Title: Transient Pupil Constriction Reflects and Affects Facial Attractiveness

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Abstract: Contradictory to the long-held belief of a close linkage between pupil dilation and attractiveness, we found an early and transient pupil constriction response when participants viewed an attractive face (and the effect of luminance/contrast is controlled). While participants were making an attractiveness judgment on faces, their pupil constricted more for the more attractive (as-to-be-rated) faces. Further experiments showed that the effect of pupil constriction to attractiveness judgment extended to intrinsically aesthetic visual objects such as natural scene images (as well as faces) but not to line-drawing geometric figures. When participants were asked to judge the roundness of faces, pupil constriction still correlated with their attractiveness but not the roundness rating score, indicating the automaticity of the pupil constriction to attractiveness. When pupillary responses were manipulated implicitly by relative background luminance changes (from the pre-stimulus screen), the facial attractiveness ratings were in accordance with the amount of pupil constriction, which cannot be explained solely by perceptual brightness induced by simultaneous or sequential luminance contrast. The overall results suggest that pupil constriction not only reflects but, as a part of self-monitoring and attribution mechanisms, also affects facial attractiveness implicitly.

Significance Statement: Pupil constriction not only reflects but also affects aesthetic appraisal evaluation, at least under certain conditions. This uncovers a heretofore unknown tight link between pupil constriction and attractiveness. These findings have profound implications with respect to the well-known theories in the James-Lange tradition concerning mind-body interaction. They also provide new clues to the neuro-physiological mechanisms underlying attractiveness decisions and to implementing various real-world applications such as BMIs (brain-machine interfaces) and marketing strategies.

Introduction

Pupillary response not only reflects the peripheral nervous system's activity in response to ambient luminance changes (i.e., the pupillary light reflex), but also the central nervous system's activity underlying cognitive functions such as attention (1-3), memory (4-6), decision making (7, 8), emotion (9, 10), and interpersonal impressions and attitudes (11-14). In the Middle Ages, women ingested belladonna to dilate their pupils, which was supposed to make them appear seductive. Nowadays, people can use cosmetic contact lenses to make the pupil appear larger (by changing the color and/or appearance of the iris). These cosmetic techniques are based on the long-held belief of a close link between pupil dilation and positive attitudes such as (sexual) interests and/or emotional arousal and thus of a mutual path between the actor and observer. Evidence in the early 60s showed that, actors' faces with enlarged pupils were perceived as more attractive to observers (11, 12, 15, 16). On the observer side, evidence indicated that people's pupil dilated when they were viewing emotionally toned stimuli, such as pictures of a baby for female participants and pictures of a partially nude man or woman for female and male participants, respectively (11, 13, cf. 14). This may be due to arousal and/or sexual attraction (17-20), which activates the sympathetic nervous system to induce pupil dilation. Together with activation of the mirror neuron system that may be involved in a positive circulation between the observer and the observed face (i.e., the actor), an intuitive prediction has been that the pupils of people who are attracted to faces they see dilate as an automatic response. Then, in turn, they would appear attractive to observers. Such interpersonal, positive feedback has been assumed for a long time.

However, there is room for skepticism because the dynamic of the pupillary response to attractiveness could be more complicated than has been thought. For example, the pupillary dilation (in observers) found in the early era may have been confounded with stimulus luminance or contrast to which the pupil responds most sensitively and/or insufficient baseline conditions (14). Recent studies, which have had finer control over stimulus luminance and contrast with various tested conditions, have found that the pupil dilates to not only positive but also to negaive emotional stimuli (9, 21). This suggests that it dilates to arousal stimuli in general, not particularly to a positive emotion and/or evluatiaon such as attractiveness. Moreover, most evidence from previous studies was based on pupil size averaged over several seconds, while the participants were asked to just passively view the stimuli (e.g., about 10 s in 11, 16, 19, 22, 23-26; 2–6 s in 9). The long-lasting, sustained pupil dilation response reflecting arousal may be different from the fast, transient component which presumably reflects other cognitive states and thus affect the feeling of attractiveness. Indeed, other studies showed that pupils in general quickly constrict in responds to the mere onset of visual presentation (even when the mean luminance is equated, e.g., 27) and that this early and reflexive pupillary constriction response is modulated by various cognitive factors such as memory (5), attention (28-31), and perceptual brightness when the physical luminance is kept the same (32, 33). For instance, in Naber et al. (5), participants were asked to memorize various natural scene images presented one by one (memorization phase) to recall later in the retrieval phase. The results showed that during the memorization phase, pupils constricted more strongly to certain images, which, upon retrieval were found to be better memorized. It was suggested that the underlying mechanism was related to cholinergic novelty signal through the parasympathetic nervous system. Together with the evidence that people tend to better memorize attractive faces than they do moderately attractive ones (34), it was surmised that the pupil constricts more strongly for more attractive faces, at least during the encoding and/or memorization period.

Aside from the literature on pupil responses to attractiveness, the issues can be discussed in a different context, namely affective decision making, which is a dynamic process to which various factors contribute, such as physiological arousal (e.g., the somatic marker hypothesis, 35), gaze (36), and perceptual fluency via mere exposure (37). Shimojo and colleagues demonstrated that active gaze engagement not only reflects but also affects preference decision making (the “gaze cascade” effect), suggesting a positive loop between seeing and liking (36). They simply revealed a gaze bias towards a to-be-chosen face to show that gaze *reflects* preference, but they were also successful in biasing preference decisions by manipulating gaze, thus demonstrating that gaze also *affects* preference. Just as gaze allows foveal scrutiny, pupil constriction improves visual acuity (38). Thus, pupil constriction may also be actively involved in the formation of preference via an enhancement of seeing and thus liking. We hypothesize that pupil constriction not only reflects but also affects attractiveness judgments.

Along that line, we further speculate that the more implicit the information (causal factor) is, the stronger the decision-making processing may be affected. This seemingly counter-intuitive prediction is proved true at least occasionally in the literature regarding to the mere exposure effect (39). Under certain conditions, repetitively presented stimuli get more preferable (i.e., a stronger mere exposure effect is produced) when they are presented subliminally rather than suprathreshold. This pattern of results has been interpreted to mean that when information is implicit, i.e., subliminal, participants often do not causally attribute their decision to the repetitive presented stimuli per se and are thus more likely to attribute it to their own internal preference. The misattribution in affective decision-making was observed in the "gaze cascade effect" mentioned above. When people's preferences were affected by their gaze manipulated (Shimojo et al. 2003, Exp. 2), most of them were not aware of the gaze bias to begin with, and those few who were aware of it did not attribute their preference to it. There was yet another study in which the participants were fully aware of all the stimuli (again faces); however, they confused their intended choice with the actual outcome. That is, they thought they preferred a particular face but in fact chose a different one beforehand, which is known as choice blindness, 40). In such cases, the retrospectively derived reasons for why a choice is made are inevitably the result of misattribution. The influence of pupil constriction on attractiveness judgment, if it occurs, could also be misattributed and implicit. This is because the pupillary response itself is implicit (more so than gaze shifts) and thus cannot be voluntarily controlled or attentively introspected.

