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Top-down effect on pupillary response: evidence from shape from shading

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Authors Note

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Abstract

Shaded 2D images often create an illusion of depth, due to the shading information and assumptions regarding the location of the light source. Specifically, 2D images that are lighter on top usually appear convex while images that are darker on top, usually appear concave, reflecting the assumption that light is coming from above. The process of recovering the 3D shape of a shaded image is called Shape from Shading. Here we examined whether the pupil responds to the illusion of depth in a shape from shading task. In three experiments we show that pupil size is affected by the percept of depth, so that it dilates more when participants perceive the stimulus as concave, compared to when they perceive it as convex. This only happens if participants make a judgment regarding the shape of the stimulus or when they view it passively but are aware of the different shapes. No differences in pupil size were found with passive viewing if participants were not aware of the illusion, suggesting that some aspects of shape from shading require attention. All stimuli were equiluminant, and the percept of depth was created by manipulating the orientation of the shading, so that changes in pupil size could not be accounted by changes in the amount of light in the image. We posit, and confirmed it in a behavioral control experiment, that the perception of depth is translated to a subjective perception of darkness, due to the "darker is deeper" heuristic and conclude that the pupillary physiological response reflects the subjective perception of light.

Keywords: pupillometry, pupil light reflex, shape from shading, depth perception, illusion

1. Introduction

1.1 Shape from shading

The term “shape from shading” refers to the process of recovering the three-dimensional shape of an object from its two-dimensional shaded image. Observers are able to do so because shading, combined with the direction of the illumination, inform us of the local surface shape by exploiting the fact that the parts of the surface facing the light-source are brighter than those facing away (Horn, 1975). For example, a convex surface lit from above will be bright at the top and dark at the bottom, whereas a concave surface lit from the same direction will have the opposite shading pattern. When the location of the light source is unknown, observers interpret, by default, the 3D shape of shaded objects as if the light source is located above (and to the left of) the scene (Adams, Graf, & Ernst, 2004; Andrews, Aisenberg, d’Avossa, & Sapir, 2013; Andrews, d’Avossa, & Sapir, 2017; Mamassian & Goutcher, 2001; McManus, Buckman, & Woolley, 2004; Ramachandran, 1988; Sun & Perona, 1998). The “light from above” prior is well explained by the fact that the sun and most artificial light sources are placed above the observer, and therefore, when the direction of the light is not clear, the observer assumes the most likely scenario, which is light coming from above. The left bias often seen in shape judgments of shaded images was attributed to either statistical regularities - suggesting that observers have more experience with light coming from the left than from the right (Adams et al., 2004; Sun & Perona, 1998); or to hemispheric lateralization - suggesting that the right hemisphere is more competent in computing the light information which results in a bias to the left (Andrews, d'Avossa, & Sapir, 2017; de Montalembert, Auclair, & Mamassian, 2010). In any case, the subjective percept of depth in shaded images is a strong and reliable illusion.

1.2 Pupil size and light illusion

In recent years it has been shown that an illusion of light can result in changes in the pupil response. Changes in the pupil's size occur automatically in response to changes in brightness, so that it constricts in response to light and dilates in response to darkness (Ellis, 1981). It is well documented that changes in pupil size are also affected by cognitive processes such as mental workload (Beatty, 1982; Hess & Polt, 1964; Kahneman & Beatty, 1966; Klingner, Tversky, & Hanrahan, 2011), surprise (Braem, Coenen, Bombeke, van Bochove, & Notebaert, 2015; Preuschoff, Hart, & Einhäuser, 2011), and even affective processing (Hess & Polt, 1960; Partala & Surakka, 2003).

One interesting finding from recent studies suggests that the pupil responds not only to light, but also to the illusion of light. Laeng & Endestad (2012) presented to participants well known illusions that create the percept of brightness, keeping the amount of actual light in the images constant. It was found that the pupil responds to the illusion of brightness as expected, so that when the image elicited a percept of light, the pupil constricted, compared to images containing the same elements and the same amount of brightness that did not elicit the percept of light. Several other studies replicated this finding with different stimuli (Binda & Murray, 2015b; Binda, Pereverzeva, & Murray, 2013b). Moreover, the pupil responds even to a presentation of words (Mathôt, Grainger, & Strijkers, 2017), or the imagination of familiar scenarios (Laeng & Sulutvedt, 2014) which are associated with different amount of brightness. Interestingly, the pupil seems to reflect also the shift of covert attention, without the movement of the eyes, to spatial locations containing stimuli of different brightness (Mathôt, van der Linden, Grainger, & Vitu, 2013).

1.2 Pupil light response - Darker is deeper.

In shape from shading experiments, the illusion of perceiving different shapes (concave or convex) is often achieved using the rotation of one stimulus. As the percept of depth depends on the shading pattern and the direction of the light, and the assumed light source direction does not change, observers interpret the change in the shading pattern as different shapes (concave or convex), depending on the direction of the shading. While the amount of light in the images is identical, there may be a reason to predict that shape from shading will produce different pupillary response, depending on the illusion of convexity and concavity. The reason comes from the “darker is deeper” heuristic (Langer & Zucker, 1994).

It has been known for centuries that observers assume that darker is deeper. In art, in order to elicit a percept of depth, the painter uses darker shades of the color. When a painter paints a pleated dress, for example, the folds on the dress are created by using darker shades of the same color. This “darker is deeper” heuristic was found to be used also in shape from shading (Christou & Koenderink, 1997) and was suggested as a default assumption for shade from shading in defuse lighting (Langer & Zucker, 1994). It is possible that human observers use the opposite assumption as well, that is, observers perceive an object that seems to them deeper, as if it is darker. If this is correct, the pupil may respond according to the subjective perception of depth so that “deeper is darker”. In that case, a percept of concavity will elicit a dilation of the pupil while a percept of convexity will elicit a constriction of the pupil.

In the current study we measured pupil diameter as a function of the perceived shape. If concave images seem darker, then the perception of concavity should affect the size of the pupil, so that stimuli that seem concave will result in larger pupil size than those that seem convex.

2. Experiment 1

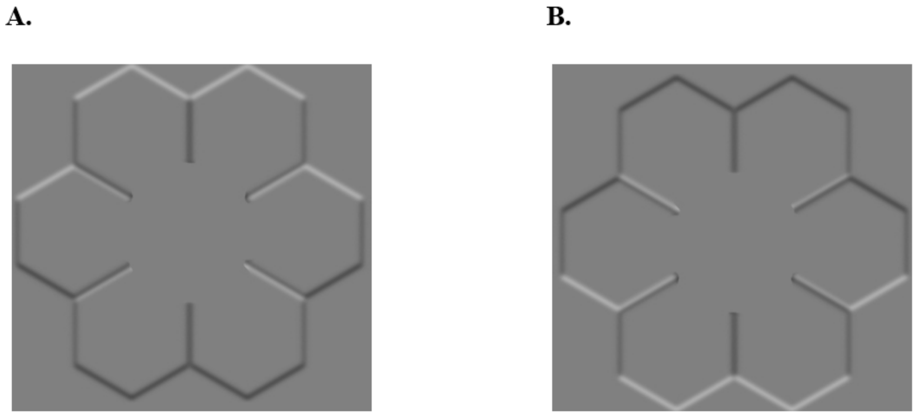
2.1 Materials and methods

2.1.1 Participants

Twenty-four undergraduate students (15 females, mean age 24.41 years, *SD* = 2.8) from Ben-Gurion University of the Negev in Israel participated in the experiment in return for 25 shekels (approximately $7) or for partial fulfillment of course requirements. The sample size was based on the sample size from Hershman and Henik (2019), who used 19 participants to get reliable pupil effects. Taking into consideration dropout rates, we increased our sample size to 24 participants. All participants had normal vision (without glasses or contact lenses) as well as normal color vision and no reported history of attention deficit disorder or any learning disabilities.

