pupil dilation change and different amplitudes of pupil dilation fluctuations that vary over time. These minor differences among participants can lead to data smoothing when averaging participants' data. Therefore, the effects of Difficulty (Figure 5.9), Performance (Figure

5.10), and Time (Figure 5.11), as well as the interactions of Difficulty by Time (Figure 5.12) and Performance by Time (Figure 5.13) were qualitatively analyzed for each individual.

Average pupil dilation fluctuation from baseline as a function of difficulty was qualitatively considered for individual participants to account for characteristic patterns of pupil dilation (Figure 5.9). All participants had either larger pupil dilation fluctuation on hard than easy problems or no difference between pupil dilation fluctuation on hard and easy problems. Three participants had average pupil dilation fluctuation on hard problems that were nearly twice as large as their average pupil dilation fluctuation on easy problems (Figure 5.9). These three participants had noticeably larger average pupil dilation fluctuations on hard problems (Pupil dilation changes between 2.6-4 on hard problems) than other participants (Pupil dilation changes between 0.2-2.6) (Figure 5.9). Participants with smaller average pupil dilation fluctuations on hard problems tended to have smaller increased pupil dilation fluctuation on hard problems than easy problems (Figure 5.9).

Average pupil dilation fluctuation from baseline as a function of performance was also considered qualitatively for individual participants to account for possible characteristic patterns (Figure 5.10). Only three participants had larger average pupil dilation fluctuation on incorrect problems than on correct problems, despite the overall marginal effect of performance on pupil dilation fluctuation, where incorrect problems had larger pupil dilation fluctuation than correct problems. One participant had noticeably larger average pupil dilation fluctuation on correct problems than on incorrect problems. The other seven participants had similar average pupil dilation fluctuation on correct and incorrect problems.

Pupil dilation fluctuation from baseline patterns as a function of time were qualitatively considered for individual participants to identify possible characteristics (Figure 5.11). Pupil dilation fluctuation patterns over time appeared to vary by amplitude and the shape of the curve describing the data. Four participants had maximum amplitudes of pupil dilation fluctuation above 3 (Figure 5.11). Four other participants had maximum amplitudes of pupil dilation fluctuation between 2-3 (Figure 5.11). Three participants had maximum amplitudes of pupil dilation fluctuation bellow 1 (Figure 5.11). Three participants exhibited pupil dilation fluctuation patterns that had a best fit curve with functions of the 4th order or higher. Four participants had pupil dilation fluctuation patterns that were best fit with cubic curves. Two participants had pupil dilation fluctuation patterns that were best fit with a quadratic curve. Two other participants had pupil dilation fluctuation patterns that were best fit with a linear curve (Figure 5.11).

The qualitative analysis of the interaction of difficulty by time on pupil dilation fluctuation for individual participants revealed that generally hard problems were represented by lower-order best fit curves than easy problems, for most participants. Three participants had greater pupil dilation fluctuation on hard problems than on easy problems over all time intervals. These participants tended to have larger pupil dilation fluctuations on both easy and hard problems compared to other participants.

The qualitative analysis of the interaction of performance by time on pupil dilation fluctuation for individual participants revealed various patterns. Generally, pupil dilation fluctuations decreased toward the end of trials on correct problems but did not or decreased less on incorrect problems. Pupil dilation fluctuation patterns on incorrect problems tended to be described by higher-order functions than on correct problems.

Discussion

Major Findings

The present study aimed to investigate how fluctuation patterns of attention relate with task difficulty and task performance on a mental arithmetic task. Mental arithmetic is a common working memory task that requires attention and reflects attentional tasks in real life. In order to reflect fluctuation patterns of attention over time, the autonomic arousal response, pupil dilation, was measured. Pupil dilation has been shown in previous studies to be partially regulated by cognitive processes. Pupil dilation measures have been used in previous studies to suggest changes in attention, task engagement, and arousal during various tasks.

The first aim was to determine whether pupil dilation fluctuation patterns, thought to reflect levels of attention, were related to task difficulty. The marginal effect of difficulty on pupil dilation fluctuation (Figure 5.4) was indicative of a potential association between attentional fluctuations and task difficultly. More difficult problems tended to have greater pupil dilation fluctuations than easier problems, but not significantly. Though previous studies, such as Breeden, Siegle, Norr, Gordon, and Vaidya (2017) and Geva et al. (2013), have supported a correlation between increased task difficulty and increased attention, the effect of difficulty on pupil dilation change was inconclusive in the present study. Since this effect of difficulty was only marginally significant, this study would need to be repeated to establish whether the effect of performance on pupil dilation changes is truly significant.

The second aim in this study was to determine whether pupil dilation fluctuation, which reflected changes in attention, correlated with task performance. A marginal effect of performance (Figure 5.5) was observed on pupil dilation fluctuations, which reflected a possible association between lower attention and lower performance rates. However, since this effect was only marginally significant, this study would need to be repeated to confirm whether the effect of performance on pupil dilation changes is truly significant.

The third aim of this study was to confirm that pupil dilation, thought to reflect attention, increased over time during mental arithmetic compared to baseline. A main effect of time on pupil dilation fluctuations was observed (Figure 5.6). This showed that pupil dilation increased during the mental arithmetic task compared to baseline. The positive correlation of increased change in pupil dilation and trial time suggested that attention was needed during the mental arithmetic task and attention increased until the problem was solved.

However, the significant interaction of difficulty by time on pupil dilation fluctuations provided an indication that patterns of attention fluctuation over time differed for easy and hard problems (Figure 5.7). A significant interaction between performance and time on pupil dilation fluctuations was observed (Figure 5.8). This interaction suggested that the fluctuation patterns of attention over the time of trials differed for correctly and incorrectly solved problems. The interaction between performance and time on pupil dilation fluctuations provided evidence that the patterns of pupil dilation change over time during mental arithmetic tasks could help predict performance because distinct patterns of pupil dilation fluctuation over time were identified for correct and incorrect problems.

Unexpected Findings

The difficulty construct developed in the mental arithmetic task varied more than expected. Though the two designed levels of the difficulty construct of the mental arithmetic task had significantly different overall performance rates, a third level of difficulty was observed. Though the medium level arithmetic problems were excluded from analysis, the pupil dilation fluctuations and performance rate were more similar to hard problems than other easy problems. Excluding medium problems from analysis meant an unequal number of easy and hard problems were compared.

The performance construct also contained an unexpected variable. The originally two-level variable (correct and incorrect), had an unexpected third level, missed problems.

Thus, mental arithmetic trials with no response from the participant were excluded. Missed problems were considered separate from incorrect problems because many factors could have lead participants to miss problems. For example, the problem could have been too hard to solve in the given amount of time, the participant may have been distracted during the problem, or the participant may not have engaged in solving the problem. Excluding missed problems further limited the number of valid cases to analyze.

Though a marginal effect of performance on pupil dilation fluctuations was observed, average pupil dilation fluctuation was slightly greater for incorrect problems than for correct problems, which was opposite from the predicted effect. However, the nature of the significant interaction of performance by time on pupil dilation fluctuations helps explain that incorrect problems had greater pupil dilation fluctuations than correct problems. The pupil dilation fluctuation pattern of correct problems was best described by a cubic curve that decreased in the rate of pupil dilation fluctuation increase over time and then began to decrease in pupil dilation fluctuation. This pattern of pupil dilation fluctuation was expected because pupil dilation fluctuation decreased toward the end of trials, as problems would have been solved. The pupil dilation fluctuation pattern of incorrect problems, on the other hand, was best described by a quadratic curve, which continued to increase in pupil dilation fluctuation throughout the time of trials. Though this pattern of pupil dilation fluctuation was not predicted, the pattern reflected how attention changed during incorrect problems. The continued increase in pupil dilation fluctuation suggested that attention continued to increase throughout the problem. The pattern of pupil dilation fluctuation on incorrect problems also appeared to be more similar to the pattern observed on hard problems. This pattern of continuous increase could suggest that problems solved incorrectly were subjectively more difficult for individual participants and therefore engaged more attention, reflected in the increasing pupil dilation fluctuation pattern.

Interpretation of Findings

Due to the possibility of temporal jitter and possible characteristic patterns of pupil dilation fluctuations among participants, the data were also analyzed by individual participants. Temporal jitter refers to slight differences in pupil dilation fluctuations among participants, such as the rate of pupil dilation change and the amplitude of pupil dilation fluctuations that vary over time. Temporal jitter has the potential to smooth out significant findings because a significant effect is not time-locked among participants. Furthermore, pupil dilation fluctuation patterns may vary among participants and may be representative of traits. Previous studies have not investigated the possible differences in attention pattern characteristics, other than to research attentional disorders, such as Benedetto-Nasho et al. (1999), who studied math computation error patterns in children with and without ADHD. Little research has been conducted on typical patterns of attentional fluctuations. As a complex higher-level cognitive process, it is likely that typical attentional fluctuation patterns differ among people based on numerous other individual differences, such as personality, motivation, and emotion. Though this study had an insufficient sample size to demonstrate significant characteristic patterns of participants' pupil dilation fluctuation, some qualitative differences were observed. These characteristic patterns may be of particular interest for future studies. Pupil dilation fluctuation patterns varied by the type of best fitting curve, amplitude of pupil dilation fluctuation, and dips in pupil dilation fluctuation over time.

The range of pupil dilation fluctuation amplitudes varied noticeably among participants. Though a larger sample size would be needed to analyze any effects, these trends can be interpreted in multiple ways. Firstly, differences in pupil dilation fluctuation amplitudes could reflect variations in participant attention. This would support the hypothesis presented in the current study. However, other co-occurring processes could have influenced the varied pupil dilation fluctuation amplitudes. For example, other cognitive processes, such as planning, motivation, or attention away from the task, could have led to varied pupil dilation fluctuation amplitudes. Alternatively, natural differences in pupil dilation reactivity and arousal, both voluntary or involuntary, among participants might have accounted for the range of pupil dilation fluctuation amplitudes.

Another possibly intriguing characteristic of pupil dilation fluctuation patterns was a slight decrease in pupil dilation fluctuation within the first two seconds of trials. Eight of the participants exhibited a dip in pupil dilation fluctuation within the first 2 seconds of trials, though the intensity of the dip in pupil dilation fluctuation varied among participants. The other three participants exhibited an initial slope of 0 within the first 2 seconds of trials. This meant that though pupil dilation fluctuation did not decline within the first 2 seconds for those three participants, for some amount of time within the first 2 seconds pupil dilation fluctuation did not increase either. Furthermore, six participants had decreases in pupil dilation within the first 2 seconds bellow the baseline.

These initial dips in pupil dilation fluctuation may portray characteristic patterns influenced by difficulty. Eight participants had initial dips in pupil dilation fluctuation on both easy and hard problems. However, the other three participants only had dips in pupil dilation fluctuation on hard problems. This may suggest that the three participants that only had initial declines in pupil dilation fluctuation on hard problems reacted to easy problems differently. Four participants had initial pupil dilations that were smaller than the baseline on easy and hard problems. Interestingly, another four participants only had initial pupil dilations smaller than the baseline on easy problems.

These initial dips in pupil dilation fluctuation may also portray characteristic patterns influenced by performance. Seven participants exhibited initial dips in pupil dilation fluctuation on both correct and incorrect problems. Two participants only had initial dips in pupil dilation fluctuation on correct problems. Another two participants only had initial dips in pupil dilation fluctuation on incorrect problems.

Though there were not enough participants to provide insight as to the underlying traits related to the differences in the patterns observed among individual participants, the patterns described provide some direction for future investigations. No clear pattern for the initial dip in pupil dilation fluctuation was identified. That is, the initial dip in pupil dilation and pupil dilation fluctuation were not noticeably related to difficulty or performance. However, more pronounced dips were associated with larger pupil dilation fluctuation amplitudes. Additionally, pupil dilation fluctuation patterns over time that had more linear shaped curves tended to have less pronounced dips in pupil dilation fluctuations. Variables not considered in the present study, such as computation strategy and emotions toward the task, may have influenced the different individual patterns described, as well.

Finally, a third potential pupil dilation fluctuation pattern profile may be related to increased pupil dilation change on incorrect problems. While eight of the eleven participants had either greater pupil dilation fluctuations on correct problems or nearly the same pupil dilation fluctuations by performance levels, three participants had noticeably increased pupil dilation changes on incorrect problems compared to correct problems. The increased pupil dilation fluctuation on incorrect problems for these three people was great enough to cause an overall average higher pupil dilation for incorrect problems compared to correct problems. This increased pupil dilation fluctuation on incorrect problems could have resulted from a distinct approach to incorrect problems that required greater attention. This would support the hypothesis of the present study that pupil dilation fluctuations correlate with attention and would provide an exception to the hypothesis that correct problems require more attention than incorrect problems. Alternatively, the increased pupil dilation fluctuations on incorrect problems could have resulted from certain problems being more difficult for the given individuals with increased pupil dilation changes on incorrect problems. This would support the hypothesis of the present study that more difficult problems require more attention but discount the hypothesis that correct problems require more attention than incorrect problems. On the other hand, a confounding variable, such as stress and anxiety from failing to solve a problem correctly, could cause autonomic arousal independent from attention that would increase the pupil dilation fluctuation. The effect of anxiety could be limited to participants particularly nervous about performing poorly. A limited effect of anxiety on incorrect problems could explain why only three participants presented this pattern.

Limitations

This exploratory study helped establish pupillometry as a potentially valuable tool for attention research, for one by providing a noninvasive and temporally precise physiological measure of pupil dilation, which is thought to reflect attention changes. However, the small sample size of this study limited its ability to distinguish possible underlying patterns of attention fluctuations from unique individual attentional characteristics and other arousal based autonomic nervous system influences. One weakness of pupillometry is that it does not directly measure brain functions. Therefore, it is possible for the autonomic arousal response of pupil dilation to respond as a result of other brain functions directly influencing pupil dilation or indirectly by affecting the cognitive processes that regulate attention. Emotions such as fear can have arousal responses similar to attention and even basic homeostatic imbalances such as hunger, dehydration, and pain can impair attention. The likelihood of confounding variables, such as these bodily functions influencing the targeted system, in this case attention, can be controlled by measuring brain activity. Equipment such as electroencephalogram (EEG) can measure electrical brain activity to confirm whether the active brain regions reflect the autonomic response changes, pupil dilation fluctuation. Furthermore, the validity of pupil dilation fluctuation measurements was not verified with alternative measures. In order to strengthen the validity of pupil dilation fluctuation measurements, other autonomic nervous system responses, such as heart rate and stomach motility could have been measured.