Here, we demonstrate that pupil constriction not only reflects but also affects visual attractiveness for faces. In our experiments, we first examined whether and how the pupil reflects facial attractiveness and found that, instead of dilating, it constricts when attractive faces are viewed (Experiment 1). This finding was replicated when the stimulus image luminance was equated (Experiment 2). Together with other tested conditions, we found that the attractiveness-induced pupil constriction is limited to intrinsically aesthetic visual objects such as faces or natural scene images, but not line-drawing geometric figures. Moreover, when participants were asked to judge face roundness, pupil constriction still correlated with the attractiveness of the faces but not with the roundness rating score, indicating the automaticity of the pupil constriction to attractiveness. Thus, pupil constriction indeed r*eflects* attractiveness judgment implicitly. To examine the causality of pupil constriction to attractiveness, we further manipulated the pupillary response implicitly (i.e., without participants knowing). We found that the facial attractiveness judgment is in accordance with the amount of pupil constriction (Experiment 3), which cannot be explained solely by the perceptual brightness induced by sequential luminance contrast (Experiment 4a and 4b). The overall results illustrate a tight mutual link between pupil constriction and attractiveness judgment.

Results

In Experiment 1, participants looked at a face presented at the center of a screen and rated how attractive the face was on a scale from 1 (least attractive) to 9 (most attractive) while an infrared camera recorded their pupillary responses. Data were sorted based on the attractiveness judgment individually to examine how the pupil reacted to attractive faces (the face-attractiveness condition). Two other conditions were added to examine whether the effect of pupil constriction to attractive faces, if it occurs, was specific to faces or attractiveness judgment. In the geometric figure-attractiveness condition, participants evaluated the attractiveness of a geometric figure, but not a face. In the face-roundness condition, they viewed the same set of the faces to rate how round the faces were, ignoring their attractiveness. The three conditions were conducted in separate blocks in a counterbalanced order across participants. Each trial started with a 3-s gray fixation display, followed by the target image (faces or geometric figures). Participants were free to inspect the stimuli as long as they wanted before making a decision. Results showed that they made a decision after around 2 s on average (see Table 1 and Supplementary Fig. S1). The pupil in general constricted in response to the presentation of the faces. Most importantly, during the inspection, the degree of pupil constriction in each participant was linearly correlated with the facial attractiveness rated immediately after the inspection in every single trial [see Fig. 1A for overall pupillary response change and Figure S1A (A) for histogram plot for statistical analysis: $F(1,12) = 3.06$, $p < .02$ for linear trend analysis]. The more attractive the face was, the more the pupils constricted. This also mostly held true when we examined the trial-by-trial results for individual participants [see Figure S1A (B)]. In contrast, the amount of pupil constriction did not correlate with attractiveness judgments for geometric figures [$F(1,12) = 0.24$, $p = .64$; see Fig. 1B and S1B] or roundness judgments for faces [$F(1,12) = 0.65$, $p = .44$; see Fig. 1C and S1C]. Intriguingly, when the faces were sorted by their attractiveness (although the explicit task demand was to judge their roundness), the degree of pupil constriction showed a linear correlation with the implicit, or task-irrelevant, attractiveness of the faces [$F(1,12) = 5.39$, $p < .05$; see Fig. 1D and S1D]—the same pattern of results as when the task demand was to judge the attractiveness (i.e., the face-attractiveness condition). Note again that the order of the three conditions (face-attractiveness, geometric figure-attractiveness, and face-roundness) was counterbalanced across participants. A further analysis involving condition order as a factor (see Material and Methods for details) showed that the pattern of the pupillary responses to facial attractiveness (either explicit or implicit) remained the same regardless of the condition order (*p*s > .05); it did not matter whether the faces were judged on attractiveness earlier than roundness or vice versa. In summary, the overall results of Experiment 1 suggest that the pupil constriction response to facial attractiveness is task-specific (in contrast to roundness judgment), automatic, and free of memory. A potential problem in Experiment 1, however, is that we controlled luminance across stimuli rather crudely, and it may be criticized that the result could be explained by the low-level factor since the pupil is very sensitive to luminance (contrast).

Thus, in Experiment 2, we aimed to replicate the finding of pupil constriction to attractive faces with additional luminance controls. First, the luminance among the faces was equated, and the mean luminance of the faces, as well as that of the fixation display presented before the faces was the same as the background (so that there was no mean luminance change over time). Second, instead of using line-drawing geometric figures, we used natural scenes. The photos were image processed to equate their mean luminance by following the same procedure as for the face images. The rest of the experimental procedures were the same as in Experiment 1. Results showed that the amount of pupil constriction was linearly correlated with the attractiveness rating not only for faces [$F(1,14) = 20.36$, $p < .001$, Fig. 2A and S2A] but for natural scenes as well [$F(1,14) = 6.48$, $p < .03$, Fig. 2B and S2B]. When participants performed the roundness task, pupil constriction was still linearly correlated with the attractiveness of the faces [$F(1,14) = 10.33$, $p < .01$, Figure 2D and S2D], but not with the roundness judgment [$F(1,14) = 3.43$, $p = .09$, Figure 2C and S2C]. In summary, Experiment 2 replicated the main finding of pupil constriction to attractiveness faces and extended it to natural scenes. We can therefore conclude that pupil constriction certainly reflects attractiveness either explicitly or implicitly.

