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Short Report

Violation of Bloch's Law that specifies reciprocity of intensity and duration with brief light flashes

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Abstract. For more than a century researchers have been reporting that the visual impact of a very brief flash is determined by the quantity of photons that the flash delivers. This has been variously described as the Bunsen-Roscoe Law or Bloch's Law, often specified as reciprocity of intensity × duration. Prior research found no evidence for such reciprocity when microsecond-duration flashes from a light-emitting diode array were used to display the major contours of nameable shapes. The present work tested with flash durations ranging up to 100 ms and also found no reciprocity. This departure from classic principles might be due to the specific range of wavelengths of the light-emitting diodes and to a mesopic level of ambient light, which together would preclude activation of rods. The reciprocity of intensity and duration may only be valid with full dark adaptation and very dim flashes that activate rods.

Keywords: Bloch's Law, flash duration, shape recognition, cone activation.

1 Introduction

A large variety of shapes can be recognized when displayed as brief simultaneous flashes from LEDs that mark the major contours, especially the outside boundaries (Greene & Ogden, 2012, 2013). Figure 1 provides examples from the inventory of shape patterns that were used in these studies. With flash durations as brief as 3 μs human respondents were able to identify—name—a large majority of the shapes (Greene & Ogden, 2013).

Finding successful shape recognition with ultra-brief displays is consistent with work done over a century ago. For example, Rood (1871) reported that he was able to identify words on a printed page from the light produced by a spark lasting less than a microsecond. It has been assumed that this perception was possible because of the quantity of photons in the flash. However, as detailed below, recent work from the present laboratory found that the effectiveness of microsecond-duration flashes for shape recognition is not determined by the quantity of photons being delivered (Greene & Ogden, 2013).

Bunsen and Roscoe (1855) proposed a photochemical basis for the focus on photon quantity, attributing the net impact of brief flashes to the total amount of chemical conversion that is produced. Bloch (1885) was the first to specify this concept as it relates to vision. He claimed that there is reciprocity of intensity and duration, i.e., intensity × duration equals a constant, for threshold perception of brief flashes. This is generally accepted as meaning that any flash producing a constant quantity of photons should have the same perceptual effect so long as flash duration is within a certain range. The upper limit of this range is commonly known as the critical duration. Most investigators who have reported evidence of reciprocity in perceptual or physiological responses have described their results as conforming to Bloch's Law. Some attribute their results to the Bunsen-Roscoe Law. Here, we follow the first convention.

A substantial number of perception studies have supported the claim for threshold reciprocity. These include absolute and discrimination thresholds for spots (Barlow, 1958; Graham & Margaria, 1935; Karn, 1936; Matchko & Gerhart, 2001; Zacks, 1970), square wave gratings (Graham & Cook, 1937), thin bars (Niven & Brown, 1944), colored stimuli (Baumbardt & Hillmann, 1961; Rouse, 1952), and motion (Brown, 1957). One study examined identification of 1/0 triads with durations ranging from 5 ms to 1 s and reported reciprocity with flashes that were shorter than 100 ms (Kahneman & Norman, 1964). That study comes closest to having task demands similar to those used here in that respondents had to read and report the three-numeral combinations that were displayed.

