Running Head: Pupil & Concept

Pupillary evidence reveals the influence of conceptual association on
brightness perception

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Abstract

Our visual experience often varies based on momentary thoughts and feelings. For example, when positive concepts are invoked, visual objects may appear brighter (e.g., a “brighter” smile). However, it remains unclear whether this phenomenological experience is driven by a genuine top-down modulation of brightness perception or by a mere response bias. To investigate this issue, we use pupillometry as a more objective measure of perceived brightness. We asked participants to judge the brightness level of an iso-luminant gray color patch after evaluating the valence of a positive or negative word. We found that the gray color patch elicited greater pupillary light reflex and more frequent “brighter” responses after observers had evaluated the valence of a positive word. As pupillary light reflex is unlikely driven by voluntary control, these results suggest that the conceptual association between affect and luminance can modulate brightness perception.

Keywords: Affect, Brightness Perception, Cognitive Penetrability, Pupillometry

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The perception of luminance (i.e., brightness) is primarily driven by the intensity of light source (Jameson & Hurvich, 1961) and its surrounding spatiotemporal contexts (Eagleman, Jacobson, & Sejnowski, 2004). Beyond these lower-level sensory factors, various cognitive processes, such as the conceptual associations related to affect, may also exert top-down influences on brightness perception (Meier, Robinson, Crawford, & Ahlvers, 2007). For example, positive stimuli appear brighter than negative stimuli (Meier et al., 2007) and neutral objects look brighter when positive thoughts are evoked (Banerjee, Chatterjee, & Sinha, 2012; Bhattacharya & Lindsen, 2016; Meier, Fetterman, & Robinson, 2015; Meier et al., 2007). Although these observations are in line with our everyday experiences (e.g., “a brighter smile”), whether these effects reflect a change in perceived brightness or a shift in response bias remains a long-lasting debate (Firestone & Scholl, 2016).

This uncertainty is largely due to the conceptual difficulty in assessing behavioral top-down effects on brightness perception (**Figure S1**). Consider the example when observers are asked to match the achromatic font color of a word with gray-scale color patches (Meier et al., 2007). If the word’s meaning modulates its perceived brightness, it should also affect the perceived brightness of gray patches used for perceptual matching. These two effects would cancel each other out and, as a result, perceived brightness of the word measured by the matching gray patch should remain constant regardless of the word’s meaning. Behavioral observations of “brighter” perception of positive words are, therefore, more likely reflect a response bias instead of a change in brightness discriminability (Firestone & Scholl, 2014, 2015,

2016). This assertion is consistent with the modularity principle of the mind (Fodor, 1983), which often assumes that cognition does not penetrate into early perception (Firestone & Scholl, 2016; Pylyshyn, 1999).

However, an emerging literature suggests that top-down factors can modulate brightness perception manifested as early as changes in pupillary light reflex (PLR). For example, brightness concepts presented as images (Naber & Nakayama, 2013) or words (Mathôt, Grainger, & Strijkers, 2017), and brightness percepts mediated by attention (Mathôt, van der Linden, Grainger, & Vitu, 2015), illusion (Laeng & Endestad, 2012), or consciousness (Sperandio, Bond, & Binda, 2018), can all modulate PLR. As PLR is considered free from voluntary control (Ebitz & Moore, 2017; Mathôt et al., 2017; Sperandio et al., 2018), these findings suggest some top-down influences on brightness perception. However, what remains unknown is whether indirect conceptual association between affect and luminance is sufficient to introduce changes in early perceptual processes, as effects related to conceptual associations (e.g., metaphors) are often assumed to operate at the post-perceptual level (Lakoff, 2014). Furthermore, it is also unclear whether these PLR effects are associated with the behavioral tendency of more “brighter” responses under positive affect – a key step forward to link perceptual changes with altered behavioral patterns (Sperandio et al., 2018).