Future Studies

Future studies could expand on the present study in several ways. Future studies with larger sample sizes could focus on categorizing characteristic attention patterns by developing participant profiles, such as by personality traits, performance traits, and most importantly attentional conditions. Future studies could also use brain imaging technologies in combination with pupillometry measures to provide a more in depth understanding of attentional mechanisms. As mentioned earlier, studies such as Iglesias-Sarmiento et al. (2017), have noted the high prevalence of math difficulties in the US. Therefore, understanding the underlying causes of math difficulties, such as decreased attention, could benefit many students, especially students with disabilities.

Previous research has found children with ADHD have lower math performance than typically developing peers (Iglesias-Sarmiento et. al., 2017; Benedetto-Nasho & Tannock, 1999). Tosto et al. (2015) deemed 20 of the 24 reviewed papers high quality that reported findings showing significant negative correlations between ADHD symptoms and mathematical performance. Iglesias-Sarmiento described the findings of previous studies that showed children with ADHD are slower, struggle to maintain and manipulate numbers in their head, and fail to follow necessary steps when solving arithmetic problems. These difficulties have been related to cognitive load and planning deficits. Furthermore, difficulties inhibiting irrelevant information have been related to selective attention deficits in ADHD (Iglesias-Sarmiento et al., 2017). Participants with ADHD were found to perform significantly worse on an arithmetic problem-solving test than controls, where a sustained and selective attention scale accounted for some of the variance (Iglesias-Sarmiento et al., 2017). In another example, Benedetto-Nasho and Tannock (1999) observed that children with ADHD had less academic efficiency, more immature computation techniques, more trading errors, and more inattentive and disruptive behavior while completing a math task. However, taking the stimulant medication methylphenidate, which is frequently prescribed for ADHD, improved all measures for the ADHD group (Benedetto-Nasho & Tannock,1999). Overall, these studies associated markedly lower math performance with ADHD, at least in part resulting from attentional deficits. This underperformance in math can be lessened by taking stimulant medication. However, stimulant medications only provide temporary solutions for mathematical underperformance and attentional deficits. Understanding the attentional mechanisms that are disrupted in ADHD could lead to better treatment options.

The techniques of pupillometry during the mental arithmetic task developed in the present study could be applied in research on the inattentional and impulsive behaviors involved in ADHD. While attention deficits are known to be chronic and pervasive in ADHD, the nature of attention deficits expressed in ADHD remain unclear (Cornish & Wilding, 2010). This means that how ADHD influences attentional processes, such as whether ADHD causes a generalized decrease in attention, a decrease in attention fluctuation from a baseline, an increase in attention variability, or other changes in attention patterns, remains unknown. The present study demonstrated the nature of temporally sensitive changes in pupil dilation during a mental arithmetic task, which reflected the nature of attention fluctuation patterns over time in typically developing college students. Therefore, future studies should utilize the techniques established in the present study to investigate how attention fluctuation patterns differ in people with and without ADHD. By comparing pupil dilation fluctuations in typically developing students and students with ADHD, future studies could provide insight to ADHD's impact on attentional processing. Furthermore, studies of this nature might be able to provide insight about the role of attentional differences in the arithmetic-deficits observed in ADHD.

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Tables and Figures

Table 4.1

Mental addition problems presented in the mental arithmetic task

	Easy Problems	Answers	Hard Problems	Answers
1	14+23+31	68	67+39+28	134
2	13+25+41	79	79+46+28	153
3	14+23+62	99	89+47+36	172
4	15+32+42	89	94+73+68	235
5	52+63+92	207	92+84+62	238
6	13+23+72	108	96+83+72	251
7	14+32+52	98	84+78+69	231
8	51+72+83	206	97+39+24	160
9	24+31+52	108	92+87+46	225
10	46+71+92	209	82+69+37	188
11	21+35+32	88	93+49+26	168
12	13+24+51	88	86+79+42	207
13	25+31+43	99	74+63+29	166
14	12+34+63	109	94+89+32	215
15	12+43+52	107	93+72+43	208
16	42+73+93	208	96+47+38	181
17	34+82+92	208	97+64+38	199
18	36+82+91	209	98+76+23	197
19	21+35+42	98	62+34+27	123
20	53+62+91	206	83+48+36	167

Table 5.1

Descriptive statistics of Performance Rates by 2-levels of task Difficulty.

Paired Samples Statistics

		Mean	**N**	**Std. Deviation**	**Std. Error Mean**
Pair 1	Easy problems	0.6909	11	0.10445	0.03149
	Hard problems	0.2000	11	0.18028	0.05436

Table 5.2

Two-level task Difficulty construct check. A paired-samples t-test comparing Performance Rates on two-levels of Difficulty was analyzed.

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	**Std. Deviation**	**Std. Error Mean**	**Lower**	**Upper**	**t**	**df**	**Sig. (2-tailed)**
Pair 1	Easy - Hard	0.49091	0.20472	0.06172	0.35338	0.62844	7.953	10	0.000

Table 5.3

Descriptive statistics of Performance Rates by 3-levels of task Difficulty.

Descriptive Statistics: Performance Rates

	Mean	Std. Deviation	N
Easy	0.8527	0.12483	11
Medium	0.3900	0.18083	11
Hard	0.2000	0.18028	11

Table 5.4

Mauchley's test of sphericity for Performance Rates by 3-levels of task Difficulty.

Mauchly's Test of Sphericity

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
Difficulty	0.927	0.681	2	0.711	0.932	1.000	0.500

Table 5.5

Repeated measures ANOVA comparing Performance Rates by 3-levels of task Difficulty

Tests of Within-Subjects Effects

Source	Type II Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Difficulty	2.480	2	1.240	50.784	0.000	0.835
Error (Difficulty)	0.488	20	0.024			

Table 5.6

Post-hoc pairwise comparisons of Performance Rates by 3-levels of task Difficulty.

Pairwise Comparisons

(I) Difficulty		**Mean Difference (I - J)**	**Std. Error**	**Sig.**	**95% Confidence Interval**	
					Lower Bound	**Upper Bound**
Easy	Medium	.463*	0.066	0.000	0.316	0.610
	Hard	.653*	0.074	0.000	0.487	0.818
Medium	Easy	-.463*	0.066	0.000	-0.610	-0.316
	Hard	.190*	0.059	0.009	0.059	0.321
Hard	Easy	-.653*	0.074	0.000	-0.818	-0.487
	Medium	-.190*	0.059	0.009	-0.321	-0.059

Table 5.7

Descriptive statistics of Pupil Dilation Fluctuations over Time by Difficulty and by Performance.

Descriptive Statistics				
	Easy Correct	**Easy Incorrect**	**Hard Correct**	**Hard Incorrect**
0.5 s	-0.04 (0.57597)	-0.9727 (1.40203)	0.3696 (1.04578)	0.0949 (0.71828)
1 s	-0.1448 (0.64371)	-1.0582 (1.46037)	0.0369 (1.05415)	-0.0611 (0.69778)
1.5 s	-0.024 (0.64035)	-0.9483 (1.13091)	0.2264 (0.71418)	0.1038 (0.85008)
2 s	0.4373 (0.694)	-0.4659 (1.36511)	0.4318 (0.75151)	0.5072 (0.98583)
2.5 s	0.6268 (0.78318)	-0.4808 (1.61644)	0.6935 (0.82222)	0.647 (1.14966)
3 s	0.6903 (0.89567)	-0.2872 (1.47476)	0.8385 (1.16209)	0.8336 (1.44613)
3.5 s	0.7182 (0.82221)	-0.1291 (0.86221)	0.9347 (1.30531)	1.0224 (1.7236)
4 s	0.8067 (0.75872)	-0.1358 (1.10331)	0.9721 (1.28132)	1.1342 (1.67524)
4.5 s	0.952 (0.79723)	-0.0885 (0.94403)	0.6884 (1.37249)	1.2671 (1.81782)
5 s	1.1718 (0.86037)	0.2702 (1.41725)	0.7208 (1.42103)	1.4009 (1.94572)
5.5 s	1.3233 (0.71626)	0.4687 (1.67641)	0.918 (1.58019)	1.3901 (1.89728)
6 s	1.4525 (0.74776)	0.6366 (2.1213)	1.3129 (1.68955)	1.2861 (1.75699)
6.5 s	1.4202 (0.65231)	0.3911 (2.0236)	1.5738 (1.77336)	1.1957 (1.88982)
7 s	1.2983 (0.75516)	0.3926 (1.77299)	2.0277 (2.00524)	1.3477 (1.86911)
7.5 s	1.2242 (0.69429)	0.5787 (1.62069)	2.0276 (1.87223)	1.5734 (2.09894)
8 s	1.1183 (0.74412)	0.6022 (1.66538)	2.1763 (1.62751)	1.8745 (2.25943)
8.5 s	1.0111 (0.84026)	0.5118 (1.59188)	2.2038 (1.50984)	1.7936 (2.10833)
9 s	0.9003 (0.85488)	0.6487 (1.53856)	2.2732 (1.74157)	2.179 (1.98799)
9.5 s	0.7761 (0.73938)	0.5439 (1.93281)	2.0637 (1.60401)	2.2645 (1.92052)
10 s	0.5218 (0.63906)	0.495 (1.68751)	2.0424 (1.4342)	2.3283 (2.19603)

Table 5.8

Repeated measures ANOVA comparing Pupil Dilation Fluctuations by Time by Performance and by Difficulty.

Tests of Within-Subjects Effects

Source	df	Sum of Squares	Mean Squares	F	Sig.
Difficulty	124.047	1	124.047	3.762	0.084
Error(Difficulty)	296.759	9	32.973		
Performance	30.485	1	30.485	4.402	0.065
Error(Performance)	62.333	9	6.926		
Time	256.112	19	13.480	19.856	0.000
Error(Time)	116.088	171	0.679		
Difficulty * Performance	27.819	1	27.819	1.187	0.304
Error(Difficulty * Performance)	210.924	9	23.436		
Difficulty * Time	32.514	19	1.711	2.320	0.002
Error(Difficulty * Time)	126.114	171	0.738		
Performance * Time	10.144	19	0.534	1.757	0.031
Error(Performance * Time)	51.949	171	0.304		
Difficulty * Performance * Time	10.296	19	0.542	1.237	0.233
Error(Difficulty * Performance * Time)	74.920	171	0.438		

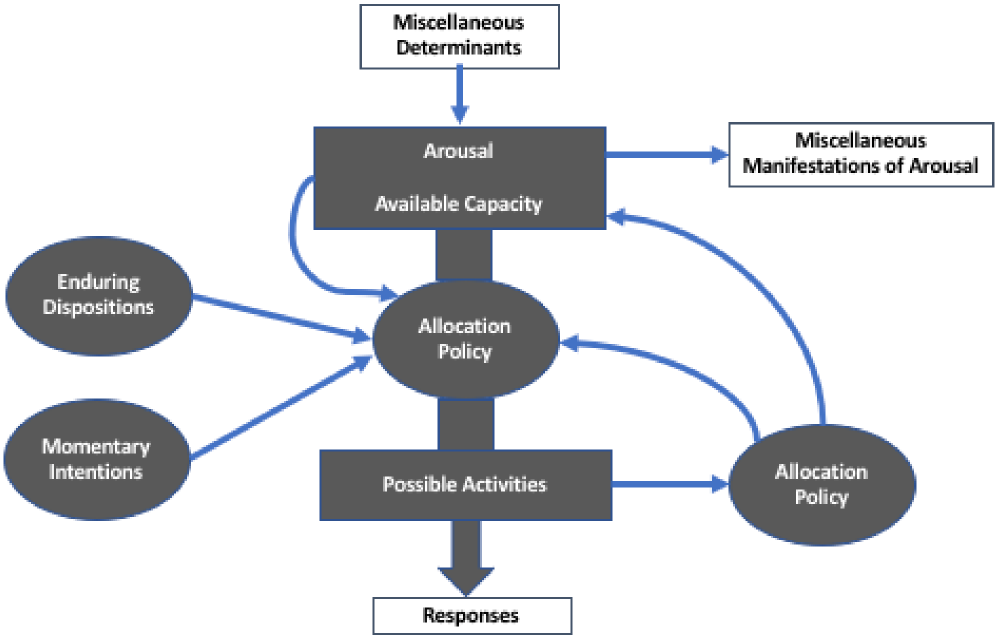


Figure 1.1. Illustration of the capacity model of attention presented by Kahneman (1973). Possible activities refer to the possible tasks presented, which can be processed by related brain structures to then elicit responses. The activation of related brain structures for processing requires attentional inputs regulated by the allocation policy. In order to allocate attentional inputs, there must be sufficient available capacity of attention networks. Other less controllable factors determine the allocation policy, including enduring dispositions, momentary intentions, and changes in arousal. Adapted from Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice-Hall.

