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The effect of motor task precision on pupil diameter

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ABSTRACT

It is well established that an increase in cognitive task demands is associated with increased pupil diameter. However, the effect of increased motor task demands on pupil diameter is less clear. Previous research indicates that higher motor task complexity increases pupil diameter but suggests that higher motor task precision demands may decrease pupil diameter during task movement. The current study investigated the effect of increased motor task precision on pupil diameter using a Fitts' Law movement task to manipulate motor response precision. Increased precision demands were associated with reduced pupil diameter during the response preparation and response execution phases of the movement trials. This result has implications for the interpretation of pupil diameter as an index of workload during tasks which involve precise motor movements.

1. Introduction

Operators in work domains such as air-traffic control and military operations face a time-pressured, multitasking environment where delays or errors caused by task overload can have serious consequences. In such situations it is important to be able to identify periods of high task demands and take appropriate mitigating action before performance degrades. This requires real-time measurements which are sensitive to within-individual responses to changing task demands and can be collected without interfering with ongoing task performance. Previous research has identified a range of physiological measurements that can index task demands including heart rate variability (HRV), electroencephalography (EEG), event related potentials (ERP), pupillometry and a range of brain scanning techniques such as positron emission tomography (PET) and functional near-infrared scans (fNIR) (Fallahi et al., 2016; Matthews and Campbell, 2010; Matthews et al., 2010; Russo et al., 2007; Tjolleng et al., 2017; Young and Stanton, 2002).

Although the situation is improving, many physiological measurement techniques are impractical to use in operational environments as they are invasive, constraining, or uncomfortable. In contrast, pupil diameter data can be collected unobtrusively without the need for physical contact using remote video cameras which are now widely available. Pupil diameter has also been shown to be a reliable index of the level of cognitive task demands, with increased cognitive task demands producing an increase in pupil diameter (Beatty and Lucero-Wagoner, 2000). However, the relationship between motor-task demands and pupil diameter is less clear. This may be due to a failure to separate the effects of movement complexity from movement precision. The current study addresses this gap by examining the effect on pupil diameter of an increase in motor task precision demands.

Pupil diameter has been shown to be a sensitive index of the level of demands associated with a wide range of cognitive tasks such as mental arithmetic, perceptual discrimination, sustained attention, visual search, working memory, problem solving and language processing (Beatty and Lucero-Wagoner, 2000; Engelhardt et al., 2010; Klingner et al., 2011; Piquado et al., 2010; Van Orden et al., 2001). The pupil diameter response to visually presented cognitive tasks shows an initial brief constriction immediately after stimulus presentation followed by a dilation associated with cognitive processing, with increased cognitive load reducing the size of the initial constriction and increasing the size of the subsequent dilation (Verney et al., 2001). This tightly-coupled relationship between increased cognitive processing and increased pupil diameter means that pupil diameter has the potential to be used as a continuous, real-time, measure of task demands.

While a considerable number of studies have consistently

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demonstrated that increased cognitive task demands produce increased pupil diameter, relatively few studies have examined the influence of motor task demands on pupil diameter. The planning and generation of a motor response can produce pupil dilation (Hupé et al., 2009) but, as discussed below, there does not appear to be a clear relationship between changes in the level of motor task demands and the pupil diameter response.

It appears that this lack of clarity may be due in part to a failure to distinguish between motor task complexity and motor task precision. Increased motor task complexity is considered to arise from the need to coordinate and sequence more intricate, or a greater number, of, low-level activities. Examples of increased motor task complexity include going from a simple to a choice reaction time task or moving from driving an automatic to a manual vehicle. In contrast, increased motor task precision is associated with the need for greater response accuracy, such as the need to press the exact centre of a response key or to stay exactly in the centre of a road lane. The current study proposes that motor task complexity and motor task precision may have opposite effects on pupil diameter. While increased motor task complexity may increase pupil diameter, it is predicted that increased motor task precision will decrease pupil diameter. This prediction is tested by examining the pupil diameter response to increasing precision demands during a Fitts' Law movement task. Fitts' Law is a model of human movement during speeded aiming tasks which identifies that the time to move and point to a target of width W at a distance A is a logarithmic function of the ratio A/W (Fitts, 1954). The law can be used to generate principled manipulations of motor task precision demands by varying target distance or target width.