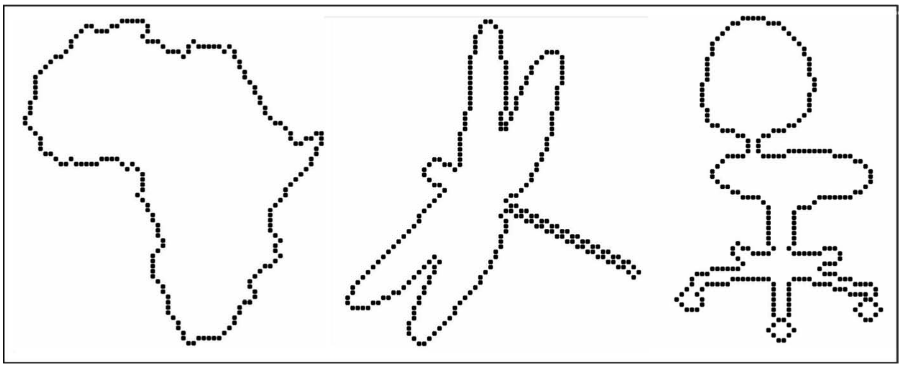

Figure 1. Examples from the shape pattern inventory: The inventory of 360 shape patterns included living creatures, vehicles, furniture, tools, and various other shapes. For most shape patterns, the dots marked only the outside boundary of the shape. Each shape in the inventory was randomly selected for display to a given respondent using an array of red-emitting LEDs. To display a given shape pattern, the LEDs were flashed simultaneously at a specified intensity and duration. For convenience, one can describe this as a singular event, i.e., as "a flash." Respondents could register that they recognized the shape pattern by saying an acceptable name.

The perceptual studies have often reported reciprocity of intensity and duration in the range of 1 to 100 ms, with the upper limit (critical duration) being shorter as a function of area, intensity, or other task conditions. Many investigators found that beyond the critical duration the perceptual judgment was controlled completely by the intensity of the flash.

Neuron activation that conforms to Bloch's Law has been reported by a number of investigators. Adrian and Matthews (1927) found a critical duration of approximately 30 ms with respect to the latency and frequency of firing of optic nerve fibers in *Conger vigaris* (sea eel). Hartline (1928) recorded what were essentially electroretinograms from the eyes of diverse arthropods, including lobster, crayfish, grasshopper, butterfly, housefly, and horse-shoe crab. He reported amplitudes of response that were constant as a function of intensity × duration for durations under 60 ms. He also reported reciprocity with single-unit recordings from optic nerve fibers of the horse-shoe crab, which was manifested with durations ranging from 0.1 to 100 ms (Hartline, 1934). Numerous other physiological studies have also claimed support for Bloch's Law (Alpern & Faris, 1956; Biersdorf, 1958; Duysens, Gulyas, & Maes, 1991; Glickman, 1987; Hood & Grover, 1974; Levick & Zacks, 1970; Rosenblum, 1971; Scheich & Korn, 1971).

No investigator or theorist has suggested that the reciprocity principle would fail at durations shorter than 1 ms. It was shocking, therefore, when shape recognition tested with flashed dot patterns found no evidence for reciprocity with flash durations that ranged from 3 to 100 µs (Greene & Ogden, 2013). Further, very small changes in intensity that kept the number of photons constant across a small range of durations dramatically altered the level of successful shape recognition. For example, a quantity of photons that provided for recognition in the 75–85% range when delivered over 10 µs did not elicit identification of any shapes with flash durations of 18 µs. Likewise, a photon quantity that was effective when delivered in 3 µs was ineffective when delivered in 8 µs.

Reciprocity of intensity and duration has been most thoroughly documented with flash durations in the 1 to 100 ms range. It seemed possible that the lack of reciprocity with the shape-recognition task might be due to the use of flash durations that were considerably shorter.

For the work being reported here, the goal of the first task was to establish a baseline quantity of photons to be used in the test of intensity × duration reciprocity. A quantity that elicits identification of about half the shape patterns with 1 ms flashes would be optimal for checking the impact of shorter as well as longer flashes. This quantity was found by testing how increments of luminous intensity altered the proportion of shapes that were correctly identified. Hereafter that proportion will be described as a hit rate that ranges from 0 to 1, and a rise produced by changes in intensity and/or duration will be designated as an activation function.