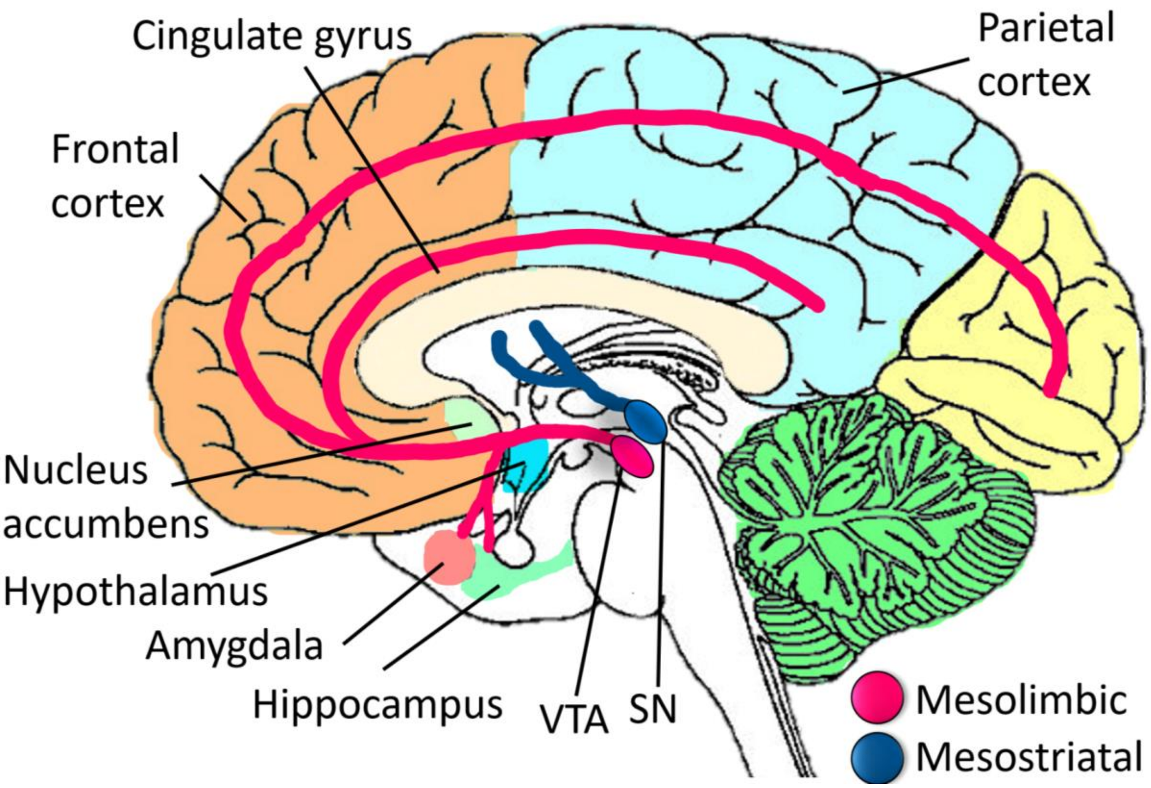


Figure 1.2. Diagram of the mesolimbic and mesostriatal dopaminergic pathways. The mesolimbic pathway (pink) innervates several brain regions associated with attention, such as the frontal cortex and nucleus accumbens. The mesolimbic dopamine pathway is thought to be involved in attentional processes. The mesostriatal pathway (blue) innervates midbrain structures, like the basal ganglia, and is primarily involved in motor functions.

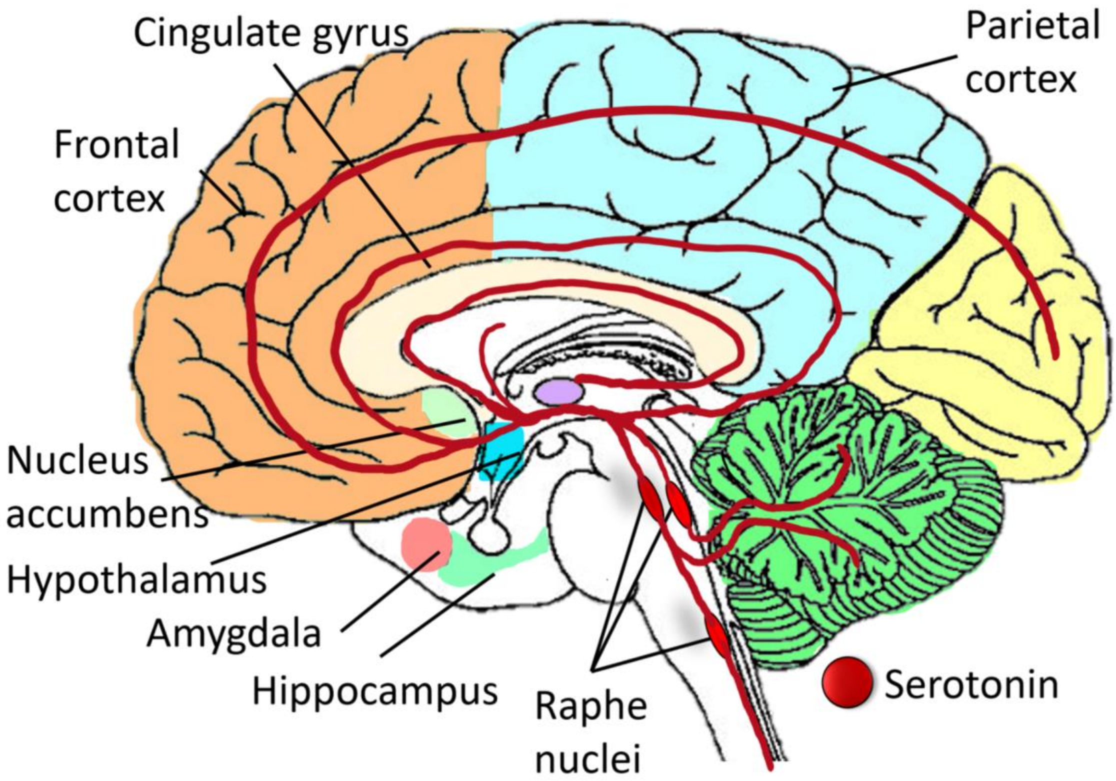


Figure 1.3. Diagram of the serotonergic pathways of the brain. Serotonin is primarily produced in the raphe nuclei in the brainstem. Serotonin neurons project (red) from the raphe nuclei into the spinal cord, cerebellum, frontal lobe, parietal lobe, and the thalamus in the midbrain.

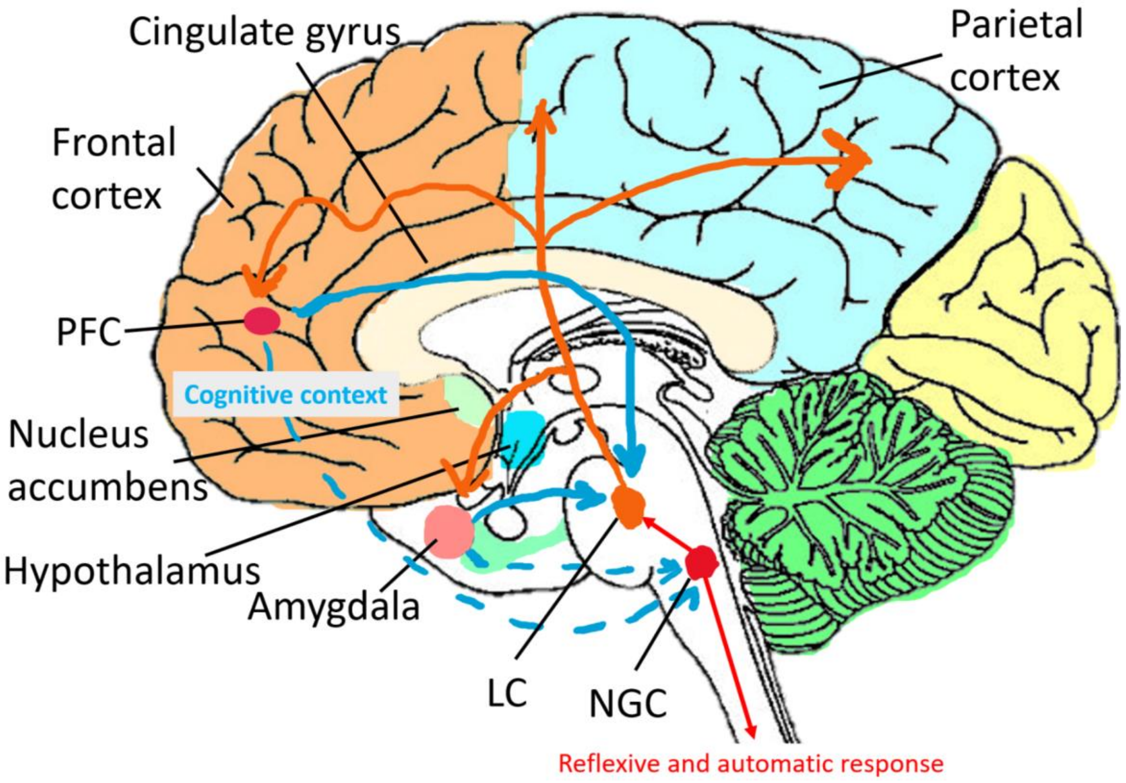


Figure 1.4. Diagram of the norepinephrine pathways. Norepinephrine is produced in the Locus coeruleus (LC). Norepinephrine neurons project from the LC forming pathways (orange) to the frontal cortex, parietal cortex, occipital cortex, and the amygdala. Proposed LC mechanism of activation, via LC inputs (blue) and nucleus giganis cellularis (NGC) (red) is also displayed. Adapted from Sara, S., & Bouret, S. (2012). Orienting and reorienting: The locus coeruleus mediates cognition through arousal. *Neuron, 76*(1), 130-141.

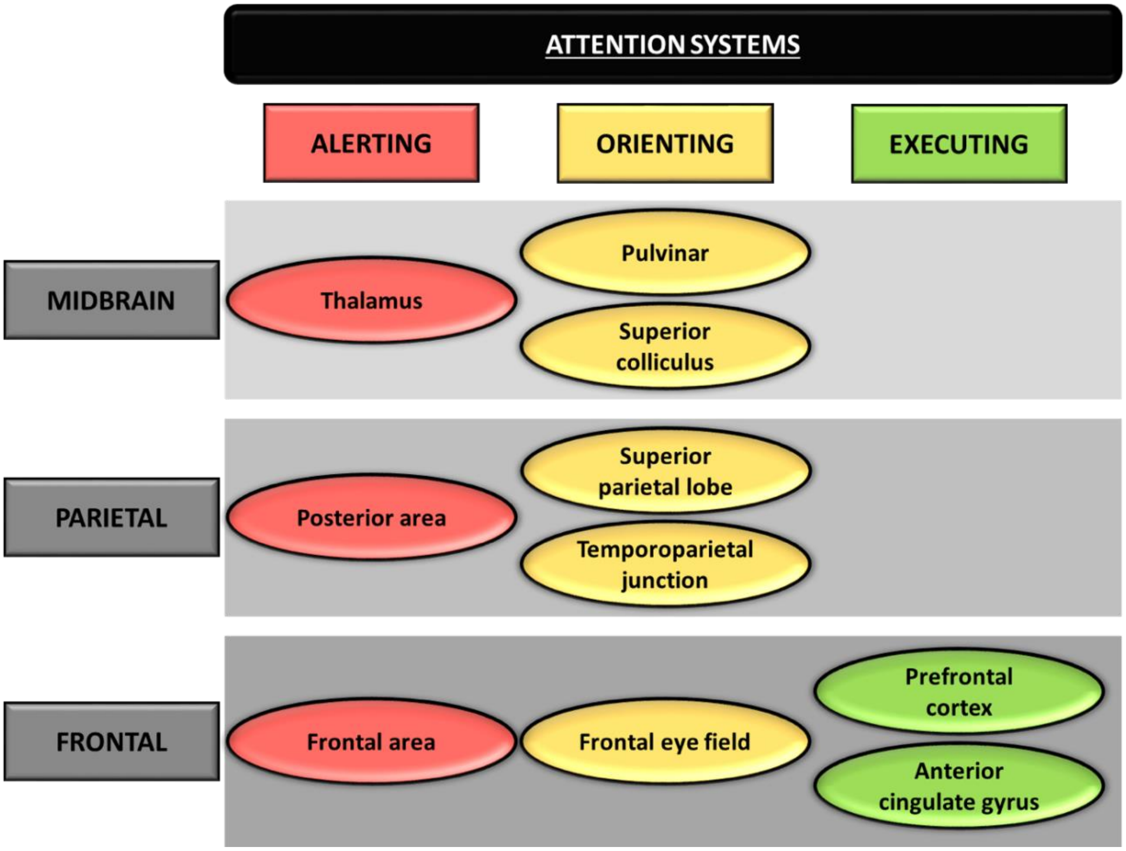


Figure 1.5. Schematic of Posner's attention networks model. The model presents three attention systems: the alerting system, the orienting system, and the executing system. Each attentional system engages brain structures in the midbrain, parietal lobe, and frontal lobe. Adapted from Cornish, K., & Wilding, J. M. (2010). *Attention, genes, and developmental disorders*. Oxford: Oxford University Press.

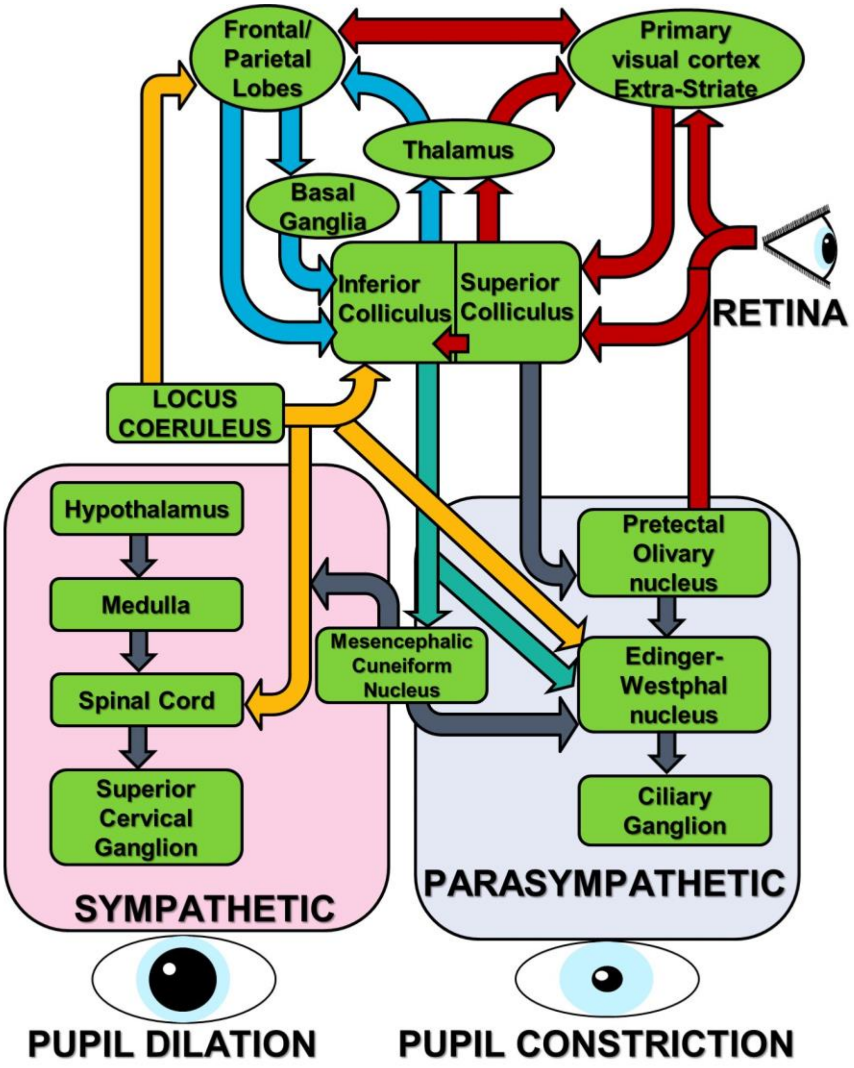


Figure 3.1. Diagram of the neural pathways involved in the regulation of pupil dilation. Pupil diameter is regulated by antagonistic pathways of the sympathetic and parasympathetic nervous systems. Preganglionic parasympathetic neurons in the Edinger-Westphal nucleus that project to the ciliary ganglion regulate constriction of the sphincter pupillae, which is responsible for pupillary constriction. Sympathetic spinal cord nerves project to the superior cervical ganglion, which controls the dilator pupillae contraction that causes pupil dilation. Adapted from Wang, C. & Munoz, D. (2015) A circuit for pupil orienting responses: implications for cognitive modulation of pupil size. *Neurobiology, 33, 134-140.*