2.1.2 Stimuli

We used a variant of the "honeycomb" stimulus, based on Andrews et al., 2013. The original stimulus comprises seven hexagonal tiles, overlaid on a uniform silver background. Bright and dark edges create the impression of a relief lit from one side. In the current study we took out the central hexagon so that the stimulus looks like a snowflake (see Fig. 1). The stimulus orientation varied over 24 levels, obtained by rotating the stimulus in steps of 15˚ (i.e., $0^{\circ}, \pm 15^{\circ}, \pm 30^{\circ}, \pm 45^{\circ}, \pm 60^{\circ}, \pm 75^{\circ}, \pm 90^{\circ}, \pm 105^{\circ}, \pm 120^{\circ}, \pm 135^{\circ}, \pm 150^{\circ}, \pm 165^{\circ}, 180^{\circ}$). The stimuli were presented at the center of a screen on a silver background (RGB: 128, 128, 128; mean luminance = 128) and subtended a visual angle of 10°, from a viewing distance of about 50 cm.



Bright edges up

Bright edges down

Fig. 1. Examples for the presented stimuli in our experiments. (A) a stimulus with shading pattern as if it is lit from 0° *creating the percept of convex.* (B) The same stimulus rotated 180° *creating the percept of concave.*

2.1.3 Procedure

The experiment was conducted in a dimly illuminated room. A keyboard was placed on a table between the participant and the monitor. Participants were tested individually. The experiment started with a block of 10 practice trials (which was not analyzed). If more than one trial was not followed by a response, another practice block of 10 trials was presented, until the participant had a response rate of at least 90%. The practice block(s) followed by three blocks of 160 trials, to a total of 480 experimental trials. Participants were instructed to take a few seconds rest between blocks. The different stimuli orientations were presented in random order in both the practice and the experimental blocks. During practice, participants received feedback indicating that their response was detected. Each trial started with a 500 ms fixation (a red dot at the center of the screen), followed by the stimulus. The participants were instructed to fixate on the center of the screen and to press as fast as possible the “m” key on the keyboard if the stimulus appeared to them as concave and the “b” key if the stimulus appeared convex. For half of the participants this response binding was the other way around. The visual stimulus stayed in view for 500 ms and was followed by a blank screen (the background) until a key press, or for a maximum of 1,000ms. Participants' response (concave or convex) was recorded, and RT was calculated from the onset of the visual stimulus to the response. Each trial ended with a 1,500 ms inter-trial interval.

2.1.4 Apparatus

Pupil size was measured using a video-based desktop-mounted eye tracker (The Eye Tribe) with a sampling rate of 60 Hz (16.66 ms inter-sampling time). Stimulus presentation and data acquisition were controlled by Psychtoolbox software (version 3.0.14) on MATLAB (MathWorks version 9.4.0.813654 (R2018a)). Stimuli were displayed on a 23-inch LED monitor (Dell E2314Hf) at a resolution of 1920x1080 pixels, with a refresh rate of 60 Hz. The participant's head was positioned on a chin rest and the distance from the eyes to the monitor was set at about 50 cm. To maintain an accurate measurement of pupil size during the task, participants were required to keep their eyes fixated on the center of the screen and to avoid eye movements for the entire task. Pupil area was determined using the Eye Tribe algorithm.

2.1.5 Data exclusion and pre-processing of the pupillometry data

To determine whether a participant's response was significantly modulated by the orientation of the stimulus, the responses were fit using a logistic regression. The logistic model contained a constant, as well the cosine and sine of the stimulus orientation. The log-likelihood of the model fits was used to determine the significance of the effect of stimulus orientation. Only data from those participants whose model fit had a significance level less than 0.01 were included in the group analysis. A detailed description of the analytical procedure is available in previously published work (Andrews et al, 2013; 2017). In addition, participants were excluded from the analysis if they had more than 30% missing samples from the eye tracker in one or more conditions.

The assumed light source direction for each participant was estimated from the shape judgments, using a procedure detailed in Andrews et al., (2013). The same procedure was used also to estimate the assumed light source direction as per the pupil response. Pupil data was processed using CHAP software (Hershman, Henik, & Cohen, 2019). First, pupil data was extracted from the Eye Tribe (pupil size in arbitrary units). Then, we removed outlier samples with Z-scores larger than 2.5 (by using Z-scores based on the mean and standard deviation calculated for each trial). Next, for each participant, we excluded from analysis the trials with more than 30% of missing samples from the eye tracker. We also excluded trials with no behavioral response. This pre-processing eliminated 3.44% of trials on average. Next, we detected eye-blinks by using Hershman, Henik and Cohen's (2018) algorithm and filled missing values by using a linear interpolation (Hershman & Henik, 2019). Next, time courses were aligned with the onset of the stimulus and divided by the baseline (baseline was defined as the average pupil size 500 ms before the stimulus onset). Gaze position in the Y-axis and convergence were also analyzed using dedicated adaptations on CHAP (Hershman et al., 2019) to these measures. Temporal analysis started from the stimulus onset and last up to 1,000 ms post the stimulus offset. Exclusion criteria for these analyses were the same as those of the pupillometry analysis.

2.2 Results

Five participants were excluded from the pupillometry analysis because their responses were not modulated by the orientation of the stimulus (see above). One additional participant was excluded from the analysis because he did not have at least 70 valid trials (trials with less than 30% of missing samples from the eye tracker) for each condition. After applying these exclusion criteria, the final sample included 18 participants (12 females, mean age = 23.94 years, *SD* = 2.4). For the analyses of both gaze position and convergence one additional participant was excluded.

Figure 2A shows the group average proportion of convex responses as a function of the orientation of the stimulus. As can be seen, on over 90% of the trials in which the bright edges were pointing up, participants responded “convex”, while only on about 20% of the trials that the bright edges were pointing down (180°) participants responded “convex”. This illustrates that participants had different illusion of depth in different orientations, according to the light from above prior. Superimposed on that are the individual assumed light source directions. The group average assumed light source direction was 9.9° to the left; comparable to previous results in a similar population (Andrews et al., 2013). In addition, RT as a function of orientation mirrored somewhat the shape judgment effect, so that RTs were slower to more ambiguous stimuli. Specifically, the shortest RTs were found for orientations 0° and up to 45° to the left and the right, as well as 180°.

To estimate the assumed light source direction of the pupil, we calculated for each participant the mean pupil size over a fixed window between 800-1200ms post the stimulus onset in each trial, and used the same procedure that was used to estimate the assumed light source direction from the shape judgment (Andrews et al., 2013). The average assumed light source direction was 12.26° to the right, confirming that the assumed light source direction is based on the pupil size relies on the light from above prior. Figure 2B shows the reciprocal of the pupil size as a function of the orientation of the stimulus and the individual assumed light source direction. A correlation analysis between the two estimates revealed a weak (0.324) and not significant (p=0.19) correlation. The lack of correlation may reflects the noisy pupil data set when divided into the different orientations, which relied on less than 25 trials per orientation per participant.