Activation functions for changes in luminous intensity with 1 ms flashes are reflected in the models of Figure 2. Figure 2A shows the activation function models for individual respondents as dashed lines, and the combined group model as a solid line. The models show that hit rate increased as a sigmoid curve as the intensity of the flash became progressively higher. Figure 2B shows the group

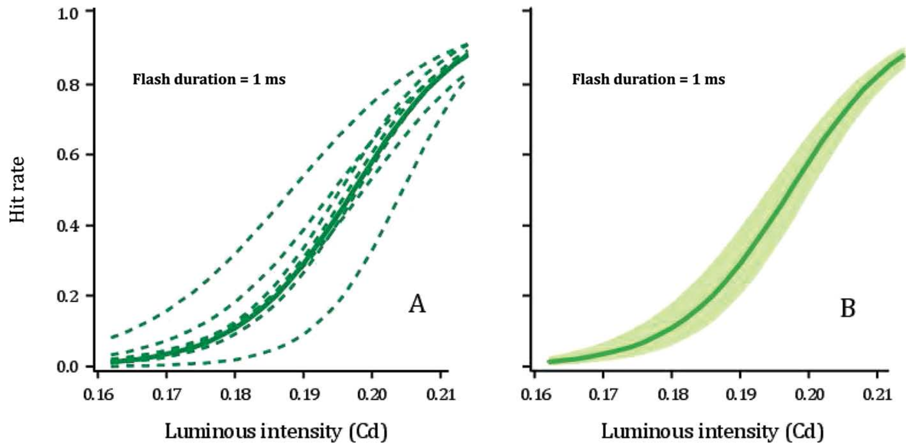

Figure 2. Activation function with flash durations of 1 ms: A. Shape patterns were displayed for 1 ms and the proportion of shapes successfully identified (hit rate) rose from zero or near zero to a maximum in the 0.8 range as luminous intensity was increased. Dashed lines reflect the models for each respondent that was tested and the solid line provides the combined model for the group. B. The group model is presented again along with a confidence band.

model again, bounded by a confidence band. [The bands in Figures 2–5 reflect the 95% confidence range. Plots of subject means for each of the experiments of this report are provided in Supplemental Figures.]

An intensity level that produced a half-maximum hit rate for eliciting recognition was used to determine the quantity of photons to be displayed at five durations ranging from 0.01 to 100 ms. For the constant-photon condition this intensity was scaled by duration, so that the product of intensity × duration would provide a constant quantity of photons.

Figures 3A and 3B show the individual and group models for the constant-photon condition. The results reflected in the constant-photon plots do not conform to Bloch's Law, which would predict hit rates at the same level across the full range of flash durations. Whereas a number of prior studies have reported that this law is valid at least in the 1 to 100 ms range, here a photon quantity that could elicit a half-maximum hit rate when displayed at 1 ms was ineffective at 10 and 100 ms. It should be noted that maintaining a constant quantity of photons at various flash durations requires adjustment of flash intensities. Specifically, the intensity used at 1 ms is adjusted up for shorter flash durations and adjusted down for longer durations. One explanation for the results shown in Figures 3A and 3B is that the threshold for activation of retinal signals is based on flash intensity rather than photon quantity, as discussed by Greene and Ogden (2013).

Many of the studies that report reciprocity of duration × intensity below the critical duration also found that the response was a direct function of flash intensity alone above the critical duration. A constant intensity condition was also tested—Figures 3C and 3D—wherein the same base intensity was used at each flash duration. The results do not support a constant intensity principle. An intensity that was sufficient to produce a half-maximum hit rate at 1 ms was insufficient to produce recognition at 0.01 and 0.1 ms, but was ample for generating a high level of recognition when that intensity was shown for 10 or 100 ms. The message appears to be that across the full range of durations, from 10 µs to 100 ms, the impact of a flash is determined by specific levels of intensity at each duration, not by a constant intensity or a constant quantity of photons.

The previous work with flashes in the microsecond range had found a very rapid decline in hit rate with changes of duration when intensity was adjusted to maintain a constant photon quantity (Greene & Ogden, 2013). Whether the same rapid decline would be seen for longer duration flashes was tested with durations ranging from 1.0 to 1.4 ms, and the results are shown in Figure 4. These models also manifest dramatic declines of hit rate with a change in duration of only 0.4 ms, providing further evidence that the lack of reciprocity is not a microsecond phenomenon.