Before we move on to the second focus of this study, namely whether pupil constriction also affects attractiveness judgment, we need to mention several additional, yet critical, issues. First, the biggest question would be why there is such a big inconsistency between our finding (pupil constriction to attractiveness) and the pupil dilation to attractiveness demonstrated in the literature. Second, it is still unclear whether the attractiveness judgment for geometric figures could indeed not induce corresponding pupil constriction. To address these issues, we conducted three additional experiments (Supplementary Experiments 1, 2 and 3; see details in Supplementary Information) to examine stimulus presentation time, task demand, stimulus category, and sequential contrast induced by luminance change. The overall results indicated that none of the above factors alone can explain the discrepancy between our finding and the literature, but, in general, the effect of pupil constriction to attractive faces (still not to geometric figures) was more effectively observed during the early time course (about 2 s after stimulus presentation) and when a task demand was required (compared with passive viewing). Pupil dilation to attractiveness was occasionally observed only for faces rated most attractive (an 8 or 9 rating score), either during a later time period (3 to 5 s after stimulus onset) or passive viewing. This is in a way consistent with the literature, where most of the evidence for pupil dilation to attractiveness came from pupillary responses accumulated for 10 s while participants just passively viewed the stimulus (e.g., 11, 16, 19, 23, 24-26). In accordance with the literature, we surmise that the role of pupil constriction in attractiveness judgment is related to how the stimulus is scrutinized under a particular cognitive set. This may be analogous to how gaze shifts intrinsically contribute to preference decisions. Alternatively, the pupil response to attractiveness (either constriction or dilation) may reflect an interactive balance between the parasympathetic and sympathetic nervous systems across time (see more details in Discussion). In any case, we consistently observed that pupil constriction reflects facial attractiveness in three experiments (Experiments 1 and 2 and Supplementary Experiment 1).

Now, the second main objective of the current study was to examine further whether pupil constriction *affects* facial attractiveness judgment (Experiment 3). To this end, while keeping the target image the same, we manipulated the luminance of the fixation display (prior to the target display) to so that it would change from black or gray to alter the amount of pupil constriction when the page flipped. Due to the nature of the pupillary light reflex (41), the pupil should constrict more strongly when the target image follows a black than a gray fixation display. We also changed the luminance of the target background to black or gray, to serve as fillers to make the critical manipulation, i.e., the fixation display change, less noticeable. With this manipulation, we also aimed to examine the relative contribution of pupil constriction and simultaneous luminance contrast (induced by the target background) to attractiveness judgment. Although the luminance of the target background may also affect the pupillary response, its influence is expected to be smaller than that of the fixation display. If the attractiveness judgment is affected more by the simultaneous contrast than the pupil constriction, the target background luminance should have a stronger influence on attractiveness judgment than the pre-stimulus fixation display. Participants rated the attractiveness of the faces presented at the center of the target display as in the previous experiment (Fig. 3A).

As expected, displaying the face after the black fixation display caused stronger pupil constriction than displaying it after the gray fixation display did [$F(1,10) = 278.43$, $p < .001$]. The target background also affected the pupillary response in that the pupil constricted less for the black target background than it did for gray one [$F(1,10) = 153.51$, $p < .001$], whereas the influence of the pupil constriction was affected more strongly by the luminance of the fixation display than that of the target background [interaction: $F(1,10) = 55.26$, $p < .001$] (see Fig, 3B). In a casual survey after the experiment, most participants reported that they were aware of the luminance change in the target background but mentioned little about the pre-stimulus display.

Critically, the attractiveness rating results are consistent with our hypothesis that when the pupil constricts more, the face is evaluated as more attractive (see Fig. 3B and S3 for individual data). Specifically, parallel to the amounts of pupil constriction, faces were rated more attractive following the black fixation display [mean rating score = 4.63 vs. 4.40, $F(1,10) = 7.22$, $p < .03$]. Note that the face images were exactly the same in their identities as well as in their luminance in both the black and grey fixation display conditions (see Materials and Methods for details). The results can only be attributed to the pre-stimulus background luminance changes. In contrast, the target background by itself did not affect the rating [mean rating scores of 4.53 and 4.50 for the black and gray target background, respectively; $F(1,10) = 0.18$, $p = .68$]. The non-significant difference in the rating between the two types of target background indicated that the simultaneous contrast alone could not affect facial attractiveness judgments. Although the target background also induced significant changes in pupil size, the effect may interact with target background luminance itself to obscure its influence on attractiveness judgment. This is consistent with the casual survey in that some participants claimed that the target background might have affected their attractiveness judgment, but how it might have done so was not consistent among their reports. Alternatively, the non-observed effect of target background to attractiveness judgment may be due to the weaker modulation of the pupil constriction compared to the effect induced by the pre-stimulus display. Either way, the results are consistent overall with the interpretation that pupil constriction due to the sequential luminance contrast shift (from the pre-stimulus background to the stimulus) leads to higher ratings of attractiveness, and that in most cases, people are not aware of the causal relationship there.

One may still argue that either adaptation to the fixation display's luminance or sequential contrast may lead to brightness differences in faces, which may affect the attractiveness judgment. In Experiment 4, we examined whether sequential luminance contrast alone, when not inducing a strong difference in pupil response, causes differences in attractiveness judgments. We divided visual fields into two halves (left/right) with luminance disparities in the fixation display and then presented the target image to the left or right visual field (see Fig. 4A). In this case, there was sequential luminance contrast to the target image (different luminance conditions depending on the spatial relationship between the target image location and the fixation display's luminance disparities, i.e., black on the left or the right visual fields), but the overall average luminance of the fixation display remained the same to induce a similar pupillary light reflex (to the face display with a gray background). Participants were allowed to move their gaze to the face position (Experiment 4a) or were instructed to always fixate the center even when the face was presented peripherally (Experiment 4b). Results showed that, compared with Experiment 3, the pupil constricted similarly regardless of whether the target image followed the black or white pre-stimulus luminance, although the pupil constriction difference was (marginally) significant in opposite patterns depending on the eye movement condition [the pupil constricted more strongly when the face followed the white hemifield than it did when the face followed the black one in Experiment 4a, $t(15) = 2.90$, $p = .01$ and vice versa in Experiment 4b, $t(16) = 2.12$, $p = .05$]. Accordingly, facial attractiveness judgments showed similar scores between the two pre-stimulus luminance conditions ($ps > .1$), while the slight rating difference tendency was in accordance with the amount of pupil constriction rather than the sequential contrast condition (compare between Fig. 4B vs. 4C). The overall results suggest the rating differences found in Experiment 3 cannot be explained solely by the perceptual brightness difference caused by adaptation to the fixation display or the sequential luminance contrast. Instead, it is more in accordance with the causal contribution of pupil constriction to attractiveness judgment.

Discussion

We found that the pupil constricts rather than dilates in proportion to facial attractiveness. The constriction response turned out to be specific to preference judgment (as opposed to a non-emotional, objective judgment of face roundness) and also to aesthetic object categories such as faces or natural scenes (as opposed to relative emotionally neutral objects such as geometric figures). However, the preference judgment is likely automatic, and thus the pupil constriction to attractive stimuli could be implicit, regardless of explicit task demand (such as face roundness). The pupil constriction to attractive faces was replicated in two experiments by using various face stimuli: natural color images (Experiment 1) and equal luminance images (Experiment 2). Moreover, we could manipulate people's attractiveness evaluation by manipulating pupil constriction (Experiment 3), and the result could not be explained by the perceptual brightness induced by simultaneous or sequential luminance contrast (Experiment 4a and 4b). In summary, pupil constriction not only reflects but also affects facial attractiveness, at least under certain conditions. Our findings have profound implications with respect to the well-known theories in the James-Lange tradition concerning mind-body interaction. They also provide new clues to the neuro-physiological mechanisms underlying attractiveness decisions and to implementing various real-world applications such as BMIs (brain-machine interfaces) and marketing strategies.