To fill these gaps, we asked participants to evaluate the emotional valence of a word and then, after a brief blank interval, judge the luminance of a gray color square (i.e., the luminance probe) while we were simultaneously recording their pupil sizes (**Figure 1A**). Although participants were told and saw in practice that there were two possible probes with a subtle difference in luminance, we presented only one probe at a constant luminance level during the experiment (Meier et al., 2007). This iso-luminant probe minimizes the impacts of selective

attention on pupil measures, as compared with simultaneous presentation of mixed information (Binda, Pereverzeva, & Murray, 2013; Leong, Hughes, Wang, & Zaki, 2019). This design also addresses whether the indirect conceptual association between affect and brightness has an impact on subsequent perceptual processes – a critical test for early perceptual modulation based on conceptual associations (Lakoff, 2014). Typically, participants reported seeing the probe as “brighter” more often after they evaluated the valence of a positive word (Meier et al., 2007). If this effect is driven by response bias, PLR should be constant as probe luminance remains the same throughout the experiment. However, if this effect is related to a change in perceived brightness, similar to the previous studies that link PLR with conscious perception (Hakerem & Sutton, 1966; Sperandio et al., 2018), PLR should be greater when observers report seeing the iso-luminant probe being “brighter,” especially after an observer correctly evaluate the valence of a positive concept.

Methods

Participants

Forty-eight volunteers (19.90 ± 0.20 [Mean $\pm$ s.e.m] years old, 35 female) participated in the study for course credits. The first 28 participants were recruited for a 1-hour experiment and the remaining 20 participants were recruited for a 2-hour experiment with increased trial counts. These data were combined and analyzed with linear mixed-effect models that factored in different trials numbers across subjects (see **Statistical Analysis**). All participants reported normal or corrected to normal visual acuity and normal color vision. Data from addition 3 subjects were excluded as we could not obtain meaningful pupil data from these subjects due to issues in eye-tracking with contact lens or eyeglasses. Informed consent was obtained at the

beginning of the experiment. Based on G*Power (Faul, Erdfelder, Buchner, & Lang, 2009), the ultimate sample size ($n = 48$) would have sufficient statistical power (80%) to detect a medium size of random effect (e.g., Cohen's $d \geq 0.36$) at a significant level of .05. This study was not preregistered. Data and Code will be made available at <https://osf.io/2vuaz/>.

Apparatus and Stimuli

The experiment was conducted in a moderately lit windowless room (~ 500 lx). Visual stimuli were presented on a 60-Hz LCD monitor (calibrated with a X-Rite i1Pro spectrophotometer) with a grey background (42 cd/m^2) at a viewing distance of 80 cm. Eye movements and pupil size (linearly associated with pupil diameter in arbitrary units, AU) were recorded with an EyeLink 1000 eye tracker (SR Research Ltd., Ontario, Canada) at a sampling rate of 500 Hz after calibration (see Xie, Lu Sing, Martinez-Flores, & Zhang, 2022 for details). Fifty words with positive meaning and fifty words with negative meaning were adopted from previous studies (**Table S1**; Meier, Robinson, & Clore, 2004; Meier et al., 2007). While word frequency was not controlled in this original study (Meier et al., 2007), word frequency did not interact with the effect of semantic valence on brightness perception (see Meier et al., 2004, 2007 for details). All word stimuli were presented in 36-point Helvetica type at the center of the screen, with a visual angle of 1.8° in height and 1.4° to 3.2° in width. A $3^\circ \times 3^\circ$ grey square (49 cd/m^2) was presented at the center of the screen as the luminance probe.

Procedure

Each trial started with a fixation point at the center of the screen for 800 ms, followed by a 400-ms presentation of a word, randomly chosen from the positive or negative word sets (**Figure 2A**). Participants were asked to judge the word's valence using two buttons on a gamepad. After a jittered blank interval between 900 ms and 1,100 ms (averaged at 1,000 ms), a

luminance probe appeared at the center of the screen for 400 ms, followed by a 3,000-ms blank interval. Participants reported whether the probe was the “brighter” or the “dimmer” one using two gamepad buttons that were different from the buttons for the valence judgment task. While the luminance probe was set constant at 49 cd/m² during the experiment, participants were told and actually saw probes with a subtle difference in luminance during the practice (48 cd/m² vs. 50 cd/m²). They completed 15 or 30 practice trials and took a few minutes break for eye-tracking recalibration before the actual experiment. Ultimately, each word was presented once or twice over the course of the experiment in random orders, yielding a total of 100 ($n = 28$) or 200 ($n = 20$) trials per subjects. During the experiment, participants were encouraged to suppress eye blinks and eye movements (see **Figure S3**) and achieve accuracy over speed. Reaction time was thus not the focus of the current experiment (see **Figure S4**).

