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Pupil dilation during recognition memory: Isolating unexpected recognition from judgment uncertainty

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ABSTRACT

Optimally discriminating familiar from novel stimuli demands a decision-making process informed by prior expectations. Here we demonstrate that pupillary dilation (PD) responses during recognition memory decisions are modulated by expectations, and more specifically, that pupil dilation increases for unexpected compared to expected recognition. Furthermore, multi-level modeling demonstrated that the time course of the dilation during each individual trial contains separable early and late dilation components, with the early amplitude capturing unexpected recognition, and the later trailing slope reflecting general judgment uncertainty or effort. This is the first demonstration that the early dilation response during recognition is dependent upon observer expectations and that separate recognition expectation and judgment uncertainty components are present in the dilation time course of every trial. The findings provide novel insights into adaptive memory-linked orienting mechanisms as well as the general cognitive underpinnings of the pupillary index of autonomic nervous system activity.

1. Introduction

In addition to the pupillary light reflex, research spanning almost fifty years has established increased pupillary dilation (PD) as a correlate of diverse cognitive demands, including mental arithmetic (Hess & Polt, 1964), working memory (Kahneman & Beatty, 1966), and decision-making spanning perceptual (Kahneman & Beatty, 1967), semantic (Ahern & Beatty, 1981) and economic domains (Fiedler & Glockner, 2012).

The pupil is also sensitive to episodic memory judgments, dilating more for recognition probes identified as studied (*old*) versus unstudied (*new*) (Gardner, Mo, & Borrego, 1974; Goldinger & Papesh, 2012; Heaver & Hutton, 2011; Naber, Frassle, Rutishauser, & Einhauser, 2013; Papesh, Goldinger, & Hout, 2012; Vo et al., 2008). As an extension of earlier work linking pupillary dilation to cognition (Beatty, 1982; Kahneman, 1973), this 'pupil *old/new* effect' has been suggested to reflect the increased 'cognitive load' or voluntary effort required during the successful retrieval of episodic content. Below we briefly outline the Cognitive Load model, highlighting how its previous applications to the pupil old/new effect may have been strained. We then consider an alternative possibility in which the initial dilation reflects an involuntary response indicating attentional orienting, and conclude by explaining how our reported memory cueing paradigm pits the effort and orienting accounts of the pupil old/new response against one another.

1.1. The Cognitive Load model and its prior application to the pupil old/new effect

According to the Cognitive Load model of Kahneman and Beatty (Beatty, 1982; Kahneman, 1973; Kahneman & Beatty, 1966), pupil dilation is a peripheral marker of arousal that serves to transiently increase cognitive capacity as a result of either the 'voluntary' or 'involuntary' deployment of attention. When voluntary, the subject chooses to engage in a problem or decision task and the inherent 'top-down' demands of the task drive both the level of cognitive effort and pupillary dilation (Kahneman, 1973). For example, in a working memory digit span task, pupil dilation increases as the number of digits to be retained also increases (Kahneman & Beatty, 1966), tracking the greater effort expended for the larger memory set size. Critically, under voluntary attention, increasingly effortful tasks should yield increasingly slowed, erroneous and uncertain responding (Kahneman, 1973). These behavioral indices of voluntary attention/effort overlap with those in response

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conflict paradigms which also yield increased pupil dilation for conditions of heightened conflict and associated uncertainty; for example, when naming colour-incongruent words in the Stroop task (Laeng, Ørbo, Holmlund, & Miozzo, 2011; Stroop, 1935) and when making left/right button-presses to spatially incompatible locations in the Simon task (Simon, 1969; Van Steenbergen & Band, 2013).

Prior applications of the Cognitive Load model to the pupil old/new recognition effect have generally interpreted it as a marker of increased voluntary effort during successful retrieval (Goldinger & Papesh, 2012; Papesh et al., 2012; Vo et al., 2008). However, there is little to suggest that hits (correct responses to studied items) are subjectively more 'effortful' than correct rejections (correct responses to unstudied items) in the way effort is characterized during the working memory, Stroop and Simon tasks mentioned above. In all of these, increasingly effortful trials are rendered less accurately, more slowly, and often with reduced subjective confidence. Contrary to this characterization, recognition hits are generally rendered more confidently than correct rejections across a range of levels of processing manipulations (Dobbins & Han, 2007; Jaeger, Cox, & Dobbins, 2012). Hits are often also rendered more quickly (Wiese & Daum, 2006) and we replicate this convergent behavioral profile in the Supplementary Information section (see SI, Section 1). Furthermore, increasing the depth of encoding also increases the pupil old/new dilation effect (Otero, Weekes, & Hutton, 2011), meaning that as studied materials become *easier* to identify, the size of the PD response to them also increases, which is the opposite of what should occur if the dilation indexed the voluntary expenditure of effort.