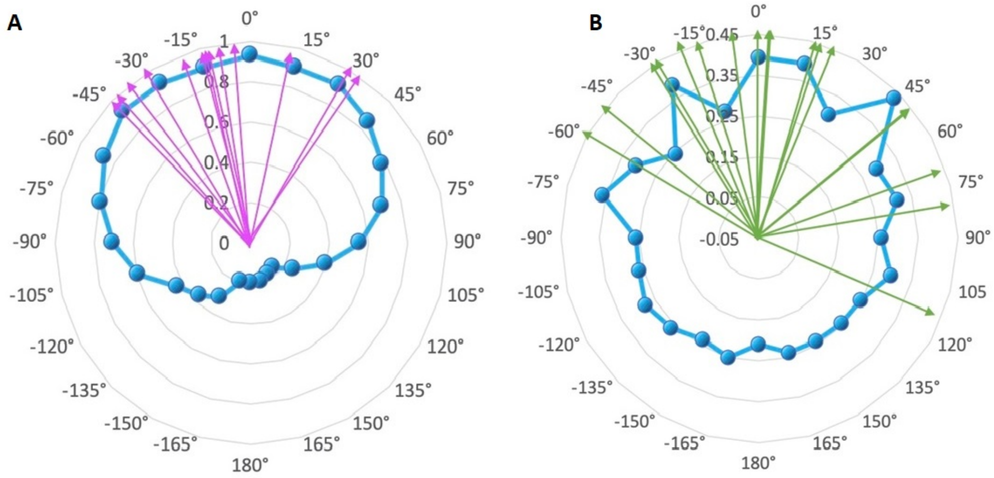


Fig. 2: **(A)** Proportion of convex responses as a function of the orientation of the stimulus, and the individual assumed light source direction based on shape judgment data. The data points in the polar plot show the proportion of trials in which participants reported “convex” for each stimulus orientation. Arrows represent the assumed light source direction for each participant. **(B)** Average pupil size as a function of the orientation of the stimulus and the individual assumed light source direction based on pupil response. The data points in the polar plot show the reciprocal of the averaged pupil size for each stimulus orientation. Green arrows represent the assumed light source direction for each participant, based on pupil size.

2.2.1 Pupillometry

Mean relative changes of the pupil size in both concave and convex responses are presented in Fig. 3A. We used Hershman and Henik’s (2019) approach to examine the temporal differences between the investigated conditions. Specifically, we ran a series of Bayesian paired sample t-tests between each two conditions over the whole time-course of pupil measurement.

Meaningful differences (i.e., $BF_{10} \geq 3$) are indicated in Fig. 3A by the horizontal line. The vertical lines (around 500 ms post the stimulus onset) represent mean response times

Our analysis indicates that a meaningful difference (i.e., $BF_{10} \geq 3$) between the investigated conditions appeared at about 740 ms after the stimulus onset and stayed for about 710 until about 1,450 ms post the stimulus onset (see 3B for the detailed Bayes factor figure). This time window is in line with previous studies that presented differences in pupil size as a function of illusory luminance (Binda et al., 2013b; Naber & Nakayama, 2013). Temporal analysis of pupil size in 12 orientations (0°, $\pm 30^{\circ}$, $\pm 60^{\circ}$, $\pm 90^{\circ}$, $\pm 120^{\circ}, \pm 150^{\circ}$, 180°) revealed a similar pattern to the behavioral effect, so that orientations 0° and -30°, which elicited the highest proportion of convex responses, also showed the smallest pupil dilation; orientation 180°, which caused the smallest proportion of convex responses, showed the largest pupil dilation; and the rest of the orientations falling in between, in close proximity to the behavioral effects. Bayesian paired-samples t-test of the reaction times suggested meaningful differences between convex (95% CIs 443ms, 544ms) and concave (95% CIs 488ms, 596ms) responses ($BF_{10} = 196.574$).

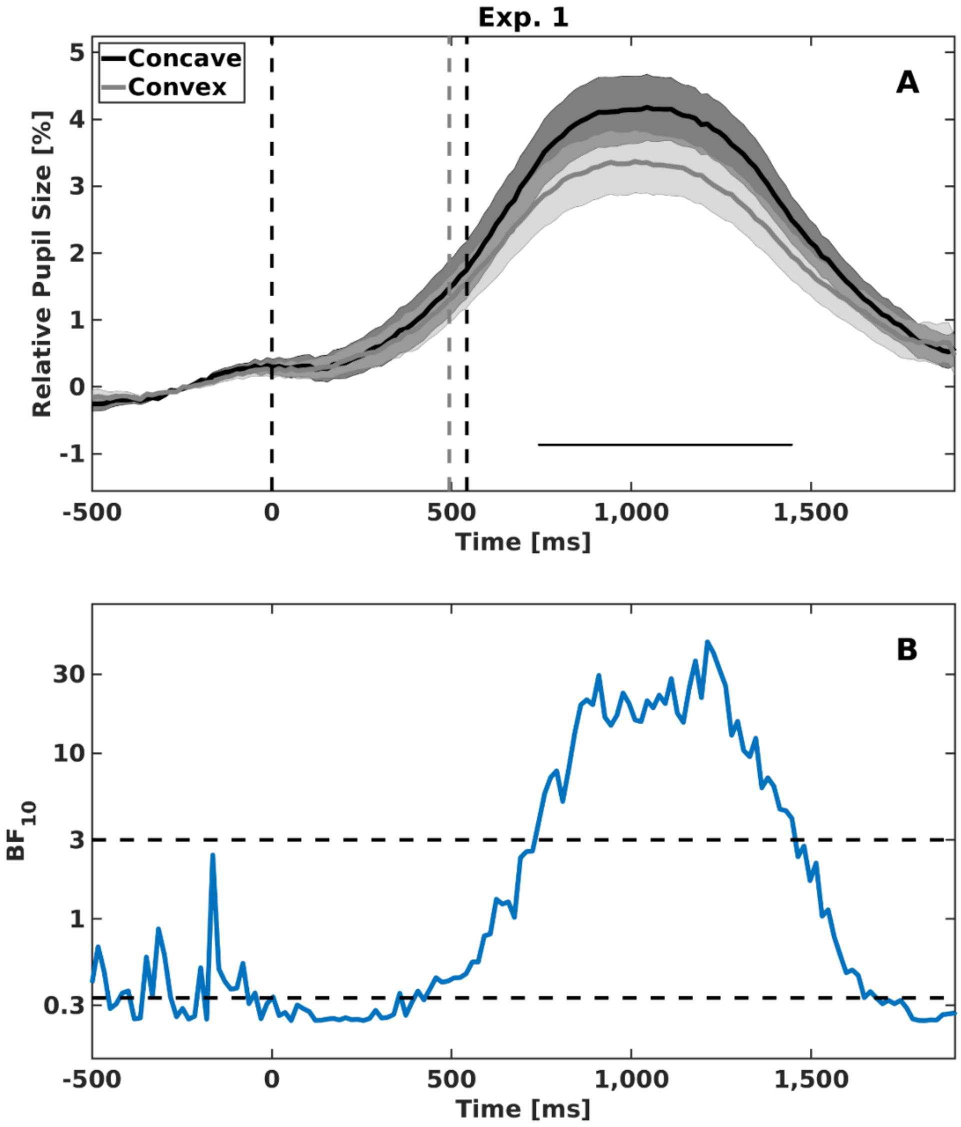


Fig. 3. **(A)** Mean relative pupil size (compared to pupil size at stimulus onset) for the investigated conditions in the Exp. 1. Participants had to decide whether the stimulus seemed concave or convex. The vertical line at 0 represents stimulus onset and the other vertical lines, around time 500 ms post stimulus onset, represent mean response times for each condition. The dark curve represents the "concave" responses and the bright curve represents the "convex" responses. The shaded areas represent 1 standard error from the mean. The horizontal line represents meaningful differences (i.e., $BF_{10} \geq 3$) between the conditions. **(B)** Bayes factors (BFs) as function of time for comparison between concave and convex responses of Exp.1. Each curve represents BF_{10} (namely, evidence for the alternative hypothesis that the two conditions are not the same). The horizontal black lines on 3 and on 0.3 represent the threshold for the decision making (BF_{10} values above 3 provide evidence for the alternative hypothesis and BF_{10} values below 1/3 provide evidence for the null hypothesis). Please note, the scale for the Y-axis is logarithmic.