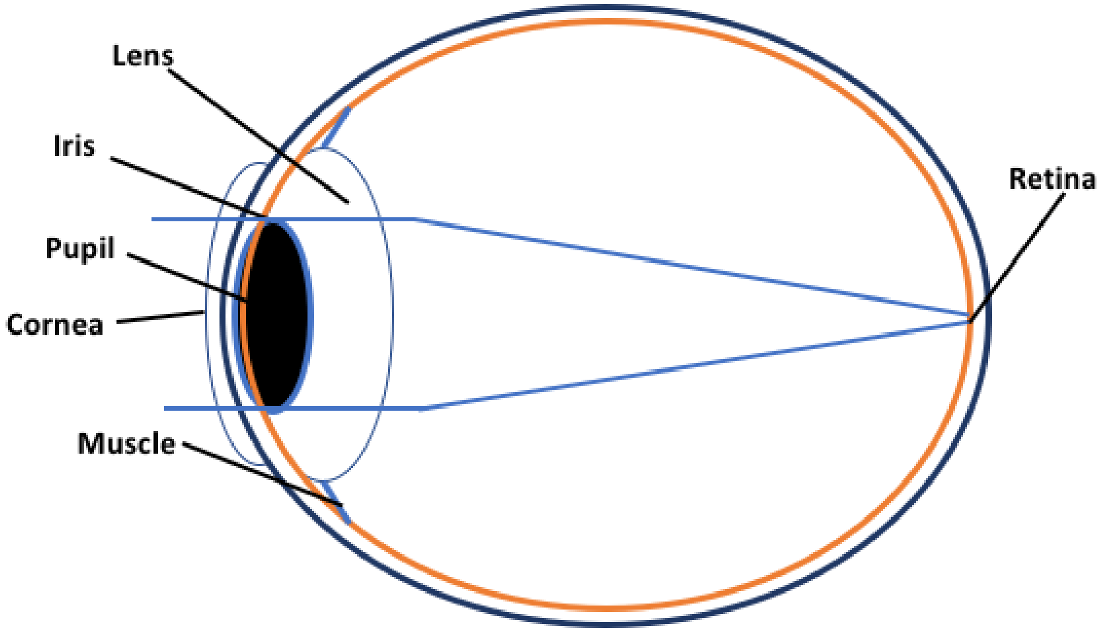


Figure 3.2. General diagram of the anatomy of the eye. The diagram shows the general structure of the eye. The pupil is a hole (black oval) formed by the iris (blue oval). Light passes through the pupil to the retina where photoreceptors initiate visual processing.

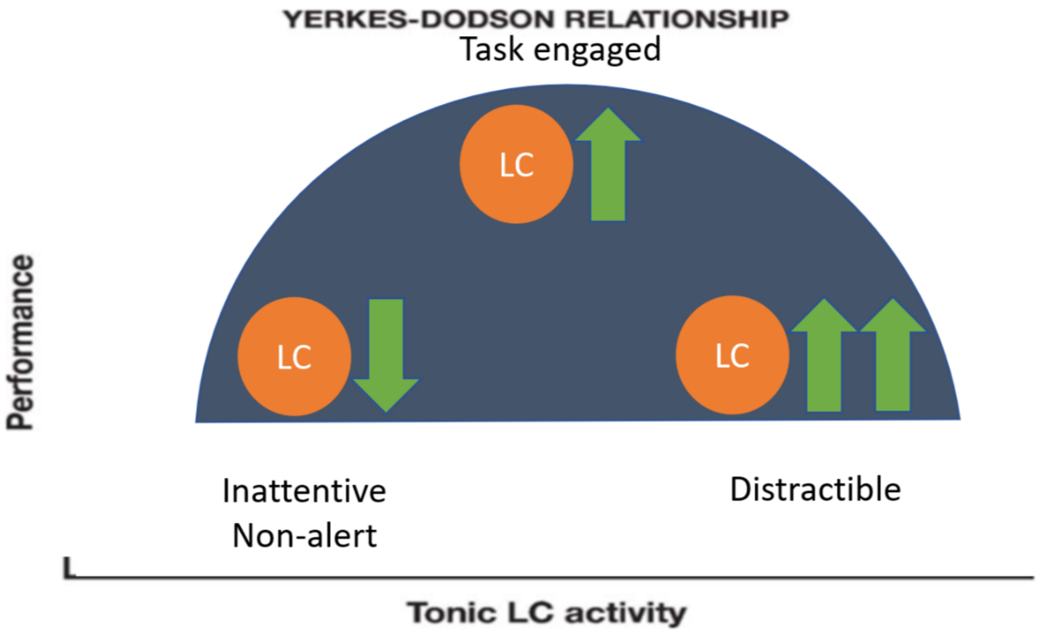
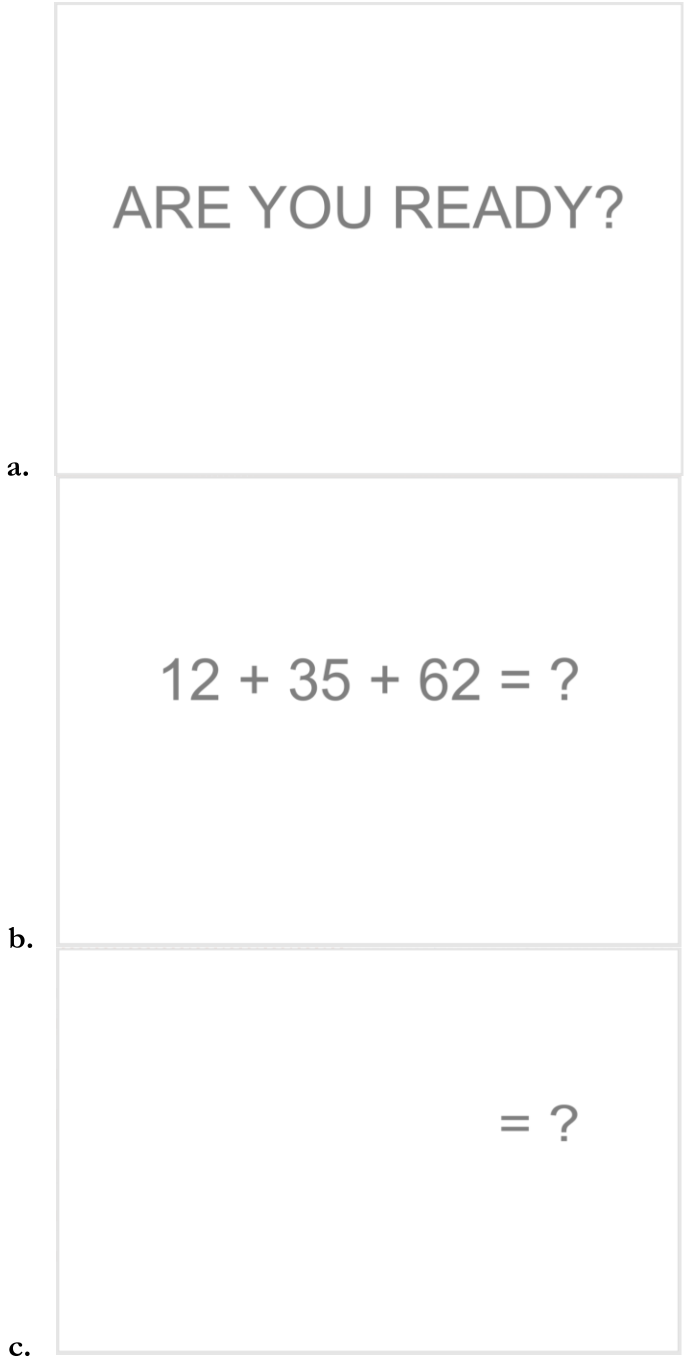


Figure 3.3. Schematic of the relationship among the Yerkes-Dodson curve, Locus coeruleus activity, and attention. Low Locus coeruleus (LC) activity (green downward arrow) is associated with low task performance (y-axis) and inattentive behavior. Intermediate LC activity (single green upward arrow) is associated with optimal task performance and task engagement. High LC activity (two green upward arrows) is associated with low task performance and distractibility. Adapted from Aston-Jones, G. and Cohen, J., (2005) An Integrative Theory of Locus coeruleus-Norepinephrine Function: Adaptive Gain and Optimal Performance, Annual Review of Neuroscience, 28:403–50.



ARE YOU READY?

12 + 35 + 62 = ?

= ?

Figure 4.1. Mental arithmetic task example slides. Before each mental arithmetic problem, the baseline pupil dilation was recorded for 5 seconds while slide a appeared on the screen (a). Following baseline recording, the mental arithmetic problem appeared on the screen for 10 seconds (b). After the mental arithmetic problem disappeared a final response slide appeared on the screen for 2 seconds (c), before baseline recording began for the next problem.

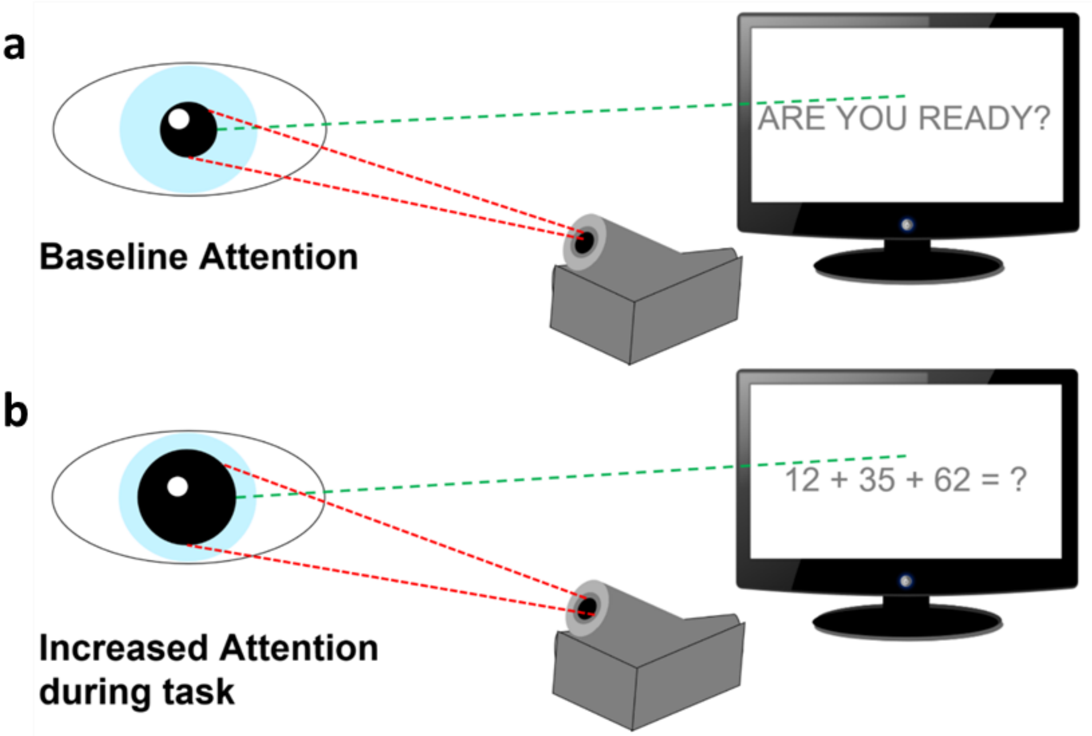


Figure 4.2. Diagram of pupil diameter recording during the mental arithmetic task. The diagram shows the infrared camera of the eye tracker record pupil diameter (red dashed line) during the (a) baseline recording while the words “ARE YOU READY” appeared on the screen and during the (b) mental arithmetic task while the problem appeared on the screen. Pupil diameter during the task was subtracted by the average baseline pupil diameter in order to calculate the change in pupil dilation.

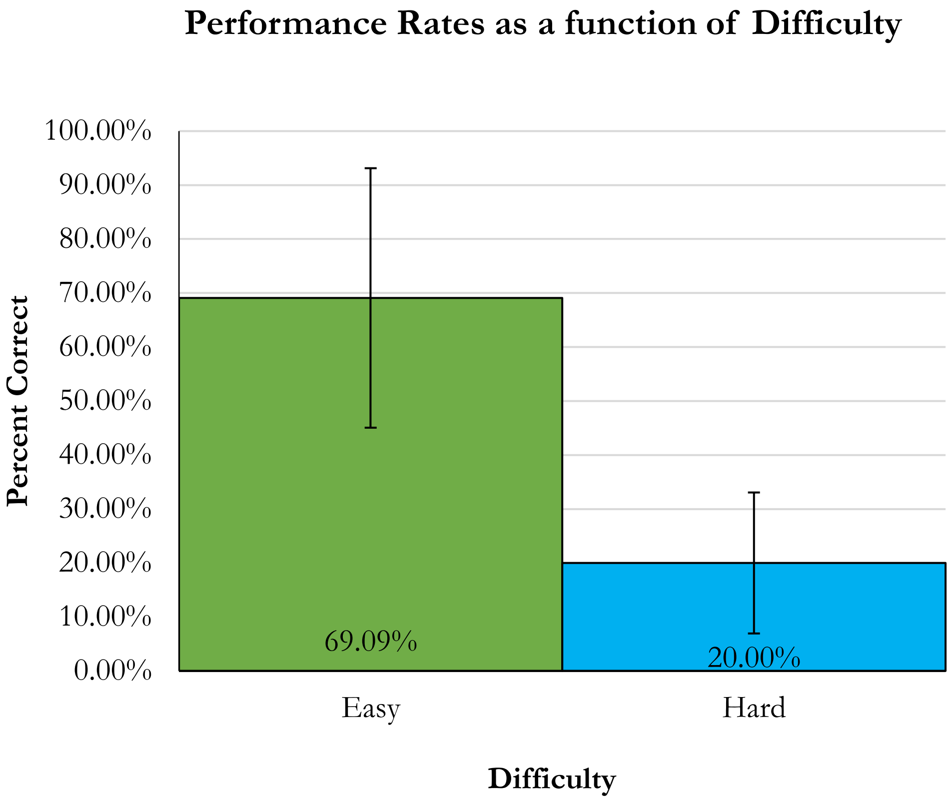


Figure 5.1. The average percent correct on problems by problem difficulty with 2-levels. The average percent on easy problems is shown in green and the average percent on hard problems is shown in blue.