Bloch's Law has been invoked to describe reciprocity of duration and intensity for a diverse set of perceptual judgments. Nonetheless, the original specification of this principle was with respect to the absolute threshold for perceiving a flash. The requirement to register, encode, and name a

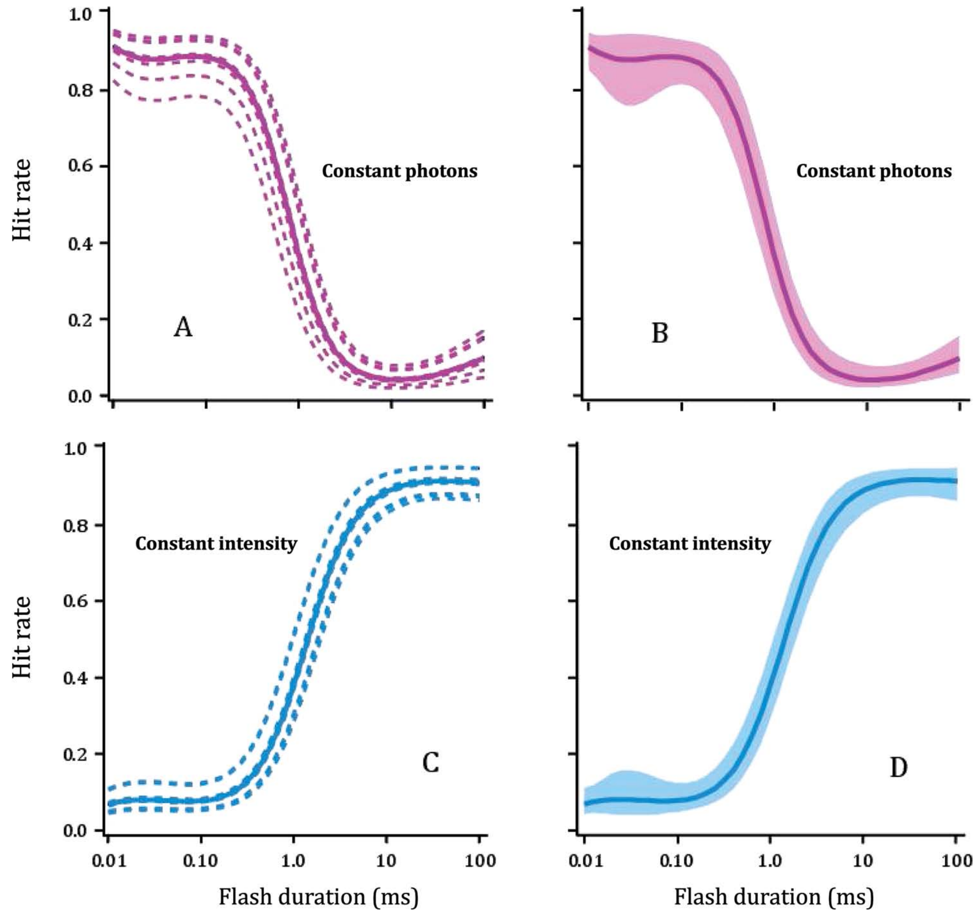

Figure 3. Hit rates across flash durations with constant photon quantities or constant intensities: The flash intensity that elicited a half-maximum hit rate with 1 ms flashes (see Figure 2) was used to calculate the quantity of photons to present at flash durations ranging from 0.01 to 100 ms. Individual and group models for the constant photon quantity condition are shown in plot A, and the group model with a confidence band for the same respondents is shown in plot B. The results are clearly in violation of Bloch's Law, which would predict a consistent impact of constant-photon flashes, i.e., the same hit rate irrespective of flash duration. The models plotted at C and D show the levels of hit rate elicited by using constant levels of flash intensity across the same range of durations.