Analysis of the gaze position as a function of time over the trial confirmed that participants had maintained fixation; peak average of pupil position did not exceed 0.23 degree (range 0.11 to 0.34). Gaze position tended to be slightly up, however these deviations are too small to be defined as meaningful saccades in pupillometry studies (Tkacz-Domb & Yeshurun, 2018). In addition, temporal analysis of convergence did not reveal any meaningful differences between concave and convex over the entire trial (i.e., $BF_{10} < 1$) Specifically, the Bays factor was between 1/3 and 1 most of the trial, with some time intervals where it was below 1/3 at 470-530 ms, 690-830 ms, 940-990 ms and between 1,250 -1,480 ms post stimulus onset.

The results of Exp. 1 showed that stimuli that are associated with concavity elicit more dilation compared to stimuli that are associated with convexity, suggesting that the pupil responds to the perception of depth.

3. Experiment 1b - Control experiment

We suggested that the stronger the perception of concavity elicited by the stimulus, the darker the stimulus will be perceived. Hence, the pupil will dilate more for perceived concave stimuli compared to for perceived convex stimuli. To directly test this “deeper is darker” hypothesis (i.e., that a different illusion of depth causes a different illusion of luminance), we conducted a control experiment with the aim to find weather the orientations of stimulus that are associated with perceived depth, are also associated with perceived luminance.

3.1 Materials and methods

3.1.1 Participants

Seventeen undergraduate students (14 females, mean age 23.23 years, *SD* = 1.09) from Ben-Gurion University of the Negev participated in the experiment in return for partial fulfillment of course requirements. All participants had no reported history of attention deficit disorder or any learning disabilities.

3.1.2 Stimuli

The stimuli in this experiment were the snowflake stimuli; the same stimuli that were used in Exp.1. Like in Exp. 1, the orientation of the stimulus was changed to create a different percept of depth, over 24 different orientations, at 15 degrees decrements. In addition, there were masks that were created by shuffling of the pixels of the snowflake stimuli. Specifically, the entire picture (281X281 pixels) was divided into 3X3 pixels that were reorganized randomly and created a scrambled picture of white, black and grey pixels.

3.1.3 Procedure

Participants were tested online by using minnoJS (Zlotnick, Dzikiewicz, & Bar-Anan, (2015), on their own devices. The program required a spacebar response, ensuring participants only use computers rather than tablets or mobile phones. To avoid a bias in brightness judgment, the experiment consisted of two separate blocks that were presented randomly. In one block the participants were asked to determine which stimulus is brighter and in the second block, which stimulus is darker. Each block consisted of 192 trials (8 trials per each of the 24 orientations) and every 96 trials there was a short break. Each trial (see Fig. 4 for a visual example) started with mask (shuffled version of the snowflake) in the center of the screen for 1,000 ms. The mask was followed by 2 snowflake stimuli in reversed orientations (e.g., 0° & 180°; 15° & 195°) that stayed on for 400 ms. Then, the snowflake stimuli were replaced by a mask for another 1,000 ms and after that, the participants were asked to decide which of the stimuli was brighter (or darker – depends on the block requirements).

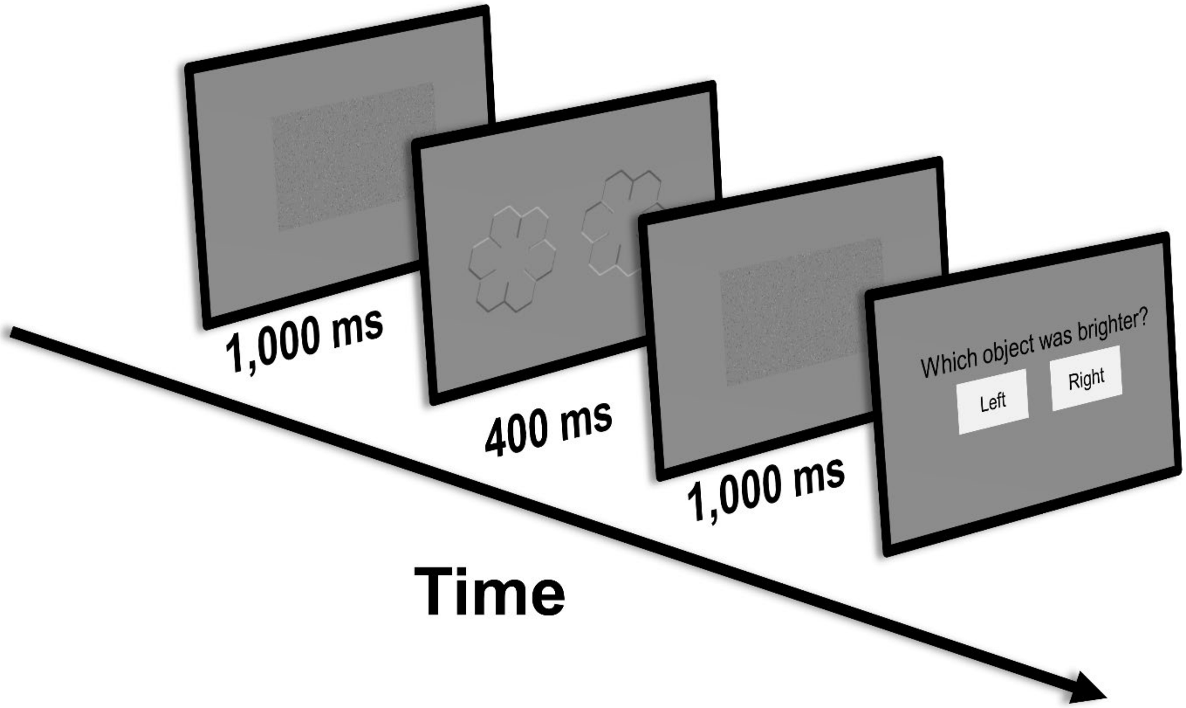


Fig. 4. An example for a typical trial. Participants were presented with a mask, followed by two reversed stimuli presented simultaneously, followed by another mask. They were asked to determine which of the two stimuli is brighter (or darker, depends on the requirements in the block).

3.2 Results

Fig. 5 shows the group average probability of “bright” responses as a function of the orientation of the stimulus compared to the reverse stimulus (across the two blocks). As can be seen, the probability of the bright responses gradually decreases as a function of the orientation. The results were subjected to a one-way repeated-measures analysis of variance (ANOVA) with orientation (0° to 165°) as an independent factor. The analysis produced a significant effect ($F(11,16) = 15.636, p < .001, \eta_p^2 = .494, BF_{10} = 3.17 \cdot 10^{19}$). Post hoc trend analysis produced also a significant effect (t(16)=4.49, p<.001, $BF_{10} = 90.15$).

These results confirm that stimuli that are associated with concavity are perceived darker than those that are associated with convexity, suggesting that the pupil's responds to the perception of depth is mediated by an illusion of light.