Preprocessing and Analysis of Pupil Data

Pupil data were prepared and analyzed using established methods (Granholm, Asarnow, Sarkin, & Dykes, 1996; Siegle, Steinhauer, & Thase, 2004). In briefly, a 2,500-ms epochs time-locked to the onset of the probe were extracted from trials with correct responses for word valence judgment. Artifacts, including blinks, were identified and interpolated using established algorithm (Granholm et al., 1996; Siegle et al., 2004). Trials with more than 50% interpolated area or with a <100 ms response time were excluded from analysis (Granholm et al., 1996; Siegle et al., 2004; Xie et al., 2022). In the end, 6.75% of trials were rejected across participants. We then applied baseline correction by dividing the pupil data by the average pupil size within 200 ms before the onset of the luminance probe (Cohen, 2014). This percentage of change normalizes individual differences in baseline pupil size and effectively capture pupil changes time-locked to the probe presentation (Ebitz & Moore, 2017), given that PLR is only weakly

correlated with baseline pupil size (Ebitz, Pearson, & Platt, 2014). The resulting PLR measures are therefore not confounded by variable pupil sizes triggered by different words on the screen before probe onset, although word valence does not have a significant impact on participants' pupil size measures (in line with Meier et al., 2007; also see **Figure S5**).

Several measures of PLR were extracted (Ebitz & Moore, 2017). First, we measured the windowed pupil size from 500 to 1,000 ms after probe presentation that captures maximum PLR period across participants (**Figure 2A & 2B**). This windowed pupil size measure is referred to as PLR magnitude (Ebitz & Moore, 2017). Second, we also measured the local minima of the pupil size measures during the 500–1,000 ms time window following probe onset as PLR amplitude (Bitsios, Szabadi, & Bradshaw, 2004; Ebitz & Moore, 2017). Both measures are highly correlated and produce comparable experimental outcomes. Furthermore, the size of measurement time window for PLR magnitude and amplitude does not significantly change the experimental outcome either, as long as this window captures the PLR peak (e.g., changing from 500-1,000 ms to 600-900 ms).

Semantic projection for word-level analysis

To investigate word-level effects, we examine how the semantic meaning of word valence is related to PLR effects between different response types across participants. First, we projected the high-dimensional semantic embeddings of each word based on GloVe (Global Vector for Word Representations; Pennington, Socher, & Manning, 2014) onto a more interpretable valence scale (**Figure S2A**) using a previously established method (Grand, Blank, Pereira, & Fedorenko, 2018). Specifically, we defined a feature subspace using the average vector of six distinct words that characterize each of the opposite ends of the valence space

PUPIL & CONCEPT

(positive: “pleasant”, “good”, “favorable”, “happy”, “great”, and “cheerful”; negative: “unpleasant”, “bad”, “unwanted”, “sad”, “awful”, and “upset”).

$$\begin{aligned} \overrightarrow{\text{Positive}} &= \frac{\overrightarrow{\text{Pleasant}} + \overrightarrow{\text{Good}} + \overrightarrow{\text{Favorable}} + \overrightarrow{\text{Happy}} + \overrightarrow{\text{Great}} + \overrightarrow{\text{Cheerful}}}{6} \\ \overrightarrow{\text{Negative}} &= \frac{\overrightarrow{\text{Unpleasant}} + \overrightarrow{\text{bad}} + \overrightarrow{\text{Unwanted}} + \overrightarrow{\text{sad}} + \overrightarrow{\text{Awful}} + \overrightarrow{\text{Upset}}}{6} \end{aligned}$$