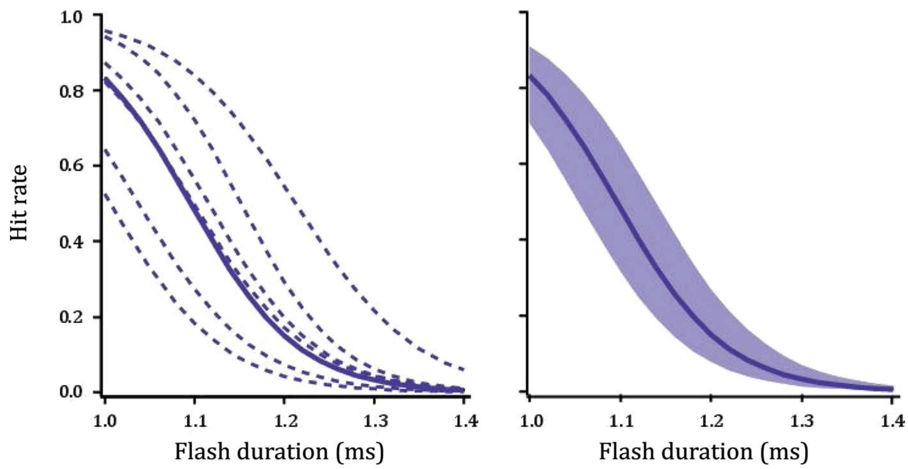

Figure 4. Decline of recognition in the 1 ms range with constant photon flashes: Flash duration was varied while keeping photon quantity constant. A quantity that could elicit a high hit rate with 1.0 ms flashes became progressively less effective at longer durations. By 1.4 ms, shape recognition was at or near zero. Individual and group models are shown at A, and the group model with a confidence band is shown at B.