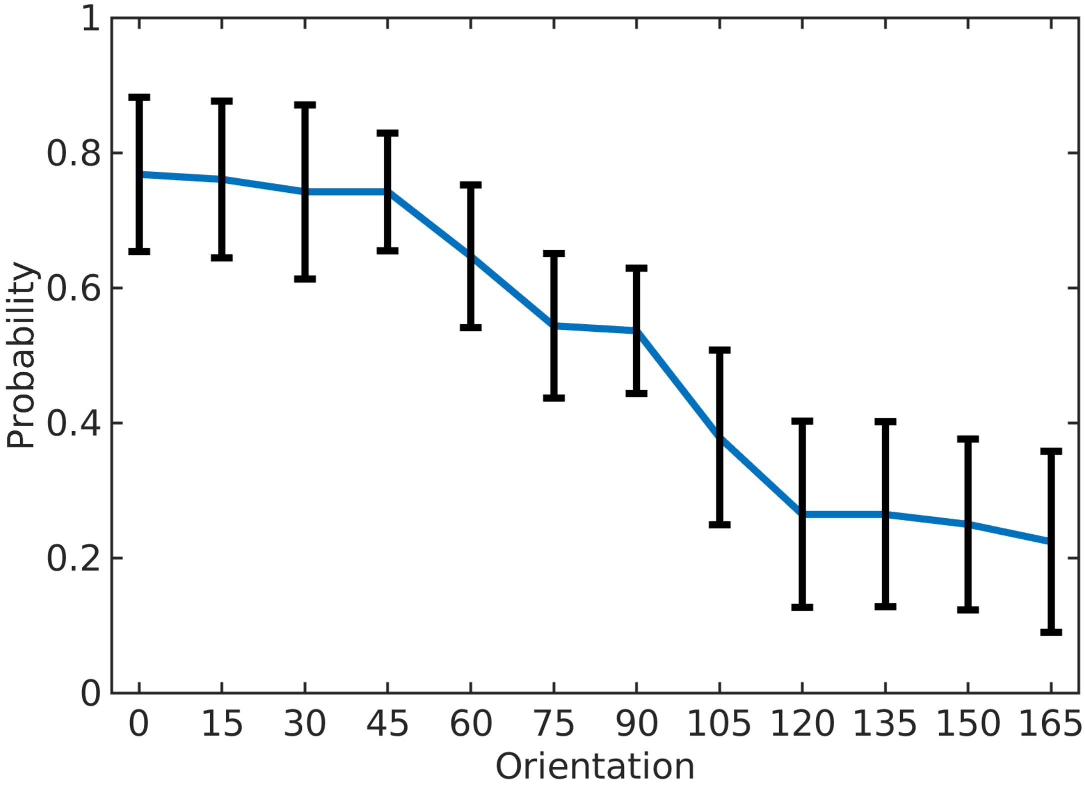


Fig. 5. The probability to decide that the object is brighter compared to the reversed object as a function of orientation. Error bars represent one confidence intervals (95%) from the means. This shows, for example, that when the orientation 0° (normally perceived as convex) was presented together with the orientation 180° (normally perceived as concave), in about 80% of the trails, participants judged 0° as brighter than 180°. The percentage of "bright" responses goes down gradually, so that orientations that are normally perceived as convex are judged as brighter than those perceived as concave, while more ambiguous orientations (around 90°) received ambiguous brightness judgments.

4. Experiment 2 - Passive viewing of the stimulus.

To ensure that the effect of the stimuli on the pupil size in Exp. 1 was a result of the perceived shape, we conducted the second experiment, where the snowflake stimulus was not task relevant. Specifically, participants were asked to make a shape judgment on a green circle or a square, while the snowflake stimulus, at variable orientations (similar to the first experiment), appears before the green stimulus, but did not require any response or decision. As no response was required, it was not possible to compare between convex and concave responses. Therefore, in line with the light from above prior (as it reflected in the behavioral results in Exp. 1), we compared trials where the bright edges pointed up (which should be perceived as convex) to trials where the bright edges were pointing down (which should be perceived as concave. Analysis of these conditions in Exp. 1 led to the same results as when subjective convex and concave responses were compared.

4.1 Materials and methods

4.1.1 Participants

Nineteen undergraduate students (14 females, mean age 24.37 years, *SD* = 1.74) from Ben-Gurion University of the Negev participated in the experiment in return for 25 shekels (approximately $7) or for partial fulfillment of course requirements. Similar to Exp.1, the sample size was based on the sample size from Hershman and Henik (2019), who used 19 participants to get reliable effects. All participants had normal vision (without glasses or contact lenses) as well as normal color vision and no reported history of attention deficit disorder or any learning disabilities.

4.1.2 Stimuli

The stimuli in this experiment were the same to those of Exp.1. In addition to the snowflake stimuli, there were also green (RBG = 0, 130, 0) circle and rectangle that were used for the shape discrimination part of the trials. The green shapes were presented randomly, and subtended a visual angle of 3.95° in both height and width, from a viewing distance of about

50cm.

4.1.3 Procedure

The procedure of Exp. 2 was similar to the one used in Exp.1 with an additional screen where participants were required to make shape judgment on a green object. Importantly, participants were not required to respond to the snowflake stimuli. Specifically, after the 500 ms of red dot fixation, the snowflakes stimuli were presented for exactly 2,000 ms, followed by a green shape. Participants were instructed to fixate on the center of the screen and to press as fast as possible the “m” key on the keyboard if the shape was a rectangle and the “b” key if the shape was a circle, or the other way around for half of the participants. The response binding was selected randomly for each participant. The green shape stayed in view for a maximum of 1,000 ms or until a key press and was followed by a 1,500 ms inter-trial interval. The experiment consisted of 360 experimental trials, with a short break every 120 trials.

4.1.4 Apparatus

The apparatus of Exp. 2 was identical to the one used in of Exp. 1.

4.1.5 Data exclusion and pre-processing of the pupillometry data

Pre-processing was the same as in Exp. 1. This resulted in exclusion of one participant, due to not having at least 70 valid trials (trials with no more than 30% of missing samples from the eye tracker) for each condition. For the 18 remaining participants (13 females, mean age = 24.39 years old, *SD* = 1.79) included in the analysis, pre-processing of pupil data eliminated 3.12% of trials on average. Another two participants were excluded from the convergence analysis.

As the snowflake stimulus did not require any response, we could not separate the trials based on participants’ subjective perception of shape. To be able to determine whether the pupil responds to concave/convex, we analyzed the results based on the “light from above” prior. It is well documented that observers assumed the light source is located above the observer, in order to interpret the 3D shape of a shaded image (Adams et al., 2004; Andrews et al., 2013, 2017; Gerardin, de Montalembert, & Mamassian, 2007; Mamassian & Goutcher, 2001; Ramachandran, 1988; J. Sun & Perona, 1998). According to this prior, a stimulus with bright parts on top and dark parts below, will be interpreted as convex, while a stimulus with the opposite shading pattern, will be interpreted as concave. Thus, it is reasonable to assume that participants will perceive the snowflake with the bright edges pointing up, as convex, while when the bright edges point down, participants will perceive it as concave (See Fig. 2 for behavioral results supporting this in Exp. 1). We therefore, separated the trials based on the orientation of the stimulus, rather than according to the participants’ response. The stimuli were divided to three groups: bright edges pointing up $(0, \pm 15, \pm 30, \pm 45)$, bright edges pointing down $(\pm 135, \pm 150, \pm 165, 180)$, and bright edges middle, either on the right or the left $(\pm 60, \pm 75, \pm 90, \pm 105, \pm 120)$. The third group of stimuli was not used in the analysis, as stimuli may be ambiguous.

4.2 Results

Mean relative changes of the pupil size in each condition are presented in Fig. 6A (meaningful similarities are presented by the faint horizontal lines). Our analysis indicates that there were no meaningful differences (i.e., $BF_{10} \geq 3$) between the investigated conditions for the entire presentation of the stimuli. (See Fig. 6B the detailed Bayes factor figure).