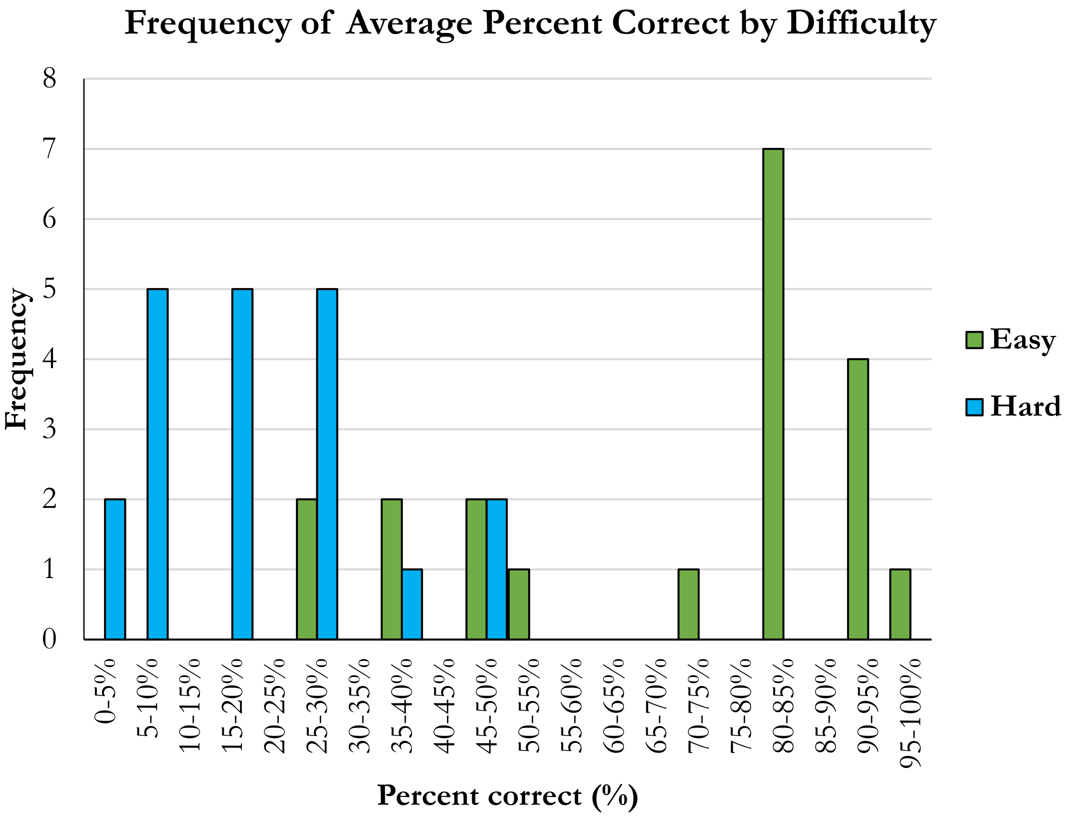


Figure 5.2. The frequency of performance rates on problems by problem difficulty. Hard problems (blue) had performance rates ranging from 0-50%. Easy problems (green) had performance rates ranging from 25-100%. (Note: easy problems had a larger range of performance.)

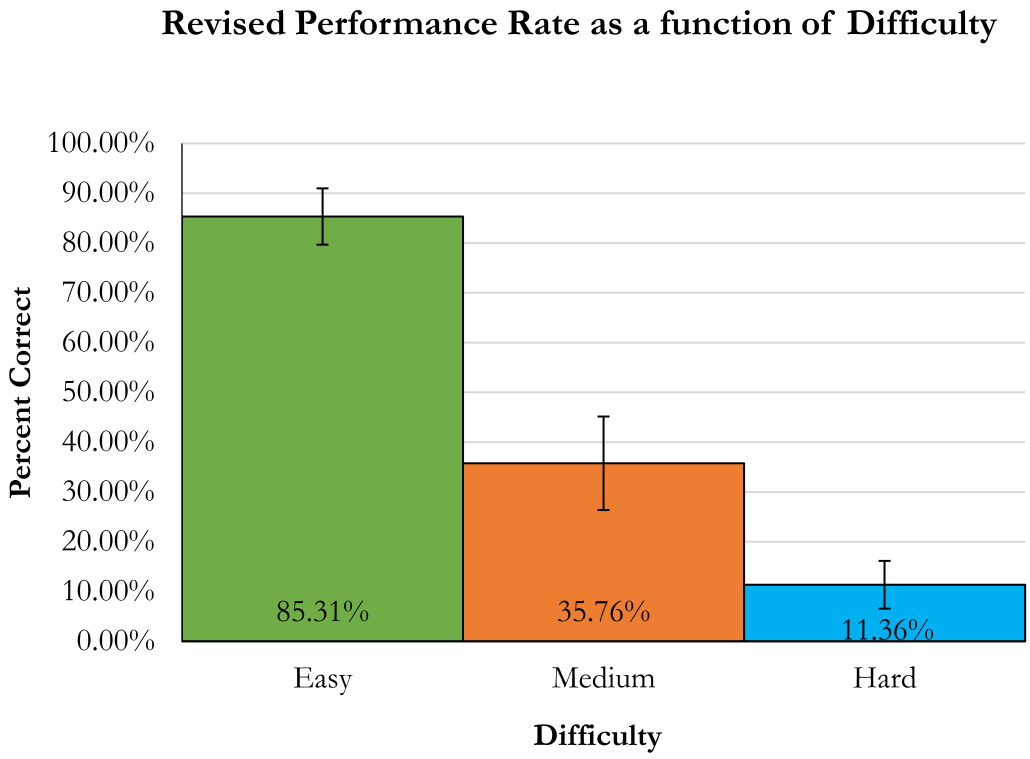


Figure 5.3. The average percent correct on problems by problem difficulty with 3-levels. The average percent correct on easy problems is shown in green, on medium problems is shown in orange, and on hard problems is shown in blue.

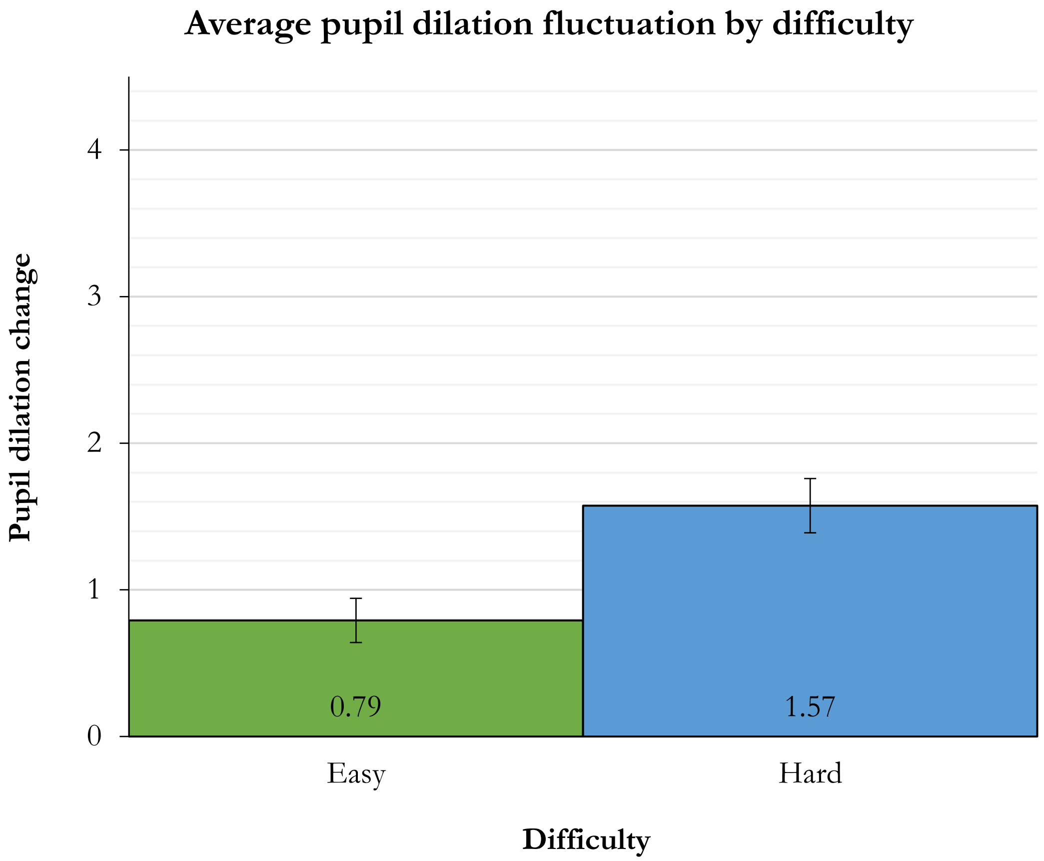


Figure 5.4. Bar graph shows pupil dilatation fluctuation as a function of difficulty. Average pupil dilation fluctuation on easy problems (green) and hard problems (blue) is shown.

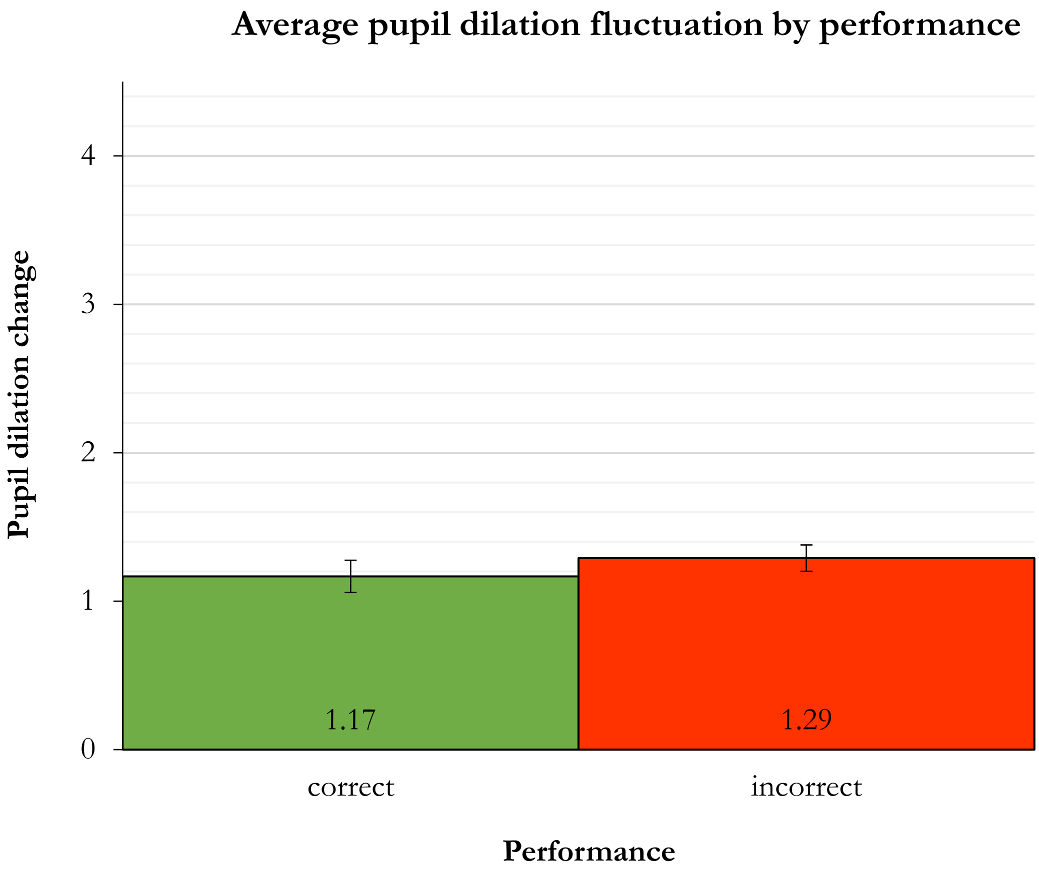


Figure 5.5. Bar graph shows pupil dilatation fluctuation as a function of performance. Average pupil dilation fluctuation on correct problems (green) and incorrect problems (red) is shown.