According to the prior study (Grand et al., 2018), this averaging procedure ensures robust approximations of feature subspaces that were not strongly impacted by the particular choice of antonyms. Next, we took the difference between positive and negative ends of the valence scale, such that a positive value would mean more positive meaning and a negative value mean more negative meaning.

$$\overrightarrow{\text{Valence}} = \overrightarrow{\text{Positive}} - \overrightarrow{\text{Negative}}$$

We then project each word’s vector onto this valence scale via a dot product calculation. This estimated value therefore captures the semantic valence value of each word from our everyday language,

$$\text{word valence projection} = \overrightarrow{\text{Valence}} \cdot \overrightarrow{\text{Word}}$$

Afterwards, we correlated word valence projection scores with the average difference scores in PLR magnitude (500-1,000 ms after probe onset) when a probe was judged as being “brighter” versus “darker” following the correct evaluation of the presented words (i.e., “brighter” - “darker”). On average, the PLR effect estimated for each word comes from data averaged across 31 ± 0.35 participants per word for the “brighter” response and 23 ± 0.33 participants per word for the “darker” response.

Statistical Analysis

In addition to within-subject statistical procedures (e.g., paired-sample t-test), we applied linear mixed-effect modeling on trial-level pupil data to take into account trial-level variations in subject-level inference. Wald's Z test is used to examine the statistical significance of mixed-effect model parameters. Furthermore, to examine word-level effect (Xie, Bainbridge, Inati, Baker, & Zaghloul, 2020), we applied Spearman rank-order correlation to evaluate the relationship between word valence projection and the PLR effect between different response types across subjects. Additionally, we performed a sensitivity analysis based on resampling the data with different sample sizes (from 5 to 47) to examine how the number of the subjects would affect this correlation estimate. This resampling analysis suggests the current sample size allows us to obtain a reliable estimate of this correlation (see **Figure S2** for details).

Results

Behavior

As accuracy was emphasized over speed, participants were highly accurate in evaluating a word's valence (positive vs. negative: 94.5% vs. 92.9%, $t(47) = 1.64$, $p = .11$, Cohen's $d = 0.24$ [95% CI: -0.05, 0.52]). Following correct word evaluation, participants frequently reported seeing the probe being "brighter" after evaluating a positive word (66.0% vs. chance of 50%: $t(47) = 9.49$, $p < .001$, Cohen's $d = 1.37$ [1.03, 1.70]). In contrast, they reported seeing the probe equally likely as being "brighter" or "darker" after evaluating a randomly intermixed negative word (51.4% vs. chance of 50%: $t(47) = 0.70$, $p = 0.49$, Cohen's $d = 0.10$ [-0.14, 0.34], **Figure 1B**). There was a significant within-subject difference between these two conditions ($t(47) =$

6.01, $p < .001$, Cohen's $d = 0.87$ [0.53, 1.20]), with 79% of participants showing this effect (**Figure 1C**), in line with previous findings (Meier et al., 2007).

Pupillometry

To examine PLR, we measured pupillary response as the percentage of change relative to the mean pupil size in the 200 ms proceeding the probe onset for each trial under different brightness response types and word valence conditions (**Figure 2A**). This procedure normalizes individual differences in pupil size with minimal impacts on PLR, considering that variability in PLR is only weakly related to baseline pupil size (Ebitz & Moore, 2017). We quantified PLR magnitude using the windowed pupil size at 500-1000 ms following probe onset when pupil constriction peaked (**Figure 2B**). The trial-by-trial measures of PLR magnitude were then subjected to linear mixed-effect models across subjects and trial types.

First, we examined whether PLR magnitude could reflect participants' behavioral judgement of probe luminance. We found that PLR was significantly greater when participants reported seeing the luminant probe as "brighter" as compared with when they reported seeing it as "darker" (Wald test: $Z = 2.86$, $p = 0.004$). This main effect of response type on PLR suggests that brightness judgement is grounded in brightness perception, instead of response bias (Hakerem & Sutton, 1966; Sperandio et al., 2018). Next, we examined how the valence of a word proceeding the probe would modulate the relationship between brightness judgement and perception. Although PLR magnitude did not differ significantly between word valence conditions ($Z = 1.56$, $p = 0.21$), there was a significant interaction effect between brightness response type and word valence ($Z = 3.27$, $p = 0.001$). Specifically, the difference in PLR magnitude between "brighter" and "darker" responses was significantly greater in the positive condition ($t(47) = 3.60$, $p < .001$, Cohen's $d = 0.52$ [0.22, 0.82]), as compared with the negative