Pupil constriction vs. dilation to attractiveness

Our counterintuitive finding of pupil constriction, rather than dilation, to facial attractiveness reveals a heretofore unknown relationship between the pupillary response and affective decision-making. The discrepancy between our results and those in the literature can be understood by considering three potential factors. First, the pupil is highly sensitive to subtle luminance (contrast) differences, and early studies (especially in the 60s and 70s) might be just not technically capable of controlling it. Second, the temporal scale of pupil size measurement may have been different in those classical studies relative to ours. Indeed, we found two phases of pupil response over time: early constriction (approximately 0 to 2 s from the stimulus onset), and late dilation (after 3 s) to attractive faces (Supplementary Experiment 2). In contrast to our approach that analyzed the dynamic changes in the pupillary response on a finer scale, previous studies just took the average pupil size over time, typically 10 s after the stimulus presentation (e.g., 11, 16, 19, 23, 24-26). They may have glossed over the two dynamic phases of the pupil response (constriction, then dilation) and thus failed to reveal the early, transient component of the pupil constriction response to attractiveness judgment. Third, the cognitive state (mental set) has an influence on pupil response (e.g., 5, 28, 29-31). The non-controlled cognitive state (i.e., passive viewing) in those classical studies (e.g., 11, 16, 19, 23, 24-26) made it difficult to uncover the effects of cognitive processes for decision and response and/or attractiveness evaluation per se. The involvement of cognitive processes may be deeper than just serving to reveal a different aspect of the relationship between the pupil response and attractiveness.

Putting the above factors aside, reviews of recent studies that demonstrate the correlation between pupil dilation and attractiveness judgment have revealed that the correlation really depends on the observer's and the observed face's gender (19, 42) and emotion (43, 44), suggesting a more complicated mechanism than a straightforward linkage between pupil dilation and attractiveness. One must conclude the traditional belief that pupil dilation reflects attractedness simply does not account for what is really going on between the brain and the eyes. It is important for future studies to closely examine the dynamic changes in pupillary response over time to isolate the effects of cognitive processes and emotional arousal.

Possible neural mechanism of pupil response to attractiveness

Pupil size is controlled by two sets of antagonistic muscles, the iris sphincter muscle and iris dilator muscle, innervated by parasympathetic and sympathetic nerves, respectively. It is thus naturally presumed that one possible underlying neural mechanism of the correlation between facial attractiveness and pupil constriction is based on the activation of the parasympathetic nervous system. Usui and Hirata (45) proposed a nonlinear dynamical model for the human pupillary muscle plant. The model states that the human pupil response to a flash visual stimulus can be explained by a combination of an early, transient parasympathetic activation (within 2 s) and a slow, sustained deactivation of the sympathetic activation, and this was confirmed by pharmaceutical manipulation (46). This is consistent with the hypothesis that early, transient pupil constriction to attractiveness is driven by the parasympathetic nervous system. The cause of pupil dilation to attractiveness, in contrast, is more complicated. It could be due to emotional arousal activating the sympathetic nervous system (9) during the longer time course and/or under a passive viewing situation, in particular when the pupil response is less affected by a flash visual stimulus. Alternatively, it could to due a deactivation and/or rebound of the parasympathetic nervous system following the early 2-s transient activation. In addition, other factors, such as stimulus properties and/or task demands, may activate the autonomic nervous system interactively. For instance, it is possible that the face and natural scene images used in the current study are more likely to induce a joyful, relaxing, and/or soothing experience that actives the parasympathetic nervous system, in contrast to inducing excitement, which may active the sympathetic nervous system dominantly. It is conceivable that attractiveness has multiple meanings, and the judgment may change depending on the context (e.g., when choosing a life partner vs. a queen in a beauty contest). The relationship between pupil response and attractiveness is not as simple as conventionally believed. To better understand the neural mechanism of attractiveness formation, further studies should investigate how different factors such as a stimulus's emotional valance and strength affect its attractiveness, together with other physiological measurements under different time courses. This approach may have potential impact on decoding complicated emotions instigated by the interaction between the sympathetic and parasympathetic nervous systems from eye metrics. In any case, our finding of pupil constriction to attractiveness, after eliminating various artifacts/side factors, is sufficient to raise the warning, in the least.

That said, this parasympathetic nervous system hypothesis alone does not directly account for the causality of pupil constriction to facial attractiveness. Instead, one may need to assume some sort of positive loop between liking and seeing to understand all the results that we report here. According to the positive loop account, the longer we see, the more we like, and vice versa, which is supported further by Shimojo et al.'s earlier findings of the gaze cascade (36). The pupil constricts to increase visual acuity/clarity to obtain a sharper facial image, to make it more attractive. Indeed, physiological evidence also supports this hypothesis: the ciliary nerves in the ciliary ganglion that innervate the iris sphincter muscle also innervate the ciliary muscle. The contraction of the ciliary muscle makes the eye lens more convex, causing accommodation to increase visual acuity. The co-occurrence of the pupil constriction and accommodation may facilitate prolonged inspection time. Moreover, prolonged gazing may further activate the parasympathetic nervous system, leading to calming and soothing. These may together participate in the decision-making formation of liking. While highly speculative, this scenario is not only feasible physiologically but nicely incorporates the parasympathetic account as a part of an entire dynamic loop as well, and is thus consistent with both the correlation results (Experiments 1 and 2) and the causal results (Experiment 3).

Mind-body interaction and implications

The finding that the pupil manipulation affects facial attractiveness judgments should be added to the long list of evidence for the James-Lange tradition of body-mind causality, regardless of whether the above parasympathetic account and positive-loop interpretations are valid. In addition to the classical association between physiological arousal and experienced emotion such as euphoria and anger (47), our findings reveal an until now unknown physiological cause, i.e., pupil constriction, to mind (facial attractiveness judgment). While the physiological status is altered for unknown reasons, a reason has to be given at the conscious level. This is not that surprising as shown in the suspension bridge effect (48), where people tend to misattribute unknown physiological arousal, i.e., the anxiety induced by walking on a suspension bridge, to romantic attraction. In our case, the physiological change, i.e., the pupil constriction, is (mis)attributed to evaluative attitudes towards facial attractiveness. The prolonged looking behavior due to the pupil constriction response is (mis)attributed to the preference for the seen image.