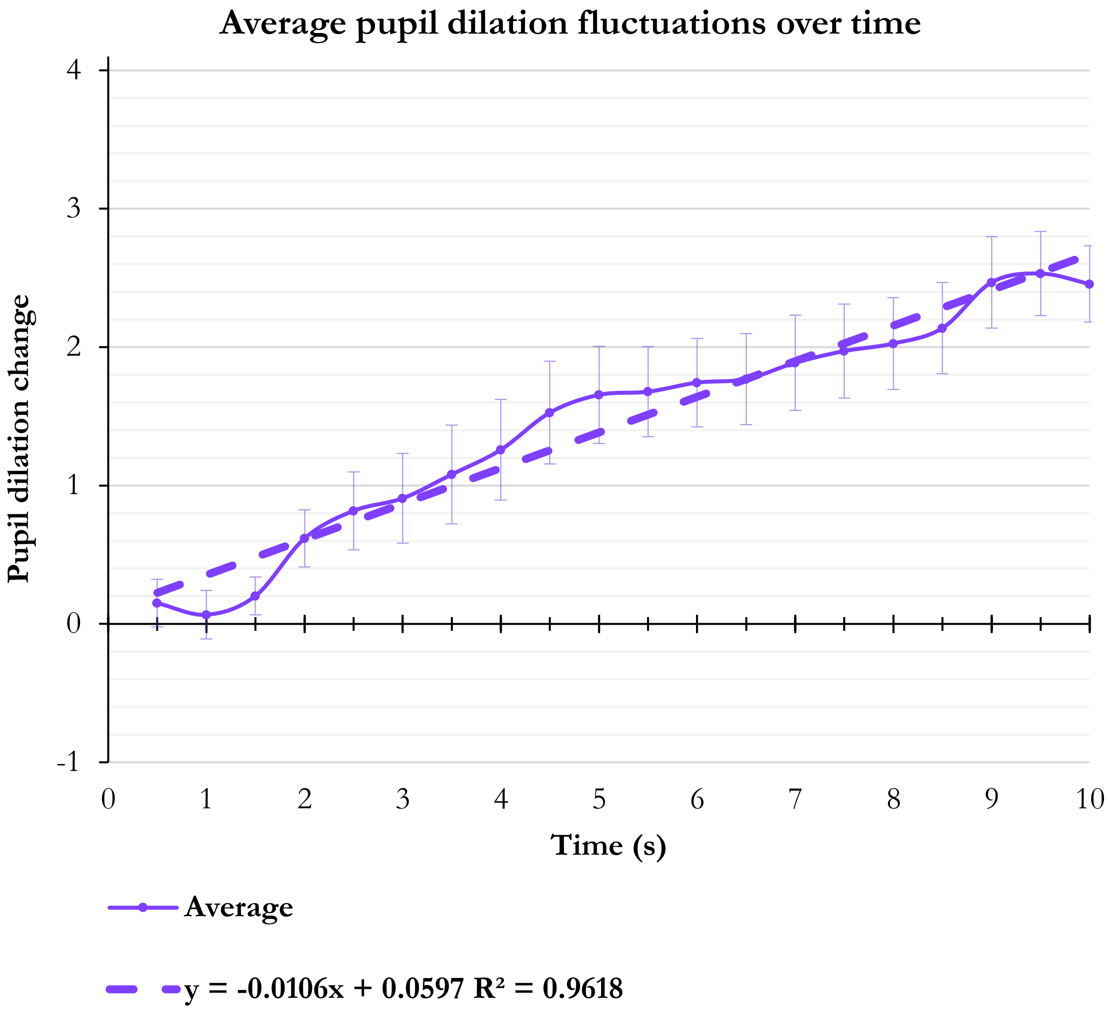


Figure 5.6. Line graph showing pupil dilation fluctuation as a function of time. Pupil dilation fluctuation over time is shown by the thin continuous line. The curve that best described the pupil dilation fluctuation over time is shown as the thick dashed line.

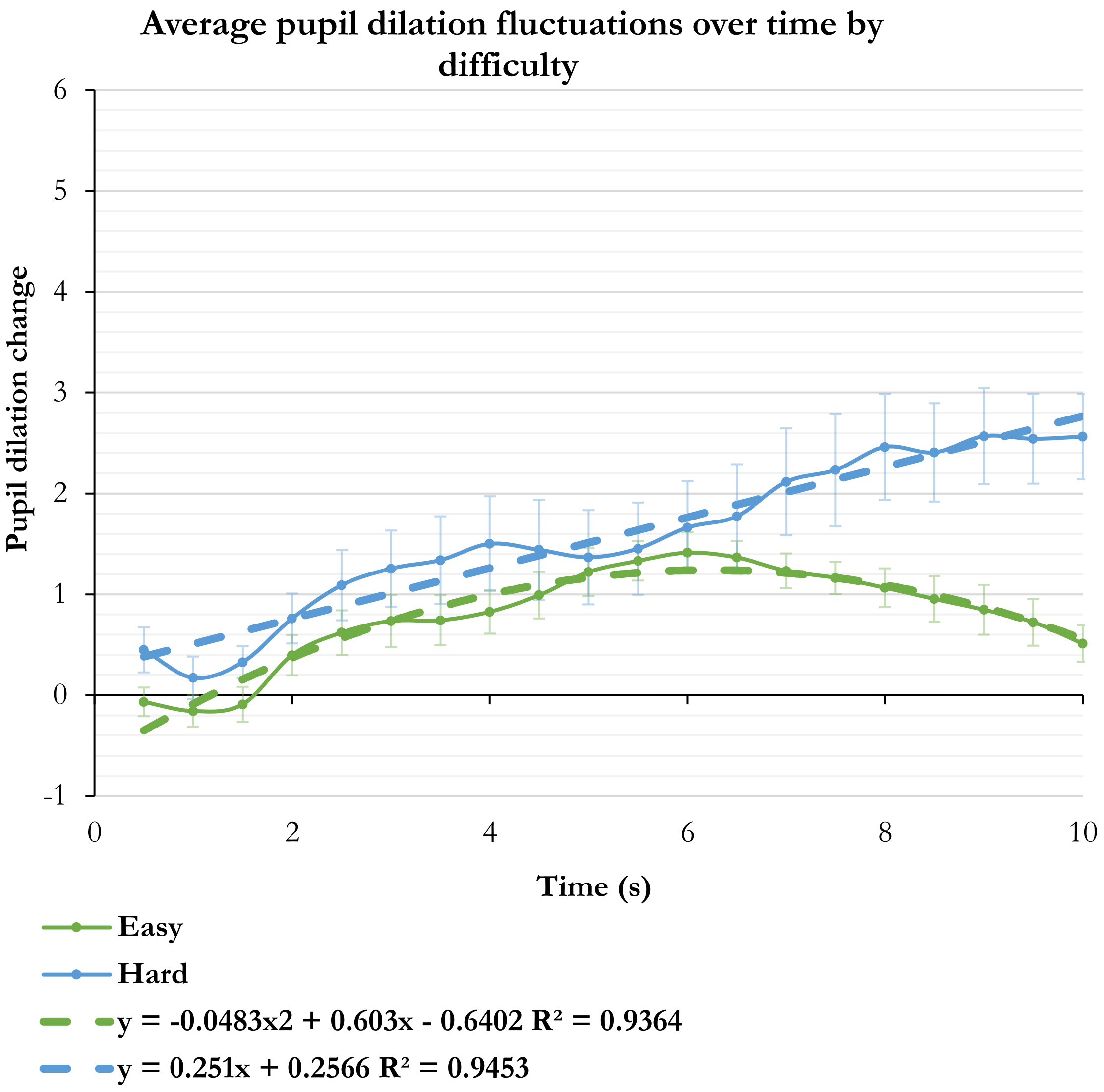


Figure 5.7. Line graph showing pupil dilation fluctuation as a function of time by difficulty. Pupil dilation fluctuation over time is shown by the thin continuous line for easy problems (green) and hard problems (blue). The curve that best described the pupil dilation fluctuation over time is shown as a thick dashed line for easy problems (green) and hard problems (blue).

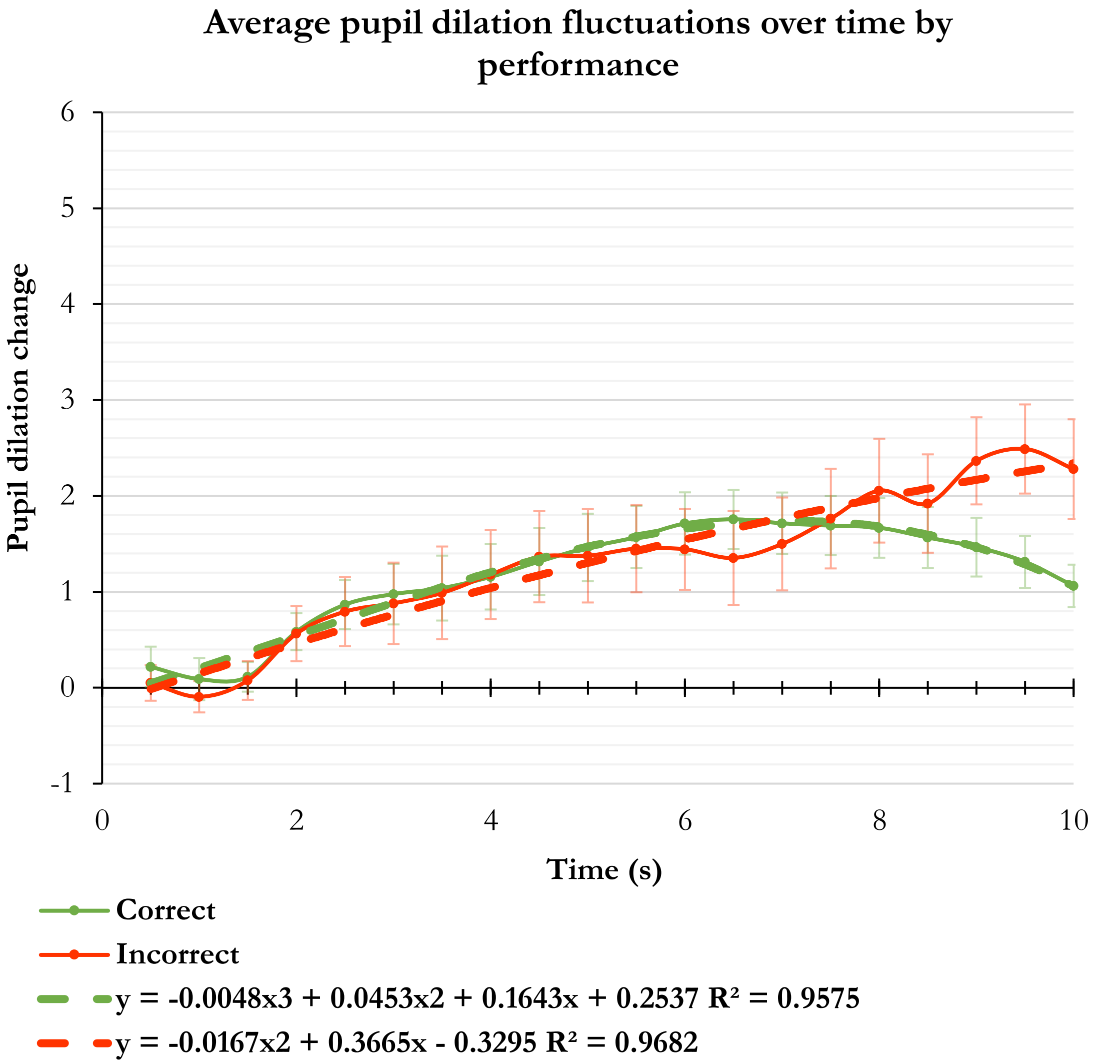


Figure 5.8. Line graph showing pupil dilation fluctuation as a function of time by performance. Pupil dilation fluctuation over time is shown by the thin continuous line for correct problems (green) and incorrect problems (red). The curve that best described the pupil dilation fluctuation over time is shown as a thick dashed line for correct problems (green) and incorrect problems (red).

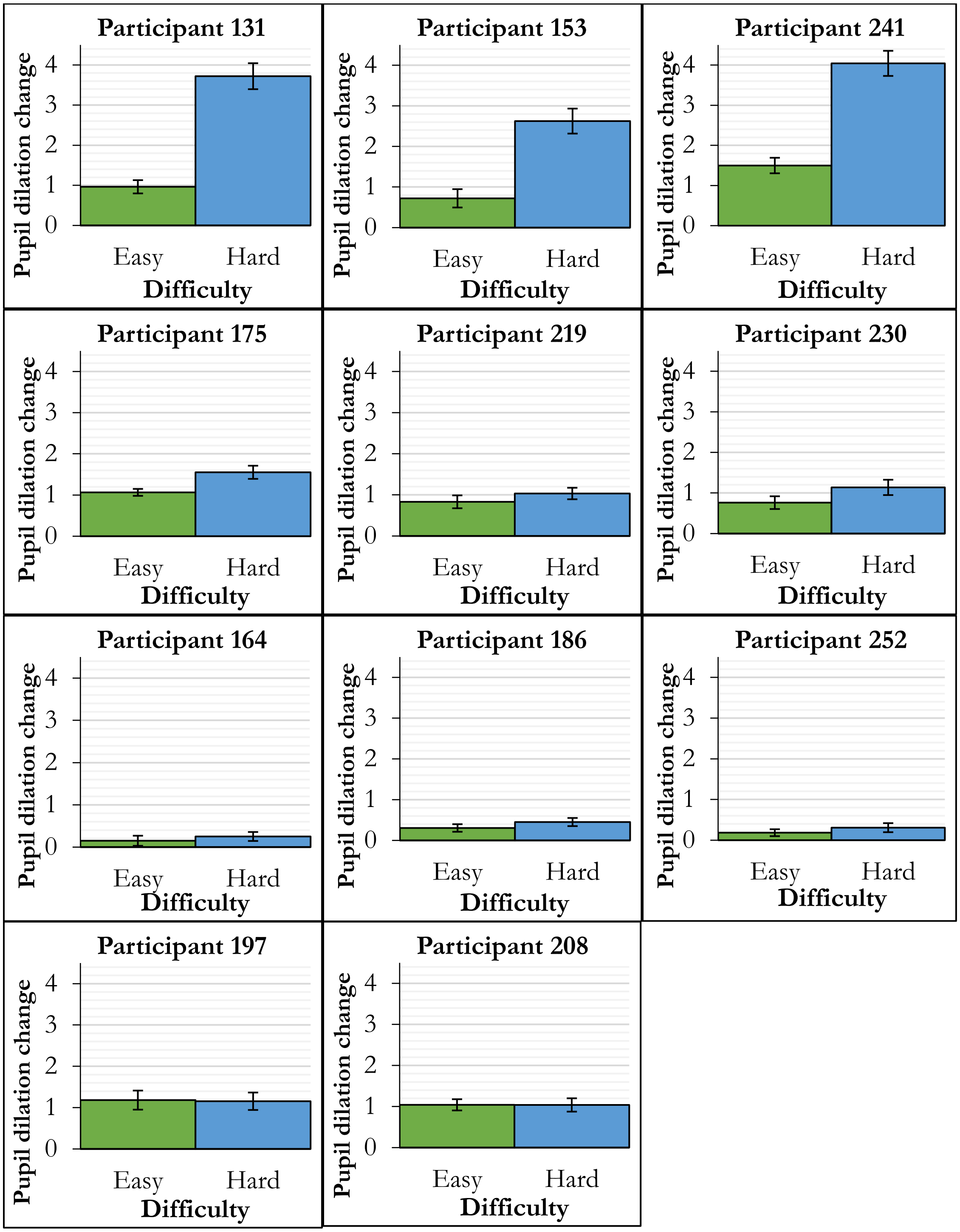


Figure 5.9. Bar graph showing individual participants' average pupil dilatation fluctuations as a function of difficulty. Pupil dilation fluctuations on easy problems are shown by green bars and pupil dilation fluctuations on hard problems are shown by blue bars.