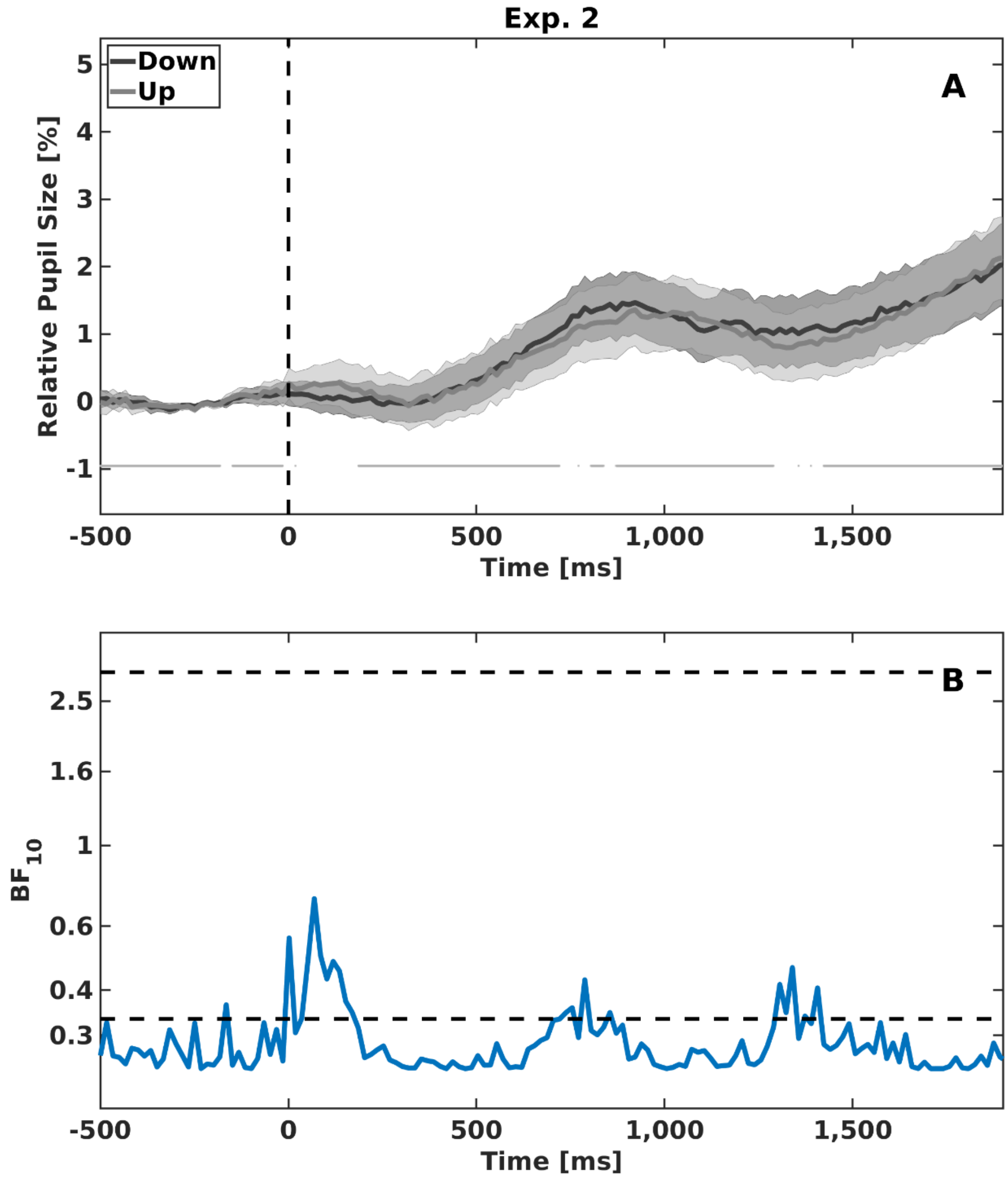


Fig. 6. **(A)** Mean relative pupil size (compared to pupil size at stimulus onset) for the investigated conditions in the Exp. 2. Participants had to ignore the stimuli that appeared for 2,000 ms and to detect a shape that appeared afterward. The vertical line at 0 represents stimulus onset. The dark curve represents the “down” condition and the bright curve represents the “up” condition. The shaded areas represent 1 standard error from the mean. The horizontal line represents meaningful similarities (i.e., $BF_{01} \geq 3$) between the conditions. **(B)** Bayes factors (BFs) as function of time for comparison between stimuli with bright parts on top compered to stimuli with bright parts on the bottom of Exp.2. Each curve represents BF_{10} (namely, evidence for the alternative hypothesis that the two conditions are not the same). The horizontal black lines on 3 and on 0.3 represent the threshold for the decision making (BF_{10} values above 3 provide evidence for the alternative hypothesis and BF_{10} values below 1/3 provide evidence for the null hypothesis). Please note, the scale for the Y-axis is logarithmic.

Analysis of the gaze position as a function of time over the trial, confirmed that participants had maintained fixation; peak average of pupil position did not exceed 0.4 degree (range 0.25 to 0.55). Gaze position tended to be slightly up, however these deviations are not defined as meaningful saccades in pupillometry studies (Tkacz-Domb & Yeshurun, 2018). In addition, temporal analysis of convergence did not reveal any meaningful differences at the entire trial (i.e., $BF_{10} < 1.5$). Specifically, the Bayes factor was below 1/3 between 270 – 570 ms post the stimulus onset, and then between 1/3 and 1 for most of the rest of the trial, with an anecdotical time point when it was 1.4 at about 1,760 ms post stimulus onset.

The results of Exp. 2 showed that when participants are not asked to respond to the stimulus or even to pay attention to the stimulus, there is no difference between the stimuli with bright edges pointing up or down.

5. Experiment 3 - Passive viewing of the stimulus with awareness to depth

The results of Exp. 2 suggested that the properties of the stimuli do not, by themselves, result in changes in pupil size. Interestingly, participants reported that they did not notice the 3D shape of the stimuli. In the next experiment we measured the pupil response to the same stimuli, with the same experimental procedure, but we encouraged participants to pay attention to the 3D shape of the snowflakes presented before the green target.

5.1 Materials and methods

5.1.1 Participants

Nineteen undergraduate students (14 females, mean age 24.95 years, *SD* = 2.28) from Ben-Gurion University of the Negev participated in the experiment in return for 25 shekels (approximately $7) or for partial fulfillment of course requirements. Similar to both Exp.1 & Exp. 2, number of participants was determined according to a previous study (Hershman and

Henik (2019), where 19 participants showed a reliable pupil response. All participants had normal vision (without glasses or contact lenses) as well as normal color vision and no reported history of attention deficit disorder or any learning disabilities.

5.1.2 Stimuli

The stimuli in this experiment were the same to those of Exp. 2.

5.1.3 Procedure

The procedure of Exp. 3 was identical to those used in Exp. 2 with one difference. In Exp. 3 the instructions to the participants included the following text: “The trials will start with a 3D object. The object could be perceived as concave or convex”. Below each possibility an example was presented (see Fig. 1 for the presented stimuli). Specifically, below the word “convex” was an object with the bright edges pointing directly up (orientation 0), and below the word “concave” was an object with the bright edges pointing directly down (orientation 180).

5.1.4 Apparatus

The apparatus of Exp. 3 was identical to those used in of Exp. 1.

5.1.5 Data exclusion and pre-processing of the pupillometry data

Data analysis was the same as in both Exp. 1 & Exp. 2. This resulted in exclusion of one participant who did not have at least 70 valid trials (trials with no more than 30% of missing samples from the eye tracker) for each condition. For the 18 remaining participants (13 females, mean age = 24.89 years old, *SD* = 2.32) included in the analysis, pre-processing of pupil data eliminated 3.07% of trials on the average. Another two participants were excluded from the analysis of the convergence analysis.

5.2 Results

Mean relative changes of the pupil size in each condition are presented in Fig. 7A

(Meaningful differences are presented by the horizontal line). Our analysis indicates that meaningful differences (i.e., $BF_{10} \geq 3$) between the investigated conditions appeared at about 690 ms after the stimulus onset and stayed for about 500 until about 1190 ms post the stimulus onset (see Fig. 7B for the detailed Bayes factor figure). This time window is in line with the results of Exp. 1 and with previous studies that presented differences in pupil size as function of illusory luminance (Binda et al., 2013b; Naber & Nakayama, 2013).