In the same vein, our finding can be also interpreted as a new example of “cognitive dissonance” and its solution, i.e., pupil constriction, at the implicit level. Cognitive dissonance refers to a mental state where a person holds more than two contradictory beliefs, ideas, or attitudes at the same time and experiences uncomfortable stress because of that. In relation to affective decision-making, it has been shown that choice per se creates preference for the chosen object (49) to reduce cognitive dissonance (i.e., people would not choose an object which they do not like). The same logic also applies to how inspection per se affects preference during which the brain and eyes, including gaze and pupil response, are involved. People prefer the object that they look at longer (36, 37). In contrast to gaze, the contribution of the pupil response to decision-making is implicit in two senses. First, it is an automatic response that is nearly impossible to voluntarily control. Second, the process of facial attractiveness formation via pupil constriction is hardly identifiable by attentive causal introspection.

After decades of neglect, pupillometry has been recently been revived by studies showing that pupil response reflects various cognitive processes, including attention (1-3), memory (4-6), decision making (7, 8), and linguistic (50) and auditory processing (51-53). However, re-examining its relationship with attractiveness judgment has attracted little interest, because of the belief in the correlation between pupil dilation and attractiveness. The current study uncovers a heretofore unknown tight link between pupil constriction and attractiveness. Additionally, it also indicates that pupil response likely participates in the mechanism underlying attractiveness judgment formation. Our finding goes beyond the scope of reading the mind from the eyes, to further imply that the neural mechanism that controls pupil responses also massively interacts with higher-level cognitive processes such as preference formation.

Materials and Methods

Participants. Forty-six adults (27 females, age range of 20–48, median age = 35 years) participated in the current study: 13 in Experiment 1, 15 in Experiment 2, 11 in Experiment 3 (the same group of participants as in Experiment 1 with two excluded due to the data lost by program error for the first two participants), 16 in Experiment 4a (the same group of participants as in Experiment 2, plus one who was excluded from Experiment 2 due to data recording loss for the last participant) and 17 in Experiment 4b (the same group of participants as in supplementary experiment 1). All had normal or corrected-to-normal vision and were naïve about the purpose of the experiments. The current study was approved by the NTT Communication Science Laboratories Ethical Committee and were performed in accordance with the Declaration of Helsinki. All participants gave written informed consent before the experiment and received payment for their participation.

Apparatus and stimuli. Visual stimuli were presented on an 18.1-inch monitor (Eizo FlexScan L685Ex) with a 60-Hz frame rate, controlled by a personal computer (Dell OptiPlex 755). In Experiment 1, in the target display, a target image was presented at the center of the screen against a gray background (21.04 cd/m^2). There were three conditions. In the face-attractiveness and face-roundness conditions, the target image was a face (6.42° width × 7.83° height), which was generated by FaceGen (Singular Inversions Inc.) software. Faces consisted of eight subcategories of the combination of two races (Asian or European), gender, and age range (old or young). There were 20 face images in each subcategory, thus 160 face images in total (mean luminance = 25.57 cd/m^2: maximum of 43.13 cd/m^2; minimum of 12.82 cd/m^2). In the geometric figure-attractiveness condition, a geometric figure, in black lines, with 10.62° width × 7.83° height was presented at the center of the screen to serve as the target. The figures were Fourier descriptors generated by a Matlab program (MathWorks Inc.) with properties specified and varied as a combination of symmetry (symmetric or asymmetric) and simplicity (simple or complex). A total of 160 geometric figures were generated (mean luminance = 16.46 cd/m^2: maximum of 23.22 cd/m^2; minimum of 4.27 cd/m^2). All the target displays were interlaid with a fixation display, which consisted of a black fixation cross (0.5° × 0.5°, 0.35 cd/m^2) against a gray background.

In Experiment 2, the stimuli and experimental structure were the same as in Experiment 1, except that instead of the geometric figures, we used natural scene images. The original images were color photos collected from public websites. They consisted of eight subcategories: animal, food, flower, mountain, sky, lake, ocean, and desert—the same database used in our previous study (54). There were 20 images in each subcategory, thus 160 images in total. The size of the images was within 8° width or 9.75° height, presented at the center of the screen. The original color natural scenes and face images (used in Experiment 1) were modified to be in the gray scale with the same mean luminance as the background (21.04 cd/m^2) by using the SHINE toolbox (55).

In Experiment 3, we used the faces that were judged as median attractive by individual participants in Experiment 1. For each participant and in each race subcategory (combined across gender and age), the rating scores were ranked order, and the 20 faces that corresponded to the median attractive rank order were used. No geometric figures were used in Experiment 3. Faces were presented at the center of the screen against a gray (21.04 cd/m^2) or a black (0.35 cd/m^2) background. The interlaid fixation display consisted of a black fixation cross (0.5° × 0.5°, 0.35 cd/m^2) against the gray background or a gray fixation cross (0.5° × 0.5°, 21.04 cd/m^2) against the black background.

In Experiment 4a, following the same procedure as in Experiment 3, for each participant we selected 40 median attractive faces (20 for each race) used in Experiment 2 based on individual judgments. In Experiment 4b, the faces were selected based on the individual judgments in Supplementary Experiment 1. In both Experiment 4a and 4b, no natural scene images were used. Faces were presented to the left or right visual field with 5.03° of eccentricity against the gray background (21.04 cd/m^2). In Experiment 4a, the interlaid fixation display consisted of a gray fixation cross (21.04 cd/m^2) against the background with luminance disparity across the visual field: black (0.35 cd/m^2) on the left and white (94.04 cd/m^2) on the right or vice versa. In Experiment 4b, the fixation cross was red and remained visible during the face target presentation.

Design. In all experiments, each trial consisted of the target display following the fixation display presented for 3 s. In Experiment 1 and 2, the three conditions were conducted as within-subject factors in different blocks with counterbalanced order among the participants. In the face-attractiveness and face-roundness conditions, the faces of different races (Asian and European) where presented in separated subblocks. Each subblock consisted of 80 face images presented in randomly assigned order. There was no break between the subblocks. In the geometric figure-attractiveness condition (in Experiment 1), all 160 geometric figures were presented in randomly assigned order. In the natural scene-attractiveness condition (in Experiment 2), the images of different subcategories were presented in separate subblocks without a break between them. The order of the images within subblocks and the order of the subcategories were randomized.

