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The relationship between baseline pupil size and intelligence

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ABSTRACT

Pupil dilations of the eye are known to correspond to central cognitive processes. However, the relationship between pupil size and individual differences in cognitive ability is not as well studied. A peculiar finding that has cropped up in this research is that those high on cognitive ability have a larger pupil size, even during a passive baseline condition. Yet these findings were incidental and lacked a clear explanation. Therefore, in the present series of studies we systematically investigated whether pupil size during a passive baseline is associated with individual differences in working memory capacity and fluid intelligence. Across three studies we consistently found that baseline pupil size is, in fact, related to cognitive ability. We showed that this relationship could not be explained by differences in mental effort, and that the effect of working memory capacity and fluid intelligence on pupil size persisted even after 23 sessions and taking into account the effect of novelty or familiarity with the environment. We also accounted for potential confounding variables such as; age, ethnicity, and drug substances. Lastly, we found that it is fluid intelligence, more so than working memory capacity, which is related to baseline pupil size. In order to provide an explanation and suggestions for future research, we also consider our findings in the context of the underlying neural mechanisms involved.

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1. Introduction

Starting in the 1960s it became apparent to psychologists that the size of the pupil is related to more than just the amount of light entering the eyes. Pupil size also reflects internal mental processes. For instance, in a simple memory span task, pupil size precisely tracks changes in memory load, dilating with each new item held in memory and constricting as each item is subsequently recalled (Hess & Polt, 1964; Kahneman & Beatty, 1966). This research established the use of pupil dilations as an indicator of momentary changes in arousal, mental effort, and attention (Beatty & Lucero-Wagoner, 2000; Hess & Polt, 1960).

Because pupil dilations occur for a wide variety of tasks involving mental effort, psychologists had inferred that the task-evoked pupillary response was reflective of central brain processes (Beatty, 1982). For some, this was seen as providing an opportune way to study the dynamics of cognitive brain function (Beatty & Lucero-Wagoner, 2000). Until more recently, though, the method of measuring pupil size to study brain function did not gain much traction in the field. It was suspected that the reason for this was, "pupillometry is not widely employed in cognitive psychophysiology because the pupil lacks face validity as a measure of brain function" (Beatty & Lucero-Wagoner, 2000).

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The discovery that changes in pupil size correspond to activity in the locus coeruleus was pivotal in establishing pupil size as an important indicator of brain function. (Joshi, Li, Kalwani, & Gold, 2016; Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014; Rajkowski, Kubiak, & Aston-Jones, 1993; Varazzani, San-Galli, Gilardeau, & Bouret, 2015). The locus coeruleus is a region in the brain stem that has projections throughout the brain and is the main source of norepinephrine in the central nervous system (Moore & Bloom, 1979). The method of measuring pupil size is becoming more common in the fields of psychology and neuroscience today due to a better understanding of the brain regions associated with pupil size, along with theoretical advancements in the role these regions play in central cognition (Aston-Jones & Cohen, 2005b).

While most researchers have focused on within-individual changes in pupil size in relation to cognition and brain activity, the present study investigates differences in baseline pupil size **between** individuals of differing cognitive ability. This investigation was motivated by preliminary findings in our lab that larger baseline pupil size was associated with better performance on the operation span task, a measure of working memory capacity (Heitz, Schrock, Payne, & Engle, 2008). That is, high span subjects had larger pupils than low span subjects even during a "passive" baseline (in the absence of performing any specific cognitive task). However, the relationship was incidental, a number of potential confounds were present, and it was only treated tangentially. Therefore, this finding required further verification.

Besides this being a fascinating relationship though, it is important to consider this in the context of how it might relate to underlying differences in brain function. It turns out that, the prefrontal cortex, one of the crucial areas related to higher order cognitive abilities such as working memory capacity and fluid intelligence (Jung & Haier, 2007; Kane & Engle, 2002), receives a large amount of projections from the locus coeruleus. Furthermore, the locus coeruleus-norepinephrine system is recognized as playing a central role in the cognitive control of behavior through its neuromodulatory effects on regions such as the prefrontal cortex (Aston-Jones & Cohen, 2005a). In light of these advancements, we feel that if the relationship of cognitive ability to pupil size is real it may point to important dynamics in brain function that give rise to individual differences in cognitive ability.

In the present series of studies, we investigated whether the relationship between baseline pupil size and cognitive ability is real, or an artifact, by controlling for a number of potential confounding variables. At the time of the Heitz et al. (2008) paper, we were not sure whether this relationship was real or due to various confounding factors; such as age, mental effort, or experience in the lab. Although, one other lab has shown that performance on the Ravens advanced progressive matrices, a measure of fluid intelligence, was similarly associated with baseline pupil size (van der Meer et al., 2010). Nevertheless, for both studies the relationship was an incidental finding, was treated tangentially, and lacked a clear explanation. Therefore, the present study is the first to systematically investigate the relationship between baseline pupil size and cognitive abilities. Furthermore, in the discussion, we provide an explanation of this finding in terms of the potential underlying neural mechanisms.

It is important to note that Heitz et al. (2008) and van der Meer et al. (2010) used only a single task as their measure of working memory capacity and fluid intelligence, respectively. It is problematic to make inferences about the relationship of a variable with constructs such as working memory capacity or fluid intelligence using a single measure because all measures are multiply determined. For example, the Raven Matrices task is the most commonly used measure of fluid intelligence. However most large scale studies show that only 50–60% of the variance in Raven scores is attributable to fluid intelligence (Carroll, 1993; Jensen, 1998). The remaining 40–50% of the variance in Raven scores can be attributed to myriad other factors such as spatial rotation skills, experience with matrix problems and motivation. Measuring a construct with a single task not only measures the abilities of interest but also other unrelated and possibly unknown factors that are specific to that particular task. Thus, the only way to establish that a variable such as pupil size is associated with a general construct, such as working memory capacity or fluid intelligence, is to use multiple indicators from a range of domains.

Therefore, in all studies we used multiple measures of working memory capacity and/or fluid intelligence, allowing us to make claims at the construct level. At the construct level we refer to working memory capacity as the ability to actively maintain attention on information in the face of interference and is associated with performance across a wide range of cognitive domains (Ackerman, Beier, & Boyle, 2005; Conway, Kane, & Engle, 2003; Harrison, Shipstead, & Engle, 2014; Heitz et al., 2006; Shipstead, Lindsey, Marshall, & Engle, 2014). Fluid intelligence refers to the ability to solve novel reasoning problems and is highly correlated with working memory capacity (Ackerman et al., 2005; Conway et al., 2003; Engle, Tuholski, Laughlin, & Conway, 1999; Harrison et al., 2014; Heitz et al., 2006; Kane et al., 2004; Shipstead et al., 2014).

Baseline pupil size was measured during a "passive" baseline while subjects stared at a fixation on a computer monitor. In Study 1, we tested whether mental effort can account for the relationship between baseline pupil size and cognitive ability. In Study 2, we assessed the reliability of baseline pupil size measures and controlled for the effects of familiarity of the environment on the relationship with cognitive ability. In Study 3, we investigated whether working memory capacity or fluid intelligence is uniquely related to baseline pupil size, while also controlling for a number of potential confounds not addressed in Studies 1 and 2.

2. Study 1: Mental effort

Given that change in pupil size is commonly used to assess the amount of mental effort in which one is allocating, it is important to test whether mental effort can account for the relationship between baseline pupil size and cognitive ability. It may be that there are differences in the amount of attention or effort high and low cognitive ability subjects allocate during a

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