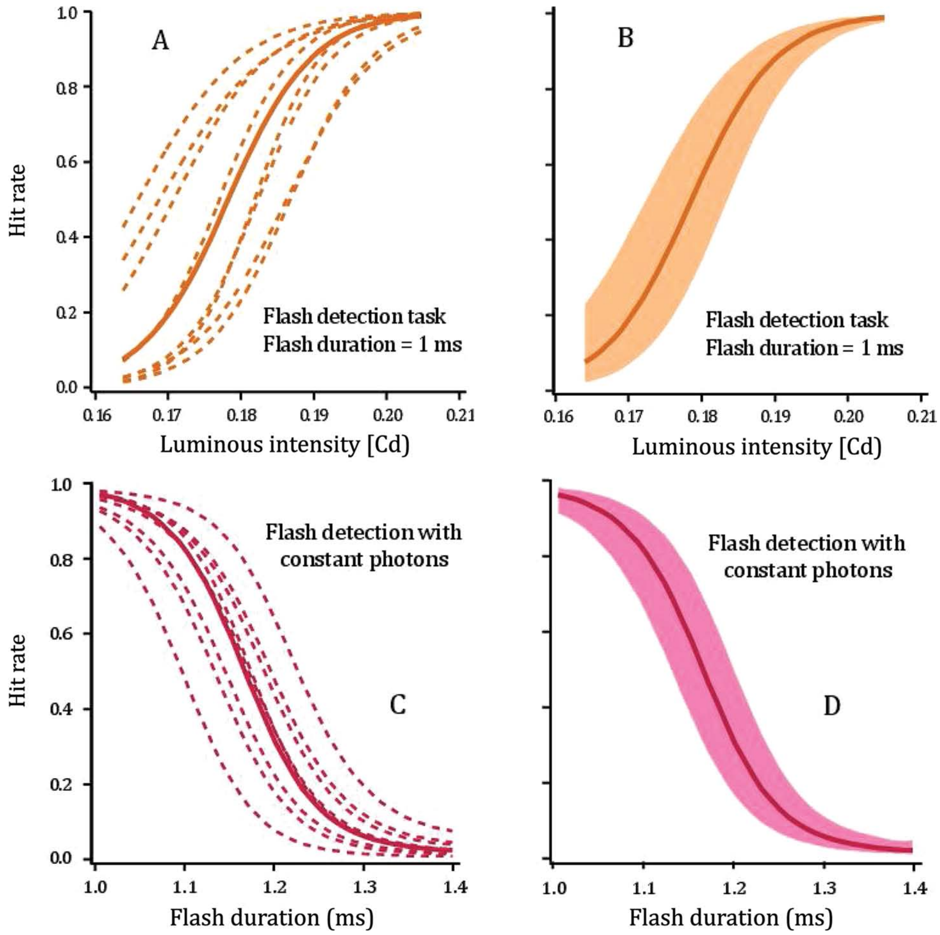

Figure 5. Activation and decline functions for flash detection in the 1 ms range: To determine whether the lack of reciprocity was specific to shape recognition, the shape inventories were displayed, requiring respondents to report whether the flash could be seen. Models for flash-detection hit rate as a function of intensity are shown in plots A and B. The intensities required for a given level of detection were in the same range as those required for recognition of the shapes, as shown in Figure 2. Plots C and D show a dramatic decline in hit rate across the 1.0–1.4 range of durations where photon quantity was held constant. Reciprocity of intensity × duration would not predict this result, therefore neither flash detection nor shape recognition results (Figures 3 and 4) support Bloch's Law.

shape doubtless involves advanced neural processing that would be expected to have more than one threshold. It would not be surprising to find that the threshold for being able to correctly name a flashed shape requires luminance levels that are well above the absolute threshold.

Additional experiments were conducted to examine whether the shape-recognition task demanded substantially different luminance levels. The inventory of shape patterns was displayed in the same manner, but respondents were asked simply to affirm whether or not the flashes were seen. This is essentially a method of constant stimuli seeking the absolute threshold for perception of the flashes.

The activation function for detection of 1 ms flashes is shown in Figures 5A and 5B. Note that the intensity range for detection, i.e., extending from a near zero threshold up through an asymptotic detection level, is approximately the same as the range of intensities that allowed shapes to be identified (Figure 2). The choice of what intensity range to test was based on pilot work, making no reference to the intensities that proved to be effective at eliciting shape recognition. Finding a substantial equivalence of the two ranges was a surprise. It suggests that respondents fail to identify a given shape when the flashed pattern is at or just below the perceptibility threshold.

The ability to detect constant-photon flashes was evaluated across the range from 1.0 to 1.4 ms, and the models are shown in Figures 5C and 5D. The declines in flash detection were almost identical to those seen with shape recognition. This indicates that the lack of intensity × duration reciprocity is not unique to the recognition task.

It is difficult to reconcile the present results with what has been reported by numerous laboratories for over a hundred years. Much of the earlier and most convincing work was done in the first half of the 20th century, with both intensity and duration being quantified with improvised methods that cannot possibly match modern standards. Nonetheless, the data in those studies manifested an amazing degree of consistency in affirming the calculations and plots of treatment effects. If the earlier work incorrectly assessed levels of intensity and/or duration of the flashes, it must surely be from systematic error sources that were technically beyond the resources of those careful investigators. [See also the recent work by Rieiro et al. (2012) that describes a potential role for observer bias.]

Various differences in task and protocol design might have contributed to differences in outcome of the present work compared to the earlier psychophysics studies. But it seems most likely that discrepancies are due to differences in emission of the LEDs compared to earlier light sources and/or to the level of ambient illumination, both of which would provide minimal activation of rods.

The emission wavelengths of the LEDs in the present display device center at 630 nm and the range of wavelengths is relatively narrow. The emission is near the end of the spectral sensitivity curve of red cones, providing minimal activation of green cones and being well beyond the longest wavelength at which rods respond (Bowmaker & Dartnall, 1980). Much of the earlier work used light from tungsten filaments, which provide wide spectral bands (for example, Barlow, 1958; Graham & Margaria, 1935). Even where the focus was on thresholds for colored stimuli (Baumbardt & Hillmann, 1961; Rouse, 1952), the available filters would not likely block enough of the spectral range to preclude responding by rods.