In Experiment 3, 4a, and 4b, the two types of fixation display and the two types of target display were conducted as within-subject factors. In each race subcategory, the 20 median attractive faces were presented for four times, in each of the 2 (fixation display) × 2 (target display) conditions. There were thus 80 trials in each race subcategory and 160 trials in total. As in Experiment 1 and 2, the faces of different races were presented in different subblocks in randomly assigned order. In each subblock, the 80 trials with different manipulation conditions were presented in randomly assigned order.

Procedure. Participants sat in front of the monitor at an 80-cm distance with their head supported on a chin-rest. In each session/experimental block, participants went through the five-point Eyelink calibration program to calibrate and validate their eye data. After the calibration procedure, the experiment started without practice trials. Participants were instructed to fixate the central fixation cross during the fixation display. Once the target display was shown, they were asked to make a judgment (attractiveness or roundness) on the target image (faces, geometric figures, or natural scenes). They were free to take their own pace in making the decision. In all experiments except Experiment 4b, they were allowed to move their gaze to the stimulus position. In Experiment 4b, they were instructed to fixate the central fixation cross even when the face was presented peripherally. In the attractiveness judgment condition, participants rated how attractive the face, geometric figure, or natural scene was, i.e., how much they liked the particular image. In the roundness judgment condition, participants rated how round the face was. They indicated their answer by pressing the number pad on a keyboard from 1 (least attractive/round) to 9 (most attractive/round). They were encouraged to use all nine numbers if possible but not necessarily equate the distribution so that they would make their judgment naturally. After they gave their answer, the next trial started with the 3-s fixation display. Participants made judgments for 160 trials straight without break. Each session took about 20 minutes, and there was more than a 20-minute break between the sessions.

Pupillary response analysis. Pupillary responses were recorded binocularly with an infrared eye-tracker camera (Eyelink 1000 Desktop Mount, SR Research Ltd.). The camera was positioned below the monitor. The sampling rate of the recording was 1000 Hz. Since pupillary responses are consensual, only data from the right eye were used. Data during blinks was interpolated using shape-preserving piecewise cubic interpolation. During the time window of -1–2-s reference to stimulus onset, blinks accounted for 15.1% of data points in Experiment 1, 8.4% in Experiment 2, 18.3% in Experiment 3, 11.6% in Experiment 4a, and 16.5% in Experiment 4b. The blink rate was in the normal range when natural blinking was allowed, consistent with our previous studies and literature (4, 51, 52). To compare the pupillary response results across participants and conditions, pupil diameter data were normalized using all the data recorded in each session and baseline corrected by subtracting the mean of the data during the 1-s period before the stimulus onset.

Statistical analysis

Experiments 1 and 2. For behavioral responses, mean reaction times and histogram of rating are shown in Fig. S1 and S2 for Experiment 1 and 2, respectively (also see Table 1). On average, participants made decisions at around 2 s. In all the conditions we tested, extreme rating scores (i.e., 1 and 9) were least given, with only about half the frequency of their adjacent scores (i.e., 2 and 8, respectively). We therefore combined trials with rating scores of 1 and 2 and those with scores of 8 and 9 together to reduce the noise due to few trials and to balance the trial numbers across conditions for further analysis.

We averaged the pupil diameter 0.5–1.5 s after stimulus onset to represent the pupil constriction/dilation response. Mean pupil diameter data was subjected to a repeated-measure ANOVA with the 7-level rating score in each condition. We also examined the correlation between the mean pupil diameter and the attractiveness rating on a trial-by-trial basis. Pearson's correlation coefficients between the mean pupil diameter and rating score for individual participants are shown in Fig. S1A-S2D. The correlation coefficients were subjected to a one-sample t-test to examine if they deviated from zero. Results of the ANVOA, linear trend analysis, and correlation analysis are shown in Table 2.

Effect of task order. Mean pupil diameter data sorted by facial attractiveness was subjected to a repeated-measure ANOVA with the 7-level rating score as the within-subject factor and task order (attractiveness judgment first or roundness judgment first) as the between-subject factor. In the Explicit-Attractiveness condition of Experiment 1, the effect of rating was significant [$F(6,66) = 2.99$, $p < .02$], but not the effect of task order [$F(1,11) = 1.38$, $p = .26$] or the interaction between rating and task order [$F(6,66) = 0.74$, $p = .62$]. The linear trend of the rating was significant [$F(1,11) = 7.48$, $p < .02$] and did not interact with task order [$F(1,11) = 0.34$, $p = .57$]. The same pattern of results was found in the Implicit-Attractiveness condition: the effect of rating was significant [$F(6,66) = 2.49$, $p < .04$], but not the effect of task order [$F(1,11) = 1.52$, $p = .24$] or the interaction [$F(6,66) = 1.21$, $p = .31$]. In contrast, the linear trend or rating was significant [$F(1,11) = 7.06$, $p < .03$], with a marginally significant interaction with the task order [$F(1,11) = 4.73$, $p = .05$]. The effect of the linear trend was significant when the participant performed the roundness task earlier than the attractiveness task [$F(1,5) = 8.42$, $p < .04$] but not the other way around [$F(1,6) = 0.93$, $p = .37$].

In Experiment 2, in the Explicit-Attractiveness condition, the effect of rating was significant [$F(6,78) = 4.72$, $p < .001$] but not the effect of task order [$F(1,13) = 2.61$, $p = .13$] or the interaction [$F(6,78) = 1.70$, $p = .13$]. The linear trend of rating was significant [$F(1,13) = 18.54$, $p < .001$] and did not interact with task order [$F(1,13) = 0.25$, $p = .62$]. In the Implicit-Attractiveness condition, none of the main effects [$F(6,78) = 1.93$, $p = .09$ and $F(1,13) = 0.82$, $p = .38$ for the effect of rating and task order, respectively] or interaction were significant [$F(6,78) = 1.01$, $p = .42$]. The linear trend of rating was significant [$F(1,13) = 9.54$, $p < .01$] and did not interact with task order [$F(1,13) = 0.08$, $p = .79$].

Experiment 3. Behavioral reaction time results showed that, on average, participants made the judgment around 2 s after the stimulus onset (see Table 1), a similar time range to that in the previous experiments. Mean pupil diameter data (i.e., average pupil diameter data 0.5–1.5 s after the stimulus onset) was subjected to a two-way ANOVA with pre-stimulus luminance (i.e., the fixation display) and target background luminance as within-subject factors. Results showed that both the main effects [$F(1,10) = 278.43$, $p < .001$ for pre-stimulus luminance and $F(1,10) = 153.51$, $p < .001$ for target background luminance] and the two-way interaction [$F(1,10) = 55.26$, $p < .001$] were all significant.