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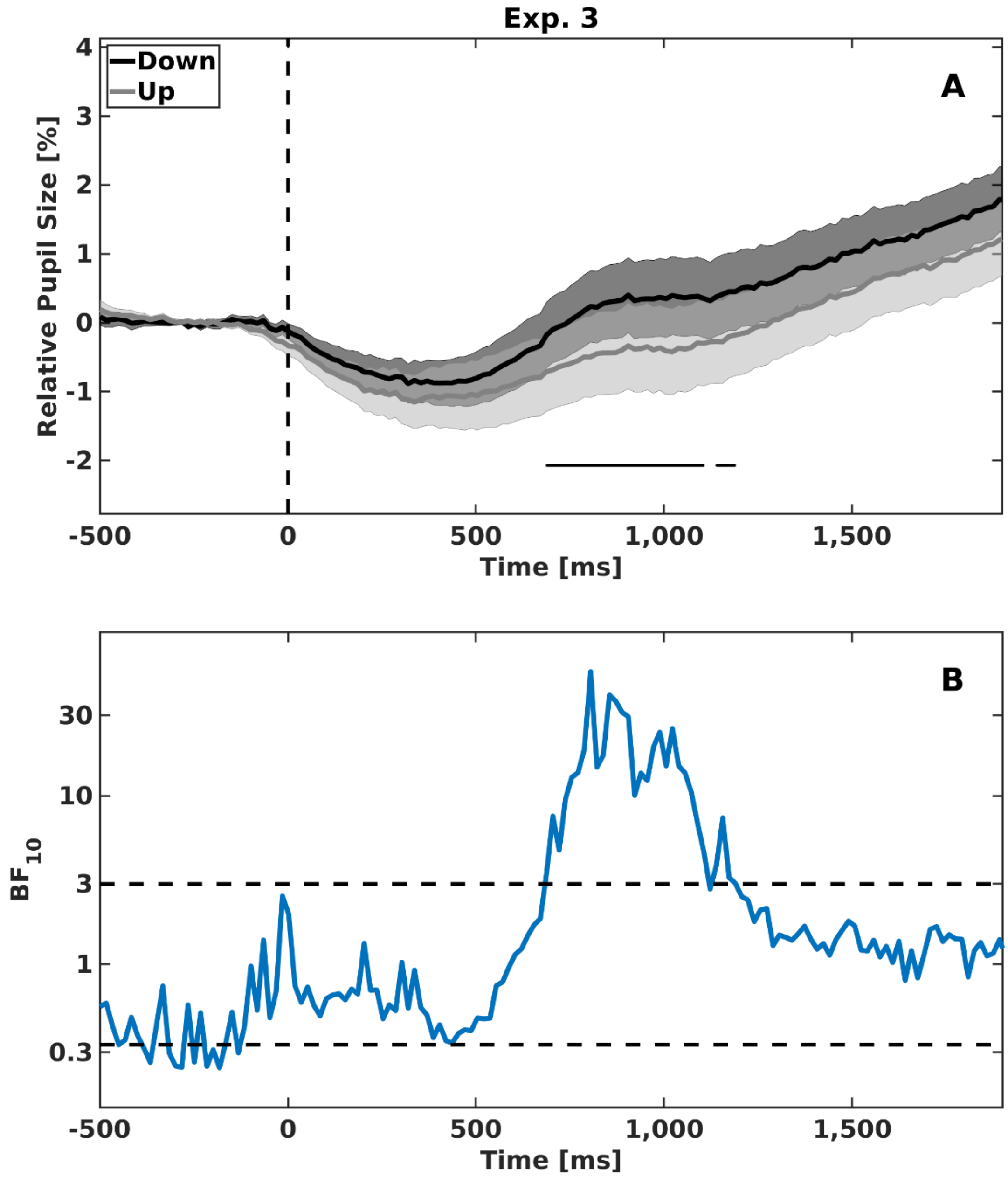

Fig. 7. **(A)** Mean relative pupil size (compared to pupil size at stimulus onset) for the investigated conditions in the Exp. 3. Participants had to ignore the stimuli that appeared for 2,000 ms and to detect a shape that appeared afterward. The vertical line at 0 represents stimulus onset. The dark curve represents the “down” condition and the bright curve represents the “up” condition. The shaded areas represent 1 standard error from the mean. The horizontal line represents meaningful differences (i.e., $BF_{10} \geq 3$) between the conditions. **(B)** Bayes factors (BFs) as function of time for comparison between stimuli with bright parts on top compared to stimuli with bright parts on the bottom of Exp.3. Each curve represents BF_{10} (namely, evidence for the alternative hypothesis that the two conditions are not the same). The horizontal black

lines on 3 and on 0.3 represent the threshold for the decision making (BF_{10}values above 3 provide evidence for the alternative hypothesis and BF_{10} values below 1/3 provide evidence for the null hypothesis). Please note, the scale for the Y-axis is logarithmic.

Analysis of the gaze position as a function of time over the trial, confirmed that participants had maintained fixation; peak average of pupil position did not exceed 0.57 degree (range 0.37 to 0.77). Here again, gaze position tended to be slightly up but these deviations were not large enough to be considered meaningful saccades in pupillometry studies (Tkacz-Domb & Yeshurun, 2018). The temporal analysis of the convergence did not show any meaningful differences for the entire trial (i.e., $BF_{10} < 1$), and tended to support the similarity between the conditions most of the trial (i.e., $BF_{10} \leq 1/3$). Specifically, the Bayes factor was between 1/3 and 1 in the first 750 ms after stimulus onset, and then below 1/3 for the rest of the trial with a short time interval when it was between 1/3 and 1 between 1,590-1740 ms post stimulus onset.

The results of Exp. 3 showed that the pupil responds differently to stimuli that are associated with concavity compared to stimuli that are associated with convexity, even if participants were not required to make any shape judgment. This experiment was the same as Exp. 2 with one exception; participants made aware of the perceived depth in the stimuli. We found that it was enough to draw the participants' attention to the perceived depth in the stimuli to elicit different pupil responses.

6. Discussion

In the current study we measured the effect of shape from shading on pupil response. Based on the "darker is deeper" heuristic, we reasoned that if a stimulus is perceived as concave it will be perceived darker than a stimulus that is perceived as convex. As a result, the pupils, which respond to light intensity, will be larger with exposure to stimuli that are perceived as concave than to stimuli that are perceived as convex. In a series of three experiment we tested this suggestion.

In the first experiment we presented to participants 2D stimuli (rotated snowflakes) and asked them to judge if the presented stimuli looked convex or concave. Analysis of pupil size showed more pupil dilation for stimuli that were perceived as concave than stimuli that were perceived as convex. In the second experiment we presented to participants the same rotated snowflakes, but participants were not asked to respond to the snowflakes at all, but rather to a shape which appeared afterward. Analysis of pupil size in this experiment showed no differences in pupil dilation between trials that were associated with convexity (i.e., trials in which the image is bright on top and dark at the bottom) and trials that were associated with concavity (i.e., trials in which the image is bright on bottom and dark at the top). In the third experiment participants' task was the same as in the second experiment but participants were made aware of the perceived depth (i.e., convexity or concavity) in the stimuli. In this experiment we replicated the results of the first experiment, namely, more pupil dilation for stimuli that were associated with concavity than stimuli that were associated with convexity.

The orientation of the shading information, combined with the assumption about the direction of the illumination, produce a percept of depth. Observers assume, by default, that the light source is located above the scene, which creates a percept of convexity when the image is bright on top and dark at the bottom, and a percept of concavity when the image is dark on top and bright at the bottom. The amount of light in our stimuli was identical in every trial, as the difference in the illusion of depth was created simply by changing the orientation of the stimulus. Hence, any changes in pupil size could not be arbitrated to the light information in the stimulus. Moreover, the passive experiment (Exp. 2) showed that no changes in pupil size is observed if participants are not aware of the illusion of depth, confirming that the change in pupil response was mediated by the perception of the illusion, and not by the properties of the stimuli.

Why would the illusion of depth result in changes in pupil size? One possible explanation is related to the heuristic “darker is deeper” (Langer & Zucker, 1994) and its effect on the pupil light effect (Ellis, 1981). When looking at an image containing dark and bright areas, observers often report that the bright areas appear convex and the dark parts, concave. The results of the current study suggest that human observers may be using also the opposite assumption, namely, “deeper is darker”, so that concave surfaces may look darker than convex surfaces. Although the amount of light in the image in our experiments was identical in all stimuli, once the stimulus was perceived as deeper, it seems that the observer assumed it is also darker and therefore, the pupil responded accordingly, and dilated more as a response to the deeper stimulus.