condition ($t(47) = 0.56, p = .58$, Cohen's $d = 0.09 [-0.24, 0.42]$; **Figure 2C**). These observations remained robust when we examined PLR amplitude estimated from the local minimum (Ebitz & Moore, 2017) during 500-1000 ms after probe onset (e.g., interaction effect between response type and word valence: $Z = 3.06, p = 0.004$). These results suggest that the PLR effect for “brighter” (vs. “darker”) response was more pronounced following the correct evaluation a positive (vs. negative) word. We then investigated whether words with more positive meanings indeed triggered larger PLR effects in a more continuous manner. To do so, we projected the high-dimensional embeddings of the vectorized word representation of each word (Grand et al., 2018) to the valence dimension and create a continuous valence measure for each word (e.g., from “unpleasant” to “pleasant”, see **Figure S2** for details). We correlated these word valence values with the subject-average PLR effects triggered by each word when participants judged the iso-luminant probe being “brighter” over “darker.” Consistent with the subject-level effects, we found that words with more positive meanings were associated with greater PLR effects ($\rho = .32 [.13, .48], p = .0013$, **Figure 2D**). Collectively, the converging subject- and word-level findings suggest that the iso-luminant probe reliably looks brighter, manifested as larger pupil constriction, when a proceeding word carries a positive meaning.

Discussion

Given the probabilistic nature of perception (Knill & Pouget, 2004), an iso-luminant visual object can be perceived as being brighter or darker across different exposures, depending on the spatiotemporal contexts (Eagleman et al., 2004) or an observer's momentary thoughts and feelings (Banerjee et al., 2012; Meier et al., 2007). Although the former is well acknowledged, whether or not associative concepts related to one's thoughts and feelings can genuinely impact

early perception has remained a long-lasting debate (Firestone & Scholl, 2016). Here, with collaborative pupillary and behavioral evidence, our findings pose a critical test against the assertion that cognition does not impact perception.

Our data suggest that the indirect association between positive concepts and luminance (e.g., “a brighter smile”) can directly impact brightness perception, in contrast to the conventional understanding that metaphorical associations primarily operate at the post-perceptual or conceptual level (Barsalou, 2008; Lakoff, 2014). This is separate from the influence of luminance concepts on brightness perception (Mathôt et al., 2017), considering that the words used in the study do not directly carry luminance information (**Table S1**) and the effects must rely upon indirect semantic mapping. In theory, this association can be scaffolded by the overlapping neural circuitry between visual perception and high-level cognitive processes (Lakoff, 2014). For instance, microsimulation at a primate’ frontal eye field is sufficient to modulate PLR controlled by brain stem nucleus (Ebitz & Moore, 2017). Future research should investigate how this frontal-brain-stem circuitry may mediate top-down PLR effects in humans.

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Figure 1. Task and behavioral findings. **(A)** An example trial. **(B)** Participants more frequently reported seeing an iso-luminance probe as “brighter” following correct valence evaluation of a positive word. **(C)** The behavioral effect across valence conditions in each participant. ***. $p < .001$.

Figure 2. PLR effects. **(A)** Participants showed greater pupil constriction when they judged the iso-luminant probe as “brighter” following correct evaluation of a positive (*right*) relative to negative word (*left*). **(B)** We quantified PLR magnitude as the windowed normalized pupil size during the maximum PLR period from 500 to 1000 ms following probe onset (Ebitz & Moore, 2017). **(C)** Subject-level analysis of the average PLR magnitude across trials shows that PLR effects linking brightness judgment and perception are stronger following participants’ correct valence evaluate of a positive word, as compared with a negative word. **(D)** Similarly, word-level analysis of the PLR effects averaged for the same word across subjects also suggest that words with more positive meanings are associated with greater PLR effects. Each dot represents data for a word out of a total of 100 words. The line represents the linear fit of the data. Example words are shown in the figure. Error bars or areas represent standard errors. a.u. = arbitrary unit; **, $p < .01$.