Also, the ambient illumination for present experiments was dim rather than dark, specifically 10 lux. Although this is still within the mesopic range that would allow for rod response, any detection with this background light level would be substantially above the absolute threshold. It is entirely possible that reciprocity of luminance × duration will be found only at the lowest limit of perception where special rod mechanisms exist to combine and amplify the light that is received (Baylor, Nunn, & Schnapf, 1984; Field, Sampath, & Rieke, 2005). More specifically, reciprocity might be found in the photochemical response systems of the rods, consistent with the initial formulation by Bunsen and Roscoe (1855).

2 Methods

Equipment, ambient lighting, and the inventory of shapes were the same as reported previously (Greene & Ogden, 2013). Five experiments were conducted, deriving data from eight new respondents in each experiment (40 total). Experiments were carried out in accordance with institutional regulations and the Declaration of Helsinki. In each of the experiments, shapes in the 360-inventory were assigned to the treatment conditions at random for each respondent that was tested, also requiring an equal number of shapes in each treatment condition.

Experiment 1 provided the data for the modeling shown in Figure 2. Flash duration for every shape displayed was 1 ms. Flash intensity for each LED emission was specified in candela (Cd). Nine levels of luminous intensity were tested, specifically: 0.16 to 0.21 Cd in 0.01 increments.

Experiment 2 provided the data for the Figure 3 models. For each respondent, half of the shape inventory was assigned at random to the constant-photon condition and the remaining half was assigned to the constant-intensity condition. Shapes were further randomly assigned to one of five levels of flash duration: 0.01, 0.10, 1.0, 10, and 100 ms. Base intensity was 0.19 Cd, this being the level that elicited a half-maximum hit rate in Experiment 1 (calculated from raw data). For the constant-photon condition the base intensity was scaled by flash duration, such that intensity × duration would yield the same quantity of photons. The base intensity of 0.19 Cd was used for all flashes for the constant-intensity condition.

Experiment 3 provided data for the Figure 4 models. An intensity of 0.21 was used to calculate the constant photon quantity that was displayed at durations ranging from 1.0 to 1.4 ms in 0.05 ms increments (nine levels of duration).

Experiments 4 and 5 provided data for the Figure 5 models. Experiment 4 tested flash intensities ranging from 0.15 to 0.20 Cd in 0.01 increments (nine levels). Flash durations were all at 1.0 ms. Experiment 5 tested with durations ranging from 1.0 to 1.4 ms (nine levels), also imposing a constant-photon condition using 0.21 Cd as the base intensity.

For each of the experiments that evaluated luminous intensity, random effects semi-parametric logistic regression was used to model the treatment effects. Conceptually, a smoothly varying “average" curve is fitted for the probability of correct response over all participants, while the idiosyncratic deviations from the average response curve are incorporated using smooth person-specific random effects. This approach invokes only a minimal number of assumptions about the response curve—the main assumption is the lack of sudden jumps, and leads to fitted curves that follow the data closely. The downsides are that the parameter estimates are not meaningful, and the precision of the estimates is reduced compared to a well-fitting parametric curve. Technically, the average effect was modeled by a cubic spline with two equally spaced internal knots, while the person-specific deviations were modeled with a random intercept and a penalized cubic spline that also had two equally spaced knots. Flash duration was transformed to logarithmic scale for both modeling and presentation. For each group model of this report the treatment effects were significant at $p < 0.0001$. Analyses were performed using SAS version 9.3 (The SAS Institute, Cary, NC), using the Glimmix procedure for the primary analysis.

Acknowledgments. David Nyberg designed the circuitry for the display system. Jack Morrison of Digital Insight fabricated the system, wrote the firmware and software required for its operation, calibrated emission intensity and duration, and contributed to the evaluation and interpretation of results in numerous ways. Prof. Jack Feinberg, USC Physics Dept., took measures to confirm calibration of flash duration and luminous intensity. Respondents were tested by Andrew Alonzo and Adrienne Visani. Statistical analysis and modeling was provided by Daniel Eastwood and Dr. Aniko Szabo, Biostatistics Consulting Service, Medical College of Wisconsin. This research was supported by the Neuropsychology Foundation and the Quest for Truth Foundation.

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