In a control experiment (Exp. 1B) we tested explicitly whether participants perceive convex stimuli as brighter than concave ones. We presented participants with two stimuli in reversed orientations and asked them to respond which of the stimuli is brighter (or darker). The results showed that concave stimuli were perceived as darker significantly more often than convex stimuli. These results are in line with the present physiological evidence and with our suggestion that concave objects are perceived as darker compared to convex ones.

As our stimuli were identical in every trial, different only in the orientation of the stimulus, any changes in the pupil size cannot be attributed to the amount of light in the entire image. In addition, the gaze position analysis confirmed that participants had maintained fixation the entire trial, with negligible deviation from fixation that are not considered as saccades in pupillometry studies (Tkacz-Domb & Yeshurun, 2018). The analysis showed that the direction of the gaze was slightly up, which could explain our results. Specifically, if participants looked at the upper part of the stimuli, then when the white edges of the snowflake were up, which resulted in a percept of convexity, observers actually looked at the white lines, so that the local amount of light was high. On the other hand, when the dark edges were up, which resulted in a percept of concavity, participants looked at the darker lines, so the local amount of light was low. However, not only that the deviations from fixation were very small compared to the size of the stimulus, and cannot be considered as saccades, also the differences between the experiments suggest that this cannot be the case. In all experiments the gaze was slightly up than the fixation, however, pupillary effect was only found in Exps 1 and 3. Moreover, the gaze deviations from fixation were larger in Exp. 2 than in Exp. 1; if gaze position was the cause for the pupil size effect, one would expect a larger pupil effect in Exp. 2. However, the absence of pupillary effect in Exp. 2 is inconsistent with this explanation. Overall the analysis indicates that these small deviations of gaze position during the trial cannot be the reason for our results.

We should also consider the effect of attention on pupillary response. As it has been shown that attending to brighter or darker parts the stimulus can cause changes in pupil size (Binda & Murray, 2015a; Binda, Pereverzeva, & Murray, 2013a; Mathôt et al., 2013), it is not impossible that attention may have had an effect in our study. Specifically, similar to the potential effect of gaze position, it could be argued that participants may have paid attention to some aspects of the stimulus more than to others. For instance, if participants allocate their attention to the upper part of the stimuli more than to the lower part, then when the white edges were up, and the stimulus was perceived as convex, observers actually attended to the white lines. In contrast, when the dark edges were up and the stimulus was perceived as concave, participants attended to the darker lines. While we cannot entirely reject this explanation, there is no reason to believe that attention will be allocated to the upper more than to the lower visual filed. In fact, there is evidence for a lower visual filed advantage in a variety of visual tasks

(Danckert & Goodale, 2001; Levine & McAnany, 2005). If pupil size was mediated by the advantage of one visual field, it is more likely to be the lower visual field, which would result in the opposite effect, namely, constriction of the pupil when the bright edges are down, i.e., when the stimulus is perceived as concave.

Another variable that may affect pupil response is the level of effort in the task. It has been documented that effort results in pupil dilation (van Steenbergen & Band, 2013). If for any reason participants found one decision harder than the other, this may have resulted in a change in pupil size. In particular, if participants found it harder to make a decision that the stimulus is concave than to make a decision that it is convex, this could have resulted in a larger dilation of the pupil to concave stimuli. In fact, when looking at response time to the two conditions in Exp. 1, RTs to concave were slightly (but significantly) slower than to convex, suggesting that it took longer to participant to decide that the stimulus is concave than it took them to decide it was convex. While this explanation is possible, the results of Exp. 3 suggest that it is unlikely to be valid, as in Exp. 3 participants were not asked to make any decision about the stimulus, but rather the awareness of the illusion of depth resulted in a greater dilation for concave than for convex stimuli.

In addition to the response of the pupil to the brightness of the stimuli, the pupil responds also to the distance of stimuli from the observer. The pupil near response (PNR) is a change in the pupil size in response to how close the object is, so that the pupil constricts in response to objects that are close by, and dilates in response to objects that are farther away. This effect is usually accounted by accommodation and convergence and divergence of the eyes (Marg & Morgan, 1949, 1950). In the current study, as there is an illusion of depth, it is also possible that the pupil responded to the apparent depth in the stimulus. When the stimulus was perceived as concave, it looked as if it was far away, and the pupil responded accordingly, namely, with dilation. In contrast, when the stimulus appeared convex, namely closed by, the pupil responded with constriction. Not much evidence exists on the cognitive effects on PNR. An early study by Enright (1987) showed PNR when participants looked at an ambiguous drawing of a box, in which the same corner can be perceived sometimes as close by and sometimes as far away (the Necker cube; Necker, 1832). Recently, Sulutvedt et al., (2018) asked participants to imagine small and large items (for example, a clothespin or a car) in different distances (30 cm and 4 meters for a small item, and 4 meters and 20 meters for a large item). Pupil size and convergence were found to be smaller for near and small items than large and far items, as expected according to the PNR (see also Mathôt , 2018 for a review article mentioning cognitive effects on PNR). We believe that this is an unlikely explanation in our experiments as the perceived relief in our stimulus is probably not large enough to cause appreciable changes in convergence and accommodation. Indeed, temporal analysis of the convergence found no differences between the investigated conditions. Further studies that will measure accommodation will be able to distinguish between the two explanations (i.e., association between depth and brightness – darker is deeper, and the perceived distance of the object).

The result of Exp. 2, that the pupil does not change in size in response to different shapes when shape judgment is not required or attention is not allocated to the task, is a bit surprising. Shape from shading is thought to be a pre-attentive process, which happens automatically, and in parallel to other processes. This notion is mainly based on findings from pop-out experiments (Braun, 1993; Enns & Rensink, 1990, 1991), the observation that the assumed light source direction is computed in a retinal, rather than an environmental reference frame (Kleffner & Ramachandran, 1992; Yonas, Kuskowski, & Sternfels, 1979), and the involvement of early visual cortex in shape from shading (Mamassian, Jentzsch, Bacon, & Schweinberger, 2003). For instance, Sun and Perona (1996) sowed that shaded cubes, but not line cubes or Y shaped line, are processed fast and are not affected by the number of items in the array, suggesting they do not require attention to be detected (see also Enns & Rensink, 1990, 1991; Kleffner & Ramachandran, 1992).

Our results suggest that it may not be the case. It seems that the ease of target segregation, as seen in visual search tasks, and perceived shape, as seen in shape judgement tasks, may be relying on different processes. We suggest that some information on shape from shading may be processed fast, in a pre-attentive manner, to allow a fast segregation from background. However, in order to progress to shape identification, where the exact shape is perceived, attention must be involved (see Wolfe & Horowitz, 2004 for more information about which aspects of the stimulus may be pre-attentive). This could explain the discrepancy between search tasks that found that shape from shading is a pre-attentive process, and the results from Exp. 2, which showed that without attention, no changes in pupil size to the different shapes can be observed. The latter suggests that the process of shape identification involves top-down processes.

In conclusion, it seems that pupils that respond to light intensity (Ellis, 1981) and also to illusory light stimuli (Binda & Murray, 2015b; Binda et al., 2013b), respond also to subjective illusion of depth. Specifically, stimuli that are perceived as concave cause to more dilation compared to stimuli that are perceived as convex. Our results suggest that pupil dilation, which is an indicator of light intensity, can also be used as an indicator of shape from shading and propose that not only darker is deeper (Langer & Zucker, 1994), but also deeper is darker.

Open Practices Statement

All experimental data and materials can be found on the OSF (Open Science Framework):

https://osf.io/gdcy9/?view_only=fabe298e8984498280b2a10349e396ad.

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