Supplementary Information

Conceptual Challenges in Behavioral Top-down Effects on Brightness Perception

Cumulative evidence has demonstrated that affective concepts can modulate brightness perception (Banerjee, Chatterjee, & Sinha, 2012; Bhattacharya & Lindsen, 2016; Meier, Fetterman, & Robinson, 2015; Meier, Robinson, Crawford, & Ahlvers, 2007; Song, Vonasch, Meier, & Bargh, 2012). These effects are generalizable across laboratory and online crowd-sourced studies (Banerjee et al., 2012; Bhattacharya & Lindsen, 2016; Meier et al., 2015, 2007). However, it remains unsettled whether these effects reflect a genuine change in perceived luminance or merely a shift in response bias (Storrs, 2015), which provides a critical test on whether cognition impacts perception (Firestone & Scholl, 2016).

While a perceptual effect refers to actual changes in perceived brightness, a tendency/bias toward reporting “bright” or “dark” without changes in perception (i.e., a response bias) can produce similar behavioral observations. A widely used approach to distinguish these two effects is based on the Signal Detection Theory (Lu et al., 2015; Wickens, 2001). In principle, noisy perception of a darker stimulus (*red*) and a brighter stimulus (*blue*) forms two bell-shaped distributions of perceived brightness across trials (**Figure S1A**). If a percept of a luminance probe (denoted by an asterisk) is below the decisional criterion (denoted as a solid vertical line), a “dark” response by the observer will be rendered. If positive affect, relative to negative affect, leads to a more liberal criterion (from the solid line to dotted line), the same percept (denoted by the asterisk) that previously led to a “dark” response under negative affect will now lead to a “brighter” response instead. This response bias could account for more “brighter” responses under the influence of positive affect without any changes in brightness perception.

Figure S1. Competing hypotheses for the effects of affective thoughts on brightness perception. Noisy perception of a darker stimulus (red) and a brighter stimulus (blue) can be modeled as two bell-shaped distributions along a continuous dimension of perceived brightness according to the Signal Detection Theory. **(A)** The response bias hypothesis predicts shifts in decisional criterion. Specifically, top-down factors may lead to a more liberal criterion (e.g., shift from the solid line to dotted line) and more “brighter” responses under top-down influences. **(B)** The perceptual change hypothesis predicts that positive thoughts should increase the perceived brightness for any stimulus along the luminance spectrum. As a result, while the relative perceptual discriminability remains the same, the same response criterion would lead to more “brighter” responses under certain top-down influences.

Alternatively, affective thoughts can modulate perceived brightness, which in theory should lead to an overall shift in perceived brightness for all percepts under positive affect (rightward shifts in the distributions of perceived brightness, dashed lines, **Figure S1B**). Assuming that response criterion remains the same, a larger proportion of the internal representations for stimulus brightness would now land on the right side of the response criterion (i.e., blue dashed distribution), leading to more “brighter” responses. Yet, no changes in brightness discriminability is expected, as the relative perceived brightness

level for the darker and brighter stimuli, namely d' , before or after perceptual shift should remain the same. As both hypotheses would lead to similar behavioral outcomes without any changes in brightness discriminability, Signal Detection Theory is less effective in distinguishing these two possibilities.

This issue reflects the conceptual challenge in distinguishing post-perceptual inferences, attention effects, or response bias from genuine perceptual effects, a problem previously termed as the “El Greco Fallacy” (Firestone & Scholl, 2014, 2015, 2016). El Greco is a Spanish artist with severe astigmatism, a distortion of the eye that “stretches” the world vertically. However, the artist’s defective perception could not theoretically explain elongation of objects and characters in his paintings, because similar perceptual elongation would have manifested in both his canvas and the subjects of his painting, and thus cancelling each other out (Firestone & Scholl, 2014, 2015, 2016). Following this idea, some researchers believe that top-down behavioral effects of affective thoughts on brightness perception should mostly be attributed to response bias instead of genuine perceptual changes (Firestone & Scholl, 2016). This appears to reinforce the popular theoretical standpoint (Pylyshyn, 1999) that cognition could not change early perception (i.e., cognitive impenetrability).

