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# Pupil dilation patterns reflect the contents of consciousness

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ABSTRACT

The study of human consciousness has historically depended on introspection. However, introspection is constrained by what can be remembered and verbalized. Here, we demonstrate the utility of high temporal resolution pupillometry to track the locus of conscious attention dynamically, over a single trial. While eye-tracked, participants heard several musical clips played diotically (same music in each ear) and, later, dichotically (two clips played simultaneously, one in each ear). During dichotic presentation, participants attended to only one ear. We found that the temporal pattern of pupil dilation dynamics over a single trial discriminated which piece of music was consciously attended on dichotic trials. Deconvolving these pupillary responses further revealed the real-time changes in stimulus salience motivating pupil dilation. Taken together, these results show that pupil dilation patterns during single-exposure to dynamic stimuli can be exploited to discern the contents of conscious attention.



## 1. Introduction

Understanding the mind means understanding the ebb and flow of conscious experience. However, objectively measuring the what and when of conscious experience has proven elusive. While various methods discriminate conscious from unconscious states (Seth, Dienes, Cleeremans, Overgaard, & Pessoa, 2008), accessing the *contents* of conscious experience has historically relied on introspection (Libet, 1993) with its concomitant bottlenecks of memory and language. What can be remembered and reported, although informative, is necessarily a fraction of what was experienced and subject to various distortions (Block, 1995; Schooler & Schreiber, 2004). As James noted, introspective analysis is like "trying to turn up the gas quickly enough to see how the darkness looks" (1890). Here we show that high temporal resolution pupillometry and deconvolution analyses can inform our understanding of conscious experience by affording a direct, temporally-sensitive window onto one of its correlates: the locus of conscious attention. We demonstrate that pupil dilation patterns can reveal what information stream is being attended on a single trial.

Pupil dilation has been used for decades to index mental processing. Hess and Polt found that participants' peak pupil diameter and latency to peak dilation differed as a function of difficulty during mathematical calculations, leading the authors to conclude that a combination of those pupillary features would comprise a metric of "total mental activity" (1964). Although standard pupillometric analyses extract both amplitude and latency measures as prescribed by Hess and Polt, these analyses typically reduce the data to a single maxima or average dilation diameter within and across trials.

Only recently have studies demonstrated the potential for pupillary time-series data to reflect conscious and preconscious dynamic processing (Einhäuser, Koch, & Carter, 2010; Kang, Huffer, & Wheatley, 2014; Laeng, Sirios, & Gredebäck,

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2012; Naber, Alvarez, & Nakayama, 2013; Smallwood et al., 2011). Naber and colleagues, for instance, exploited pupillary sensitivity to light by manipulating stimulus brightness over time. They found that the frequency of this overlaid luminance "flicker" was mirrored in pupil dilations when that stimulus was attended (2013). This finding suggests that information about selective visual attention to static stimuli is objectively measurable in the eyes. However, this method requires overlaying an identifying pulse onto a static visual stimulus, and this pulse relays nothing about the stimulus except its identity. Our conscious experience is shaped by multimodal information that often occurs in streams, relaying meaning dynamically over time (e.g., music, conversation). Here, we extend recent pupillometric efforts by investigating whether *natural* patterns of pupil dilation – obtained under constant light conditions and in response to common and unmanipulated informational streams – can be used to identify the contents of conscious attention on a single trial. This approach differs from more traditional pupillometric approaches in three key ways: it considers the dynamic pupillary response to dynamic stimuli, it tests the sensitivity of the pupillary response to naturally occurring salience changes in real-world stimuli, and it aims to discriminate this sensitivity on a single trial.

Previous research suggests that the pupils are indeed sensitive to momentary fluctuations in attention. Under conditions of controlled light, pupil diameter exhibits a close positive relationship with exclusive norepinephrine (NE) release by locus coeruleus (LC) neurons (Rajkowski, Kubiak, & Aston-Jones, 1993; see Fig. 1). As NE effects changes in attention and arousal (Berridge & Waterhouse, 2003), the pattern of pupil dilation dynamics (PDy) over time reflects these changes on a sub-second time-scale. This characteristic makes PDy a candidate biomarker for tracking the locus of consciousness. Although "attention" and "consciousness" are not synonymous, they are tightly coupled. As Koch and Tsuchiya (2007) noted: "When we attend to an object, we become conscious of its characteristics; when we shift attention away, the object fades from consciousness." In the following studies, we tested whether fluctuations in pupil diameter comprise a temporally sensitive readout of conscious attention during single exposure to a dynamic stimulus (music). We predicted that different musical clips would be defined by different patterns of attentional salience, and thus that the pupillary dilation pattern in response to the simultaneous presentation of two clips would discriminate which clip dominated conscious awareness on a trial-by-trial basis.

## 2. Methods

### 2.1. General descriptions

#### 2.1.1. Participants

All participants were recruited from Dartmouth College and compensated for their participation monetarily (in accordance with standard rates) or with course credit. All participants were over 18 years of age, with normal or corrected-to-normal vision and audition. Written informed consent was obtained prior to the start of the study.

#### 2.1.2. Materials

Eight 30-second clips were taken from well-known classical instrumental pieces. In order to control for potential salience differences associated with valence (Harrison, Singer, Rotshtein, Dolan, & Critchley, 2006), we used equal numbers of negatively- and positively-valenced music clips, and dichotic pairs were always comprised of same valence clips. Music clips

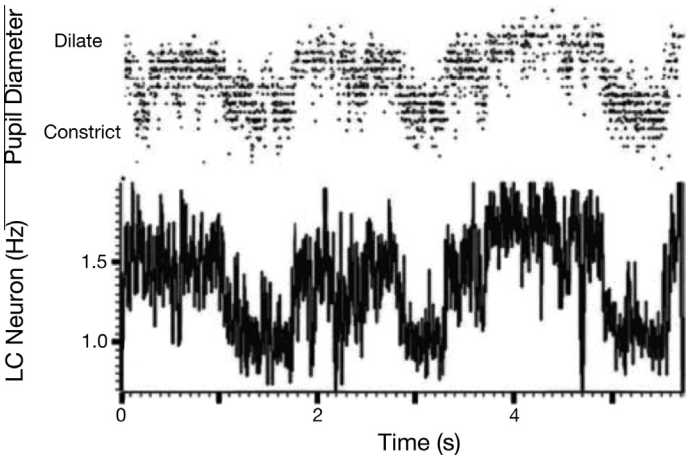


**Fig. 1.** Pupil dilation dynamics and locus coeruleus activity are tightly coupled. Using single-unit recording, Rajkowski and colleagues demonstrated the existence of a close positive relationship between norepinephrine release by the locus coeruleus neurons in the monkey and pupil diameter (1993). This figure is adapted from Rajkowski et al. (1993).