Overall, the behavioral characteristics of successful recognition judgments do not fit well with the notion that the pupil old/new effect occurs because hits are more effortful than correct rejections, as conceived by the voluntary component of the Cognitive Load model. However, this model also has an involuntary component that has been neglected in applications of cognitive load theory to pupillometry research in recognition memory. We next consider if this could explain the pupil old/new effect.

1.2. Involuntary attention and the orienting response

The involuntary component of the cognitive load model is closely related to the orienting response (Kahneman, 1973), which is traditionally evoked in 'bottom-up' fashion by stimuli that perceptually violate an observer's predictive model (Sokolov, 1963a, 1963b). The dilation response and other autonomic indices of orienting (such as the P300 event-related potential) have been well documented via the oddball paradigm, in which unexpected stimuli such as unpredictable (and rare) shifts in the intensity or frequency of tone pips ('oddballs') interspersed among regularly occurring tones ('standards') trigger prominent pupil dilation (Friedman, Hakerem, Sutton, & Fleiss, 1973; Hillyard, Squires, Bauer, & Lindsay, 1971). This involuntary response signals a rapid and involuntarily increased allocation of resources to the processing of the unexpected stimulus, and is hence not *directly* linked with voluntary 'effort' and its behavioral signatures of slowed, erroneous and uncertain judgment (Kahneman, 1973). Thus an alternative possibility is that the pupil old/new effect is driven by the involuntary rather than voluntary component of the cognitive load model.

However, while oddballs are often labelled as 'novel' in that they are unanticipated by the observer's prior predictive model, this 'perceptual novelty' is fundamentally different from 'novelty' during episodic recognition memory. During the former, the stimulus stands out because it violates *perceptual expectations* given recent experiences. In contrast, during typical verbal recognition memory tasks, the unstudied items are not novel in the sense that they violate perceptual or linguistic expectations because both studied and unstudied items are drawn from equally known common words. Rather, unstudied items are *episodically* 'novel' because they fail to evoke memories of the current study context, and not because the linguistic features of the items themselves are unanticipated. Hence, the involuntary component of the Cognitive Load model does not seem to afford a straightforward explanation of the pupil old/new effect because in standard recognition memory paradigms there are no perceptual oddballs present. Nonetheless, even if one were to misapply the notion of perceptual novelty orienting to episodically 'novel' recognition stimuli, the Cognitive Load model makes an incorrect prediction; namely, greater dilation for correct rejections than hits, which is converse to the actual old/new pupil response evoked during recognition memory.

However, the observation that target oddballs across multiple sensory modalities are capable of eliciting a common neural signature has led to the suggestion that unexpected information in a more general sense (rather than *perceptual* information *per se*) might be the key driver of the orienting response (Corbetta & Shulman, 2002; Downar, Crawley, Mikulis, & Davis, 2000). Thus if one expands the notion of the orienting response to encompass orienting to information that is generally unexpected, even when that information is recovered from long term memory, then the involuntary component of the Cognitive Load model may be an appropriate characterization of the pupil old/new response. Under this reconceptualization, the pupil old/new effect would reflect orienting to recovered episodic information and, as with other orienting phenomena, it would be potentiated by the degree this information is unexpected. This conceptualization is consistent with various recognition models inspired by functional neuroimaging that assume a role for bottom-up attention in the processing of unexpected memorial content (Cabeza, Ciaramelli, Olson, & Moscovitch, 2008; O'Connor, Han & Dobbins, 2010) and it is also consistent with a recent conceptualization of the pupil dilation response as signalling the surprise value of diagnostic information during economic decision-making (Preuschoff, 't Hart & Einhauser, 2011). This characterization of the recognition pupil response as reflecting an involuntary orienting process has to date neither been considered nor tested.

The possibility that pupil old/new effects reflect orienting phenomena requires manipulating two elements; namely an expectation or prior belief and an information outcome with respect to that belief. It is the difference or distance between the expectation and outcome that regulates the degree of unexpectedness/surprise and hence the strength of involuntary orienting (e.g., Baldi & Itti, 2010). Unfortunately, standard recognition memory tests that evoke the pupil old/new response do not actively control the expectations of the observers. Thus even if episodic information is unexpectedly recovered on some trials (generating a modest dilation response in the trial average), standard recognition paradigms have no way of establishing when retrieval outcomes are more versus less expected because they do not manipulate memorial expectations at the level of individual trials. Here we use explicit memory cueing to do so and below we explain how this paradigm sets up competing predictions for voluntary and involuntary attentional accounts of the pupil old/new effect (see Supplementary Information Section 3 for further discussion on how uncontrolled expectations operating in standard recognition paradigms might account for previous old/new effects).

1.3. Competing predictions for the old/new effect set up by explicit memory cueing

We collected pupillometry data during recognition using an Explicit Memory Cueing paradigm developed by O'Connor et al. (2010). In the cued phase of the paradigm, cues or 'hints' which