Resolution of this long-lasting debate requires additional evidence for certain physiological markers of brightness perception, such as pupillary light reflex (PLR). Although PLR is traditionally thought to be driven by bottom-up stimulus factors and to be avoided in experimental designs (Beatty & Lucero-Wagoner, 2000), recent research has revealed robust modulation of PLR by cognitive factors (Hartmann & Fischer, 2014; Mathôt & Van der Stigchel, 2015), including brightness concepts of images (Naber & Nakayama, 2013) and words (Mathôt, Grainger, & Strijkers, 2017), attention (Mathôt, van der Linden, Grainger, & Vitu, 2015), illusion (Laeng & Endestad, 2012), and consciousness (Sperandio, Bond, & Binda, 2018). These PLR effects are taken as evidence for changes in perceived brightness since they are similar to PLR evoked by different luminance levels of physical light. Furthermore, PLR is often considered free of voluntary control and response bias (Binda, Pereverzeva, & Murray, 2014; Hakerem & Sutton, 1966; Sperandio et al., 2018), which provides a fair test to distinguish between response bias versus perceptual effects by circumventing the potential pitfalls of confounding post-perceptual inference or attention effects with ongoing perceptual effects (Firestone & Scholl, 2016).

Additional Analyses for Word-level Effect

Here, we summarize additional analyses for the word-level effect. First, the semantic projection of word valence (**Figure S2A**) captures significant difference between positive and negative words chosen by the previous studies (Meier, Robinson, & Clore, 2004; Meier et al., 2007), suggesting the robustness of semantic projection in formulating interpretable stimulus feature in the semantic space ($t(98) = 9.89$, $p = 2.07e-16$, **Figure S2B**). Similar examples for other concepts, such as “size”, “safety”, and “intelligence”, can be seen in the study by Grand and colleagues (Grand, Blank, Pereira, & Fedorenko, 2018).

Second, we evaluated whether the current correlation would be specific to the average valence scale features. To do so, in each of the 5,000 iterations, we randomly chose three word pairs out of the six word pairs without replacement to quantify the valence scale, and then repeated the correlation analysis between word valence projection and PLR effect. We took the average correlation as the ultimate measure of correlation strength and compared it against the null distribution constructed by the correlation estimates based on shuffled word ranks. On average, we found that the valence scale defined by arbitrary three valence-related word pairs would be significantly correlated with the PLR effect estimated across participants (mean $\rho = .27$, $p = .004$ relative to the null distribution based on shuffled word ranks, **Figure S2C**). This result suggests that our current observation is robust to different ways of defining the valence scale and is not were not strongly impacted by the particular choice of antonyms (Grand et al., 2018).

Finally, we performed a sensitivity analysis based on resampling to examine how sample size would affect this correlation estimate. We resampled the data at each sample size k (from 5 to 47) across 5,000 iterations and compared these results against shuffled word rank data. As shown in **Figure S2D**, although different participants have different tendency in reporting the luminance probe as “brighter” or

“darker”, we found that the significant rank-order correlation between word value projection (based on six word pairs) and the PLR effect could be observed with at least 19 participants from our current sample. The ultimate sample of the 48 participants in the present study may thus provide an adequate estimate for this effect.

Figure S2. Schematic illustration of semantic projection (Grand et al., 2018) and word-level analysis. **(A)** Based on GloVe features (Pennington, Socher, & Manning, 2014), each word can be projected onto an axis that is defined by the anchoring words with extreme meanings along the feature axis (e.g., “pleasant” vs. “unpleasant” for valence). **(B)** This semantic projection can capture the difference in negative and positive words independently chosen from previous studies (Meier et al., 2004, 2007). **(C)** Resampling sensitivity analysis to evaluate how the selection of word pairs in defining the valence scale would affect the correlation estimate between word valence projection and the PLR effect at the word level. Across 5,000 iteration of random selection of three word pairs from the six chosen valence-related word pairs in the current study, the average correlation estimate between word valence project and PLR effect is significantly greater than the null estimated by shuffled word rank data (marked in gray). **(D)** Resampling sensitivity analysis to evaluate how sample size would affect the correlation estimate between word valence projection and PLR effects in **Figure 2D**. Error bars represent the standard deviation of the resampling distribution (i.e., standard error) across 5,000 iterations at each sample size level. Shuffled word rank data (marked in gray) reflect the null distribution for the word-level effect. a.u. = arbitrary unit; ****, $p < .00001$.