Facial attractiveness rating scores were subjected to a two-way ANOVA with pre-stimulus luminance and target background luminance as within-subject factors (see Fig. S3). Results showed the main effect of pre-stimulus luminance [$F(1,10) = 7.22$, $p = .02$] but not the main effect of target background luminance [$F(1,10) = 0.18$, $p = .68$] or the two-way interaction [$F(1,10) = 2.97$, $p = .12$].

Experiment 4. The range of the mean reaction times, listed in Table 1, is similar to that in the previous experiments. Mean pupil diameter 0.5–1.5 s after the stimulus onset was smaller when the face followed the white hemifield [$t(15) = 2.90$, $p = .01$] when eye movement was allowed (Experiment 4a). The effect was reversed when the participants fixated the central fixation cross throughout the trial (i.e., eye movement not allowed, Experiment 4b): mean pupil diameter was smaller when the face followed the black hemifield [$t(16) = 2.12$, $p = .05$]. The facial attractiveness rating did not differ between these two conditions in Experiment 4a [$t(15) = 0.59$, $p = .56$] or 4b [$t(16) = 1.63$, $p = .12$].

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Figure Legends

Figure 1. Pupil response results in Experiment 1. Mean pupil diameter as a function of time reference to the target onset during (A) attractiveness judgment for faces, (B) attractiveness judgment for geometric figures, (C) roundness judgment for faces, and (D) roundness judgment for faces when the data was sorted by the attractiveness of the faces. Curves are parameterized with average rating across participants (1 for least attractive and 9 for most attractive for panel A, B, and D; 1 for least round and 9 for roundest for panel C). The gray shadow represents the time window for averaging the pupil size to present the amount of pupil constriction for statistical analysis (see Materials and Methods for details). See also Fig. S1A-D.

Figure 2. Pupil response results in Experiment 2. Mean pupil diameter as a function of time reference to the target onset during (A) attractiveness judgment for faces, (B) attractiveness judgment for natural scenes, (C) roundness judgment for faces, and (D) roundness judgment faces when the data was sorted by the attractiveness of the faces. Curves are parameterized with average rating across participants (1 for least attractive and 9 for most attractive for panel A, B, and D; 1 for least round and 9 for roundest for panel C). The gray shadow represents the time window for averaging the pupil size to present the amount of pupil constriction, for statistical analysis (see Materials and Methods for details). See also Figure S2A-D.

Figure 3. Procedure and results in Experiment 3. (A) Illustration of experimental procedure (not to scale). (B) Pupil response results: mean pupil diameter as a function of time reference to the target onset during the facial attractiveness judgment. Curves are parameterized with pre-stimulus and target background luminance conditions. Dotted lines represent the gray pre-stimulus condition. Solid lines represent the black pre-stimulus conditions. Gray lines represent the gray target background conditions.

Black lines represent the black target background conditions. The numbers on the right are mean attractiveness rating scores corresponding to the pre-stimulus and target background luminance conditions. Individual rating data is shown in Fig. S3.

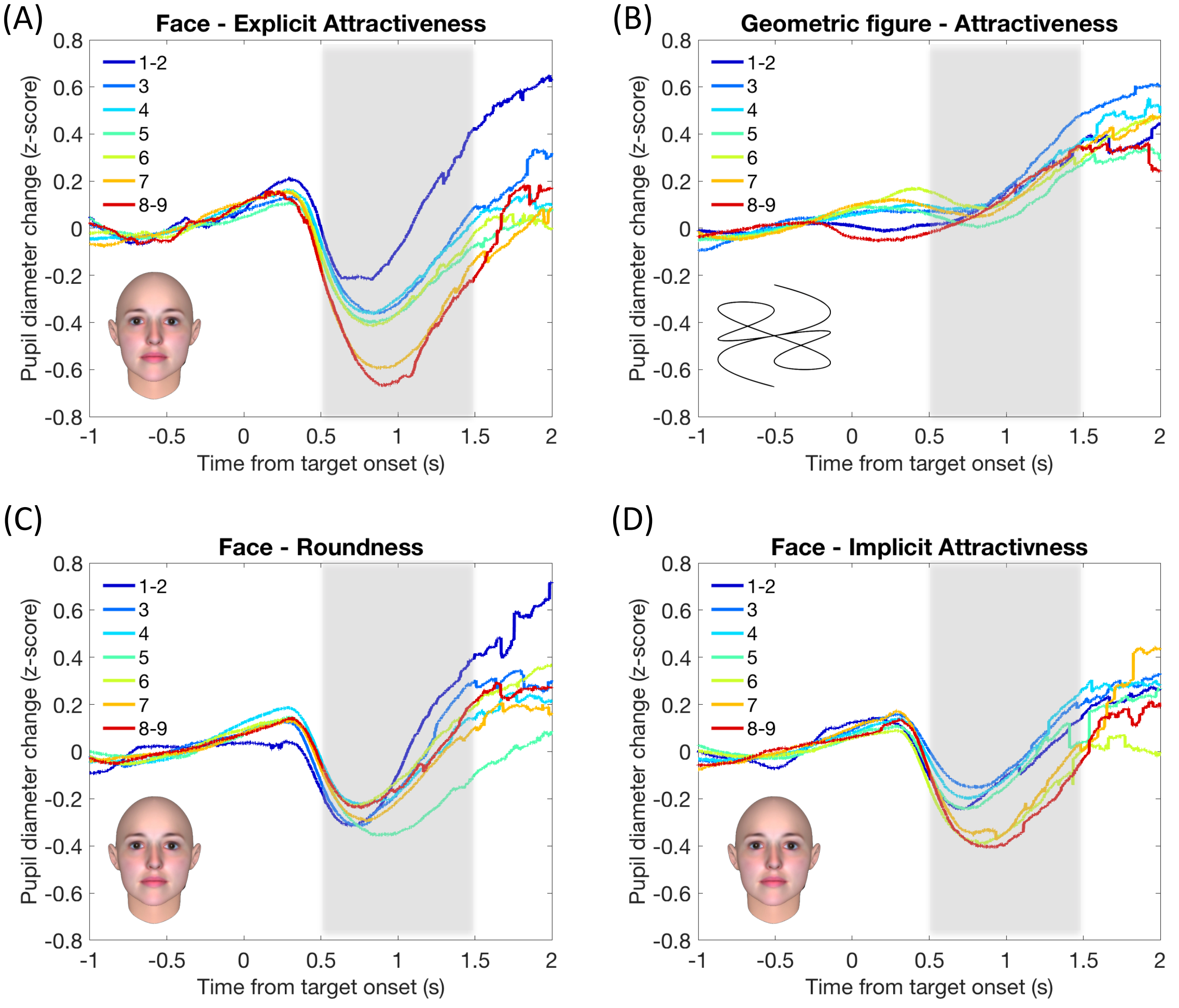
Figure 4. Procedure and results in Experiment 4. (A) Illustration of experimental procedure (not to scale). (B-C) Pupil response results in Experiment 4a and 4b, respectively: mean pupil diameter as a function of time reference to the target onset during the facial attractiveness judgment. Curves are parameterized with the relationship between the target face and pre-stimulus hemifield's luminance conditions. The numbers on the right are the mean attractiveness rating scores corresponding to the pre-stimulus hemifield's luminance conditions. Individual rating data is shown in Fig. S4.