Considering first the effect of motor task complexity on pupil diameter, early work manipulated motor task complexity by requiring participants to perform a series of single, double, or triple key presses and found that pupil diameter increased with the number of key presses required (Richer and Beatty, 1985). More recent work examined the pupillary response to a cued finger-movement task and found that cues which required movements that are difficult to encode and execute produced a greater increase in pupil diameter than cues which required less demanding movements (Moresi et al., 2008a; Moresi et al., 2008b). These results indicate that increased motor task complexity produces increased pupil diameter.

Considering next motor task precision, only four studies appear to have examined the effect of precision demands on pupil diameter and these have produced an inconsistent pattern of results. In Washburn and Putney (2001), participants used a joystick to move a cursor into a circle displayed in the centre of a computer screen, which triggered the brief display of a visual stimulus on the left or right of the screen. Two stimuli were then presented and participants had to decide which of these matched the initial visual stimulus. Two levels of cursor precision were used to trigger the visual stimulus display. In the high-precision condition the cursor had to be exactly on top of the centre pixel of the circle in order to trigger the visual stimulus and in the low-precision condition the cursor had to be within 0.5 degrees of the centre pixel. In the high−precision condition participants were slower to trigger the visual stimulus and had a larger pupil diameter just prior to the visual stimulus display than in the low-precision condition. This result suggests that motor responses which require higher precision may generate an increase in pupil diameter, but this interpretation is complicated by the possible effects of the subsequent visual recognition task. The high-precision condition caused the initial fixation location to be closer to the screen centre than during the low-precision condition which may have made the encoding of the target stimulus located at the edge of the screen and its subsequent recognition more difficult. An increase in expected task difficulty can increase pupil diameter (Steinhauer et al., 2004), which may have contributed to the increase in pupil diameter observed during trial initiation and makes it difficult to solely attribute the increase in pupil diameter to the need for increased motor response precision.

In a more direct test of the effect of motor response precision on pupil diameter Demberg et al. (2013) increased the difficulty of a simulated driving task by increasing vehicle speed and the speed at which the required steering direction changed. This manipulation had no significant effect on pupil diameter. In contrast, the addition of a secondary linguistic processing task was associated with a significant increase in pupil diameter. The dissociation between the effects of motor task precision and cognitive demand suggests that pupil diameter may respond in different ways to these variables.

A third study explored the effect of motor response precision on pupil diameter during discrete movements of a simulated laparoscopic surgical tool between pairs of targets (Jiang et al., 2014a). Low, medium, and high precision levels were created by reducing the diameter of and increasing the spacing between target pairs. The change in demand between each demand level corresponded to a constant increase in Fitts' Law difficulty score (Fitts, 1954). Pupil diameter was measured over a 7-s period which commenced 3 s before the tip of the laparoscopic tool began to move. A baseline pupil diameter for each precision level was calculated by averaging across the first second of the measurement period and the change in pupil diameter from baseline was analysed across the measurement period. A complex precision level × time interaction effect was obtained where just prior to the start of tool-tip movement pupil diameter was larger in the high precision condition than in the medium precision condition, but by the time of movement completion approximately 1 s later pupil diameter in the high precision condition had constricted to the extent that it was significantly smaller than pupil diameter in the low and medium precision conditions. Jiang et al., 2014a proposed that the constriction in pupil diameter observed during the high-precision movements was caused by the need for participants to make larger shifts in gaze location (saccades) in this condition due to the increased spacing between target pairs, rather than the need for more precise movements.

This proposal was tested in a follow-up study that independently manipulated target size and target spacing (Jiang et al., 2014b). Contrary to predictions, the study found no difference in the pupil diameter response to increased task demand between the constant spacing and constant size conditions. This offered no support to the proposal that larger shifts in gaze location may moderate the pupil diameter response to task demands. The study also found no evidence that reduced target size or increased target spacing produced an early constriction in pupil diameter, but as it used only eight participants who completed only six trials per condition it may be that the study had insufficient power to detect any effect that was present. This would appear to leave open the possibility that the pupil constriction observed in the initial study may have been associated with the increased motor response precision demands of the task.

Indirect support for this proposal can be found in studies examining non-pupil physiological responses to motor response precision demands. These studies have found that tasks requiring high levels of movement precision such as golf putting and target shooting produce increased suppression of task-irrelevant brain regions in experts compared to novices (Janelle and Hatfield, 2008; Milton et al., 2007; Yarrow et al., 2009). This neural efficiency in experts is thought to be due in part to the use of highly automated motor processes which require little attentional control (Beilock et al., 2002). Lower EEG alpha power has also been observed around the initiation of holed putts compared to missed putts