Eye movements could not account for the current experimental findings

As summarized in **Figure S3**, participants shown no systematic eye movements before or after the probe onset. The pupil diameter measures in the present study were, therefore, unlikely to be contaminated by eye movements.

Figure S3. Density maps for gazes within 200 ms pre or within 2000 ms post probe onset relative to the display screen.

Reaction Time Effects

We also applied the mixed-effect model to participants' trial-by-trial reaction times to the luminance probe in brightness judgement. We found that participants' responses to the iso-luminant probe were not statistically different from one another across positive and negative trials based on the linear mixed-effect model (mean reaction times for negative and positive conditions: 656 ms vs. 666 ms, $Z = 1.82$, $p = 0.074$). Yet, they reported more quickly when they saw the probe being "brighter" relative to being "darker" (mean reaction times for "brighter" vs. "darker" responses: 629 ms vs. 694 ms, $Z = 5.28$, $p < .0001$). However, this reaction time effect again was not significantly different from one another between positive and negative conditions (interaction effect between emotion conditions and response types: $Z = 1.86$, $p = .062$). Considering that reaction time was not emphasized throughout the experiment, the differences in reaction time, therefore, may not be sufficient to account for significantly more "brighter" responses and greater PLR effect observed primarily in the positive condition (**Figure 1B & 2C**).

On average, it took 661 ± 24 ms for participants to render a judgement for the probe brightness level (**Figure S4**). This follows within the time window when PLR peaks around 500 ms to 1000 ms after stimulus onset. Note, processes leading to PLR would have occurred much earlier than the reaction times and the maximum PLR time window. Therefore, PLR magnitude measures often capture the pupillary responses to the probe a few hundred milliseconds before the PLR peak (Ebitz & Moore, 2017).

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Figure S4. Reaction times for the luminance probe across participants in different experimental conditions.

Pupillary Responses Time-locked to Correct Word Judgement

We have also investigated pupillary responses to the affective words used in the current study, based on similar analysis informed by Mathôt and colleagues (2017). Consistent with Mathôt et al., we did not obtain significant evidence that word valence alone could have a significant impact on pupil size measures before or ~0.5s after participants' correct judgement of word meaning in valence. In line with Mathôt et al.'s observations, we did find that pupil sizes triggered by negative words were numerically larger than that triggered by positive words. Yet, this difference did not reach statistical significance. Overall, these analyses suggest that pupillary responses to the iso-luminant probes following word judgement could not be attributed to different pupillary responses to positive and negative words.

Figure S5. Pupillary responses time-locked to correct judgment of word valence.

Table S1. Words used in the current study

Negative words		Positive words	
aimless	insane	active	love
argue	insolent	agile	loyal
beggar	liar	ambitious	mature
bitter	mediocre	baby	mercy
cancer	mosquito	brave	neat
cheat	nasty	candy	nurse
clumsy	neurotic	champion	polite
crime	obnoxious	clean	power
critical	poison	cordially	pretty
crooked	pompous	devotion	prompt
crude	profane	dream	radiant
cruel	rude	earnest	reliable
danger	sarcastic	ethical	righteous
dead	shallow	faith	satisfying
defeat	sloppy	festival	sensible
delay	sour	garden	sincere
devil	spider	generous	sleep
diseased	steal	genius	studious
divorce	stingy	gentle	sweet
enemy	theft	gracious	talented
fickle	touchy	heaven	trust
foolish	ugly	hero	truthful
fraud	unfair	justice	victory
greedy	vain	kiss	wise
hostile	vulgar	leisure	witty

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