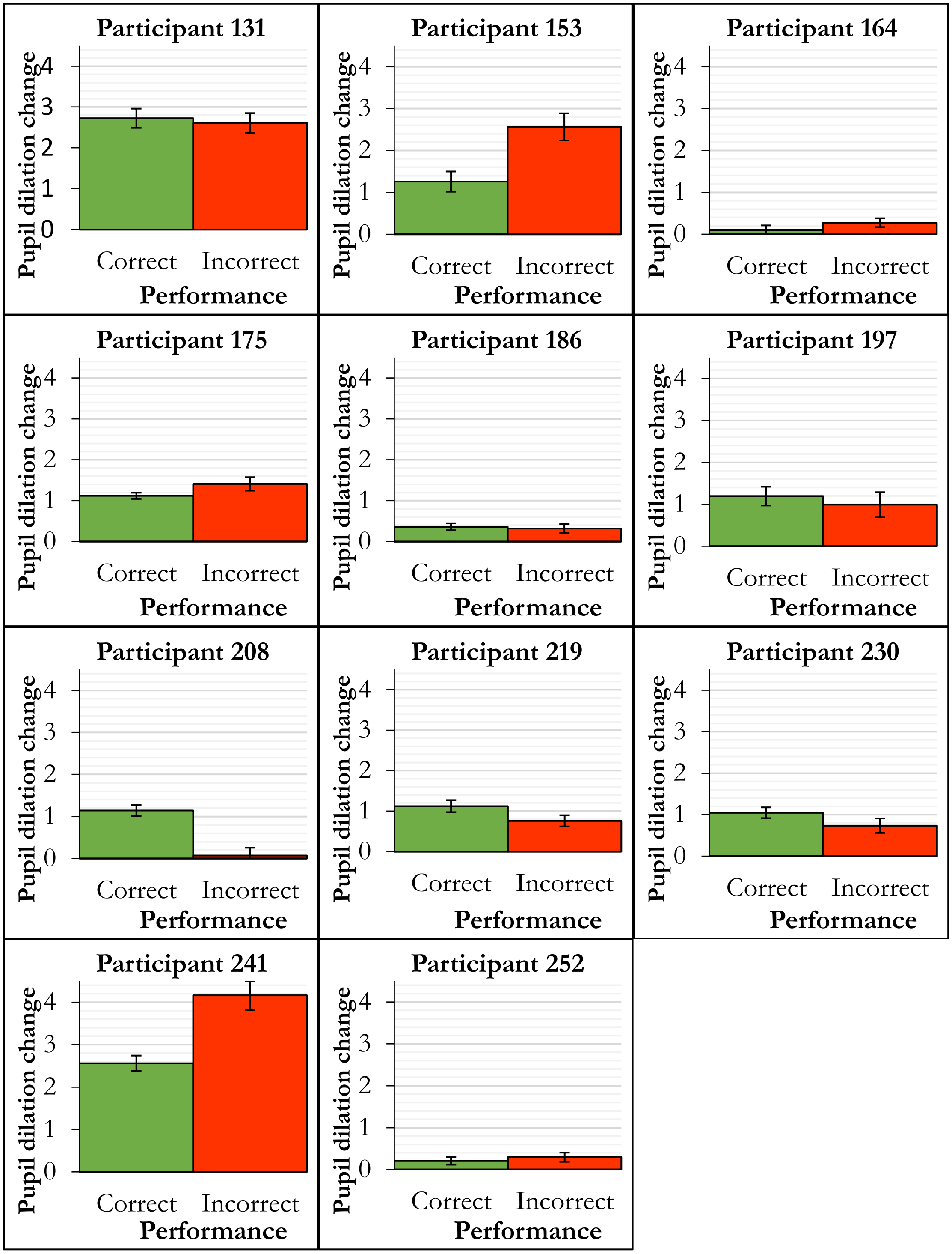


Figure 5.10. Bar graph showing individual participants' average pupil dilatation fluctuations as a function of performance. Pupil dilation fluctuations on correct problems are shown by green bars and pupil dilation fluctuations on incorrect problems are shown by red bars.

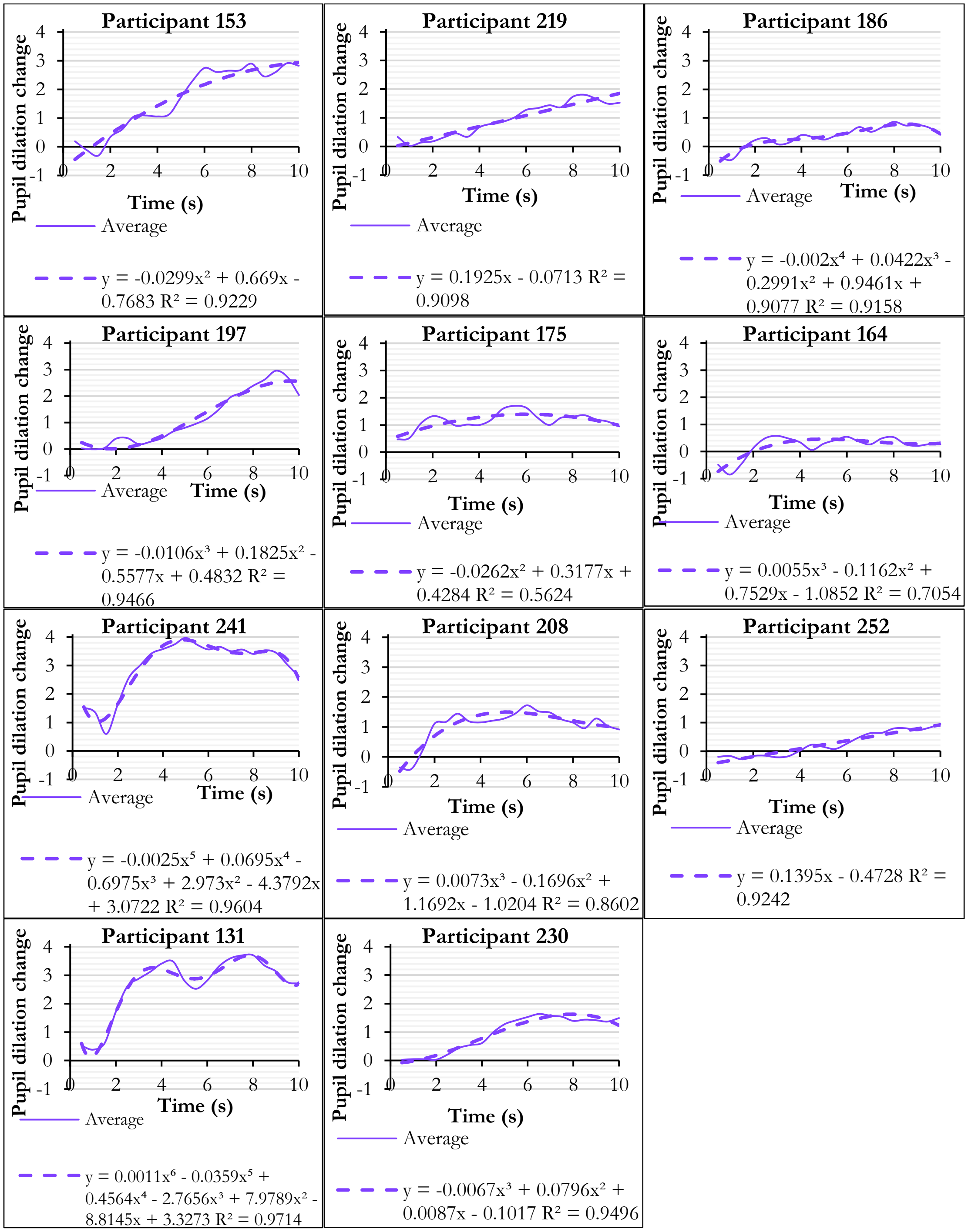


Figure 5.11. Line graph showing individual participants' pupil dilatation fluctuations as a function of time. Pupil dilation fluctuation data over time are shown by the solid, thin purple line. The best fit trendline describing the pupil dilation fluctuation data over time is shown by the thick dashed purple line.

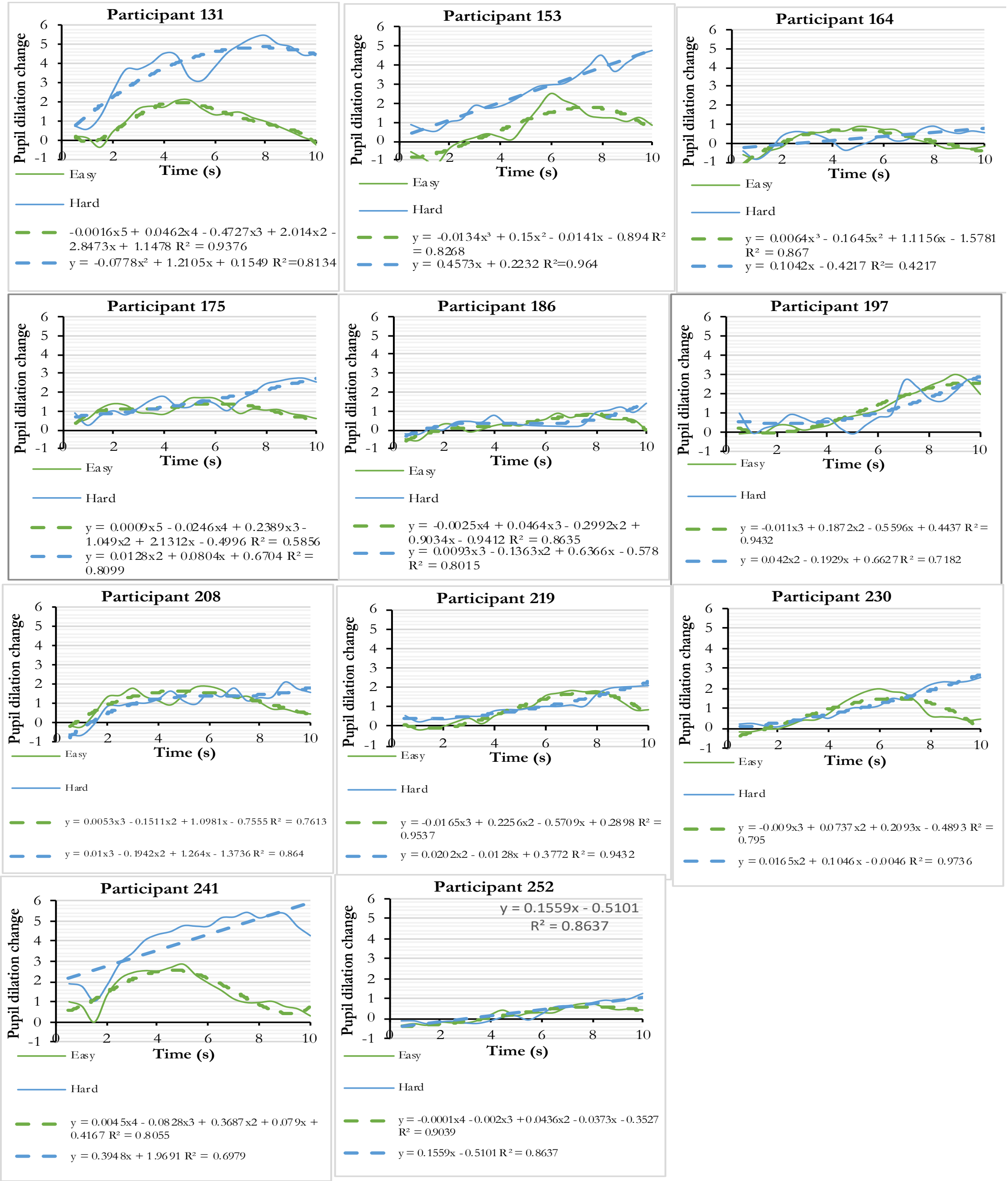


Figure 5.12. Line graph showing individual participants' pupil dilatation fluctuations as a function of time by difficulty. Pupil dilation fluctuation data over time are shown by the solid, thin lines for easy problems (green) and hard problems (blue). The best fit trendline describing the pupil dilation fluctuation data over time is shown by the thick dashed lines for easy problems (green) and hard problems (blue).

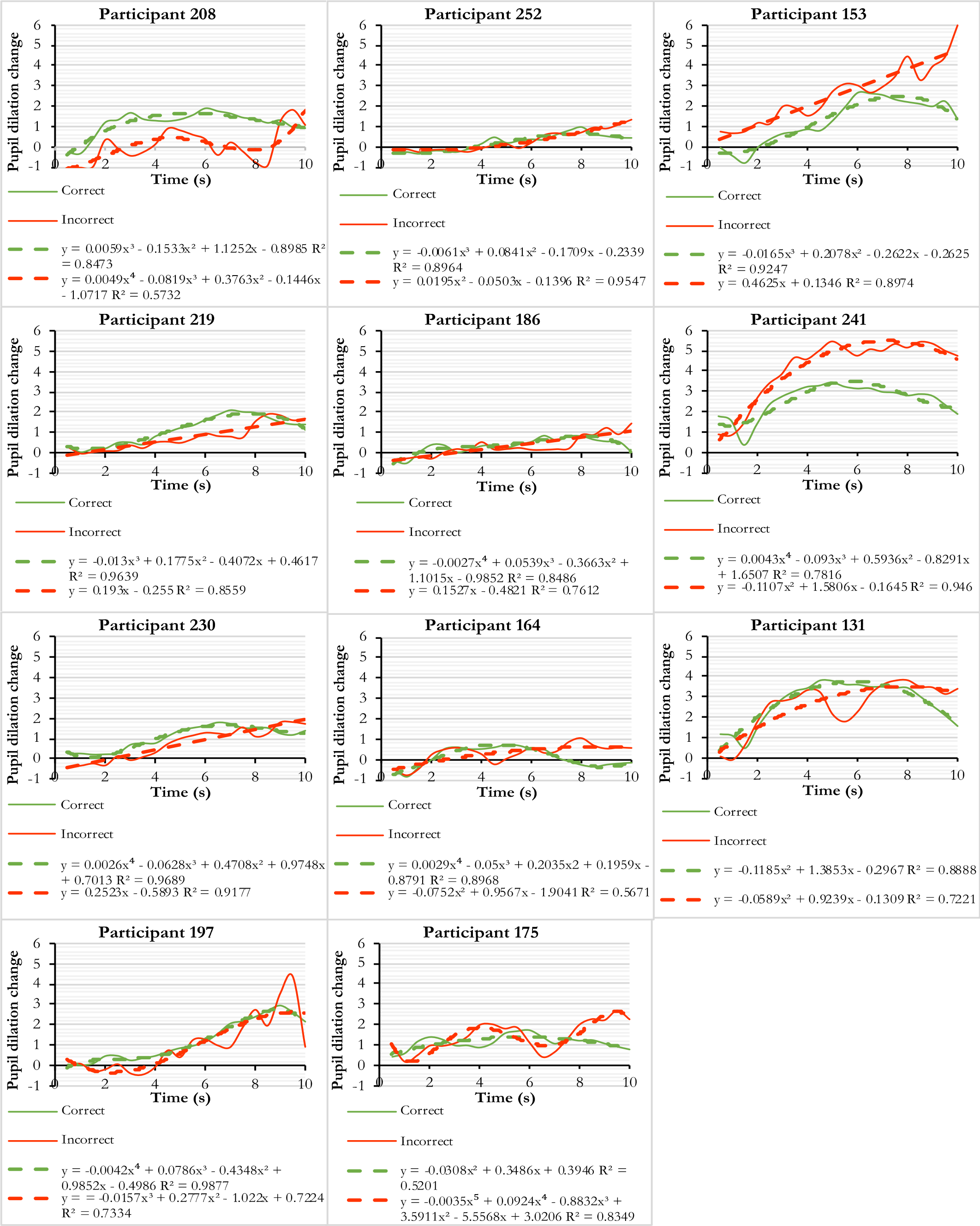
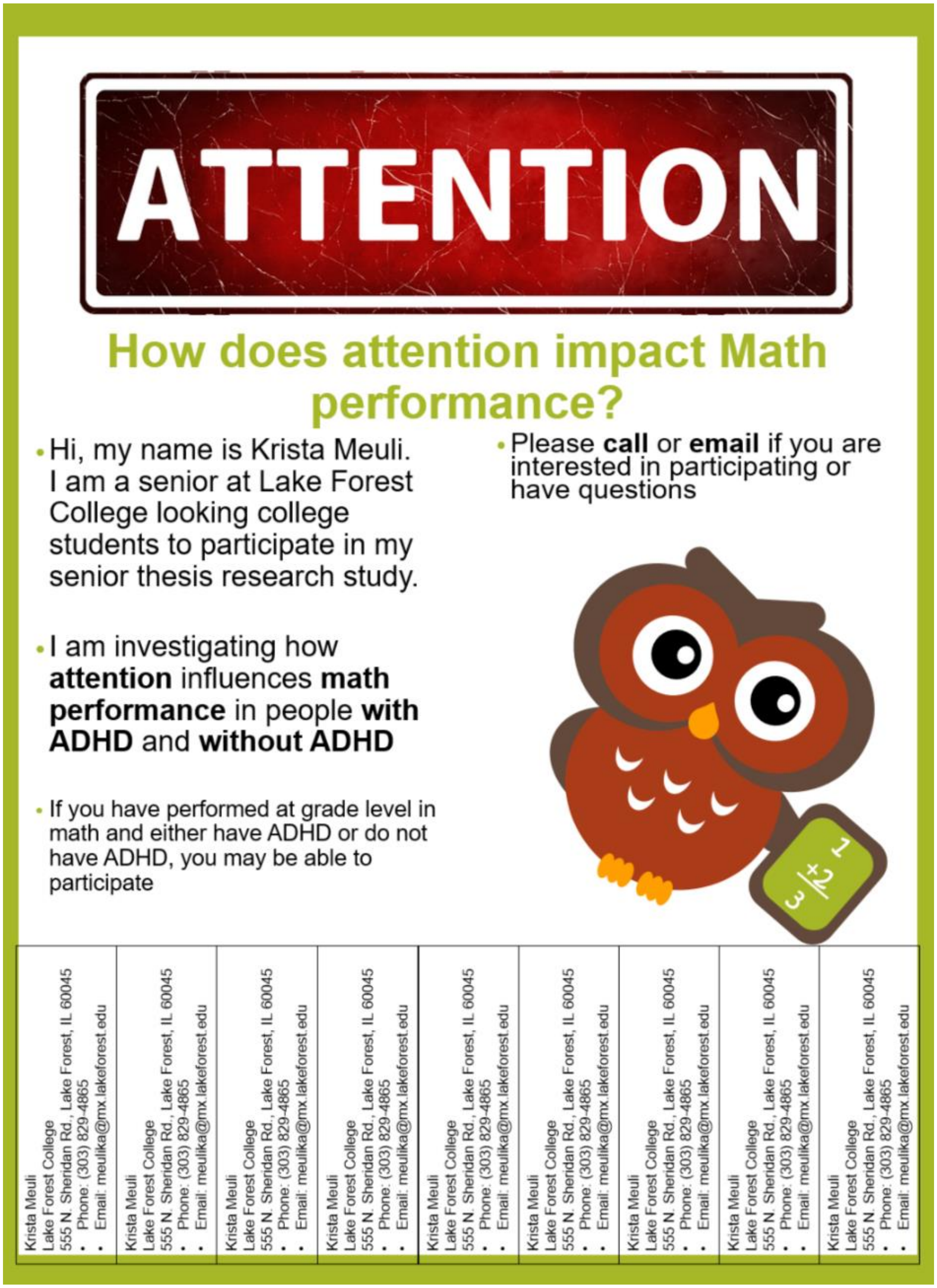


Figure 5.13. Line graph showing individual participants' pupil dilatation fluctuations as a function of time by performance. Pupil dilation fluctuation data over time are shown by the solid, thin lines for correct problems (green) and incorrect problems (rec). The best fit trendline describing the pupil dilation fluctuation data over time is shown by the thick dashed lines for correct problems (green) and incorrect problems (red).

Appendix

Appendix A

Recruitment flyer



ATTENTION

How does attention impact Math performance?

- Hi, my name is Krista Meuli. I am a senior at Lake Forest College looking college students to participate in my senior thesis research study.
- I am investigating how **attention** influences **math performance** in people **with ADHD** and **without ADHD**
- If you have performed at grade level in math and either have ADHD or do not have ADHD, you may be able to participate
- Please **call** or **email** if you are interested in participating or have questions

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Appendix B

Recruitment follow-up email

Hello!

My name is Krista Meuli. I am contacting you to follow up regarding your indication that you would be interested in participating in my study. Thank you for your interest in participating in my senior thesis study.

Additional information:
My study is investigating how fluctuations in attention relate to math performance in people with and without Attention Deficit/ Hyperactivity Disorder (ADHD). To measure changes in attention, I will track changes in participants' pupil dilation using an ISCAN eye tracker, which tracks eye movements and pupillary changes by tracking the reflection of light on the eye. This will require you to sit fairly still while the eye tracker is calibrated to their eyes and for the duration of the task, a total of less than 20 minutes. The task will involve solving a set of mental arithmetic problems in a limited amount of time. The problems will involve basic addition.

I am happy to answer any further questions about my study. If you feel you will be willing and able to perform the tasks in my study, I would like to set up an appointment. Please let me know a time that you are available based on my availability listed below. Only you and members of the lab will be able to see the time for which you sign up. Once you select a date and time for the appointment, you will receive a confirmation of the appointment with directions to the lab. You will also receive a reminder 24 hours before the appointment. This can be via phone call, email, or text message based on your preference.

If you choose to participate in my study, I will ask you to complete a short information questionnaire that you can fill out beforehand and bring with you to the appointment. This questionnaire will ask questions regarding any medical history of attention related conditions and your math abilities. I have attached a copy of the participant information questionnaire. You are welcome to contact me regarding questions about the form. However, if you prefer not to answer any of the questions, unfortunately, you will be unable to participate in my study because the questions on the form ensure you are able to perform the tasks asked of you without undue difficulty or discomfort and that you fit the target population of the study. If you have any of the conditions listed in question 4 (e.g., dyslexia, poor vision), you will, unfortunately, not meet the requirements to participate in the study, as these conditions may influence your ability to perform tasks in the study. If you answer yes for at least one of questions 5-6 (e.g., specific math disability), you may not meet the requirements to participate in the study because this study is specifically investigating math performance in people who have performed at grade level. If you answer yes to question 7(i.e., math anxiety), you may not meet the requirements to participate in the study because participation may cause undue stress for you. Again, please feel free to call or email me if you have any questions about your eligibility for this study. I can be reached at 303-829-4865. If I do not answer, please leave your name and number and I will get back to you as soon as possible.

Notes for the visit:

- Please bring the completed participant information questionnaire.

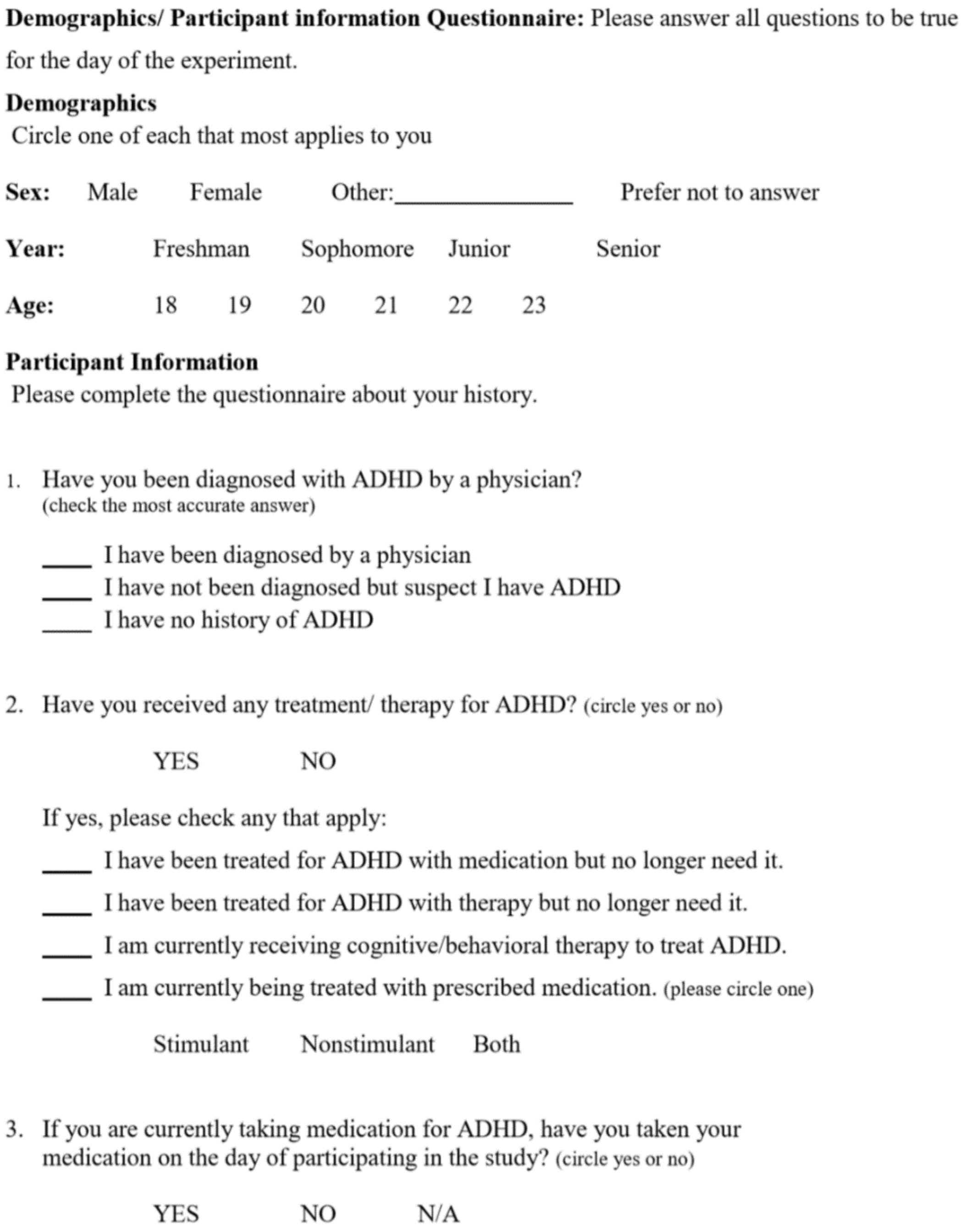
Availability:

- Mondays: 8am – 3pm & after 6pm
- Tuesdays: after 1pm
- Wednesdays: 8am – 2pm & after 4:30pm
- Fridays: 8am – 2pm & after 4:30pm
- Saturdays: anytime
- Sundays: 8am – 2pm & after 4pm

Thank you again for your interest!

Appendix C

participant demographic/ information questionnaire.



Demographics/ Participant information Questionnaire: Please answer all questions to be true for the day of the experiment.

Demographics
Circle one of each that most applies to you

Sex: Male Female Other:______________ Prefer not to answer

Year: Freshman Sophomore Junior Senior

Age: 18 19 20 21 22 23

Participant Information
Please complete the questionnaire about your history.

1. Have you been diagnosed with ADHD by a physician?
   (check the most accurate answer)

   ____ I have been diagnosed by a physician
   ____ I have not been diagnosed but suspect I have ADHD
   ____ I have no history of ADHD

2. Have you received any treatment/ therapy for ADHD? (circle yes or no)

   YES NO

   If yes, please check any that apply:
   ____ I have been treated for ADHD with medication but no longer need it.
   ____ I have been treated for ADHD with therapy but no longer need it.
   ____ I am currently receiving cognitive/behavioral therapy to treat ADHD.
   ____ I am currently being treated with prescribed medication. (please circle one)

   Stimulant Nonstimulant Both

3. If you are currently taking medication for ADHD, have you taken your medication on the day of participating in the study? (circle yes or no)

   YES NO N/A

4. Have you ever been diagnosed with any of the following conditions/disorders that may influence your ability to pay attention or solve math related problems excluding ADHD? (check all that apply)

____ Dyslexia
____ Poor vision
____ Anxiety disorders
____ Depressive Disorders
____ Sensory Processing Disorder
____ Other: ____

5. Do you have a history of difficulty in math?
(i.e. failing grades, performing below grade level, needing support outside the classroom, etc.)

YES NO

Explain (optional):____

6. Do you have a history of excelling in math beyond grade level?
(i.e. placement in accelerated math classes or classes above grade level)

YES NO

Explain (optional):____

7. Have you ever experienced math related anxiety?

YES NO

If yes, could performing a mental arithmetic task involving basic addition and subtraction provoke any anxiety? ___________________________________