Table 1. Mean reaction times (ms) under each condition in all experiments. Numbers in parentheses are standard errors among participants (also see Fig. S1 and S2).

Experiment 1	Face –Atrractiveness	2308 (120.4)
	Geometric figures – Attractivenss	2392 (272.1)
	Face – Roudness	2296 (145.1)
Experiment 2	Face –Atrractiveness	2016 (184.0)
	Natural scenes – Attractivenss	2027 (169.5)
	Face – Roudness	1938 (132.2)
Experiment 3	Gray – Gray	2185 (178.9)
	Gray – Black	2081 (159.7)
	Black – Gray	2199 (179.7)
	Black – Black	2228 (233.3)
Experiment 4a	Black hemifield	1678 (69.36)
	White hemifield	1683 (73.48)
4b	Black hemifield	2122 (154.61)
	White hemifield	2151 (179.73)

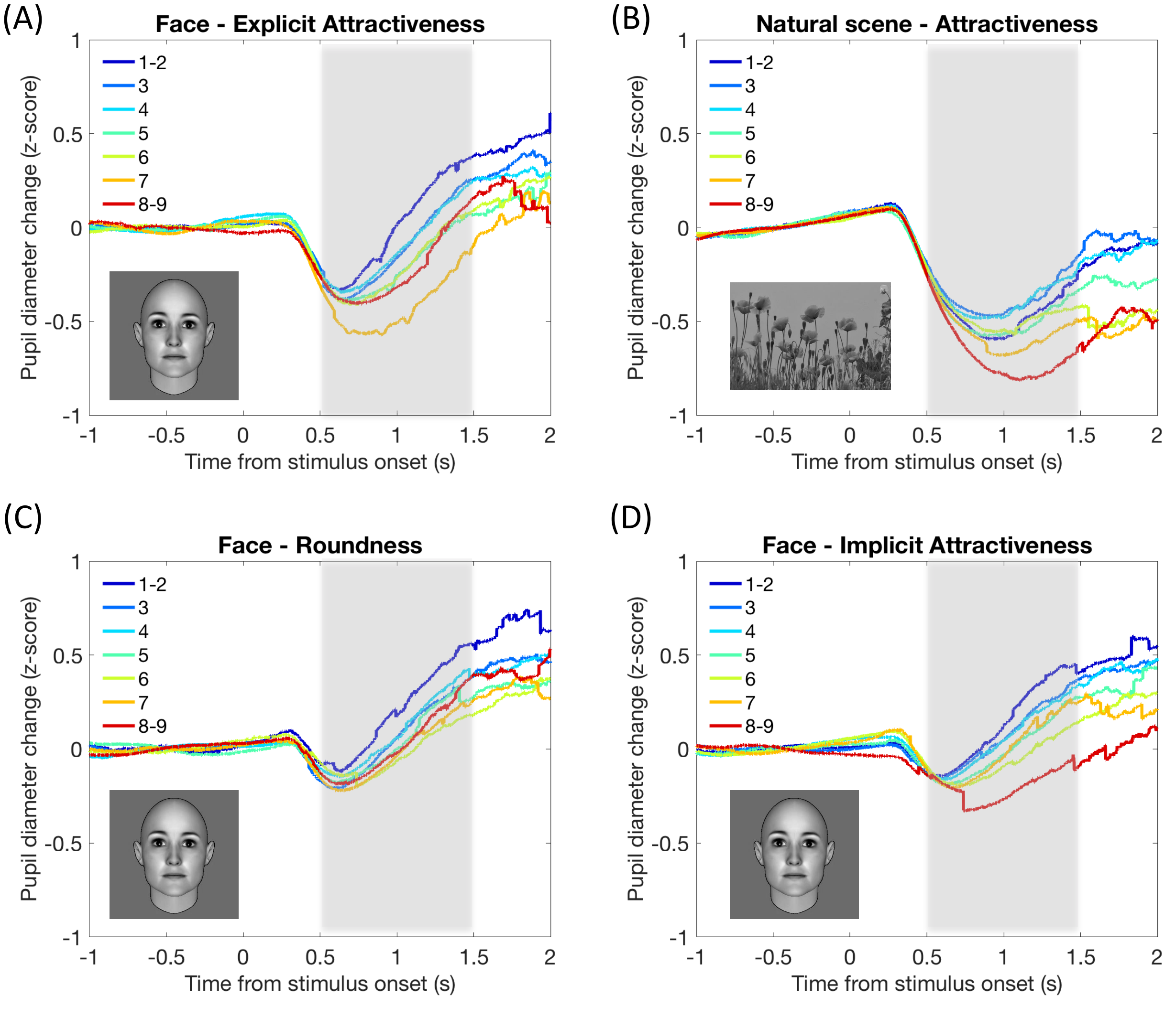
Table 2. Statistical results for the mean pupil size 0.5–1.5 s after the stimulus onset in Experiments 1 and 2 (also see Fig. S1A-S2D).

		ANOVA		Linear Trend Analysis		Pearson's Correlation Analysis		
		***F*-statistic**	***p*-value**	***F*-statistic**	***p*-value**	**mean *r***	***t*-statistic**	***p*-value**
E1	**(A)**	**3.06**	**.01***	**7.91**	**.02***	**-0.09**	**-2.50**	**.03***
	(B)	**0.36**	**.90**	**0.24**	**.64**	**0.00**	**0.02**	**.98**
	(C)	**1.66**	**.14**	**0.65**	**.44**	**0.03**	**0.70**	**.50**
	(D)	**2.45**	**.03***	**5.39**	**.04***	**-0.12**	**-2.94**	**.01***
E2	**(A)**	**4.49**	**<.001*****	**20.36**	**<.001*****	**-0.09**	**-3.13**	**<.01****
	(B)	**3.15**	**.01***	**6.48**	**.02***	**-0.10**	**-3.93**	**<.01****
	(C)	**1.13**	**.35**	**3.43**	**.09**	**-0.06**	**-2.32**	**.04***
	(D)	**1.93**	**.09**	**10.33**	**<.01****	**-0.07**	**-2.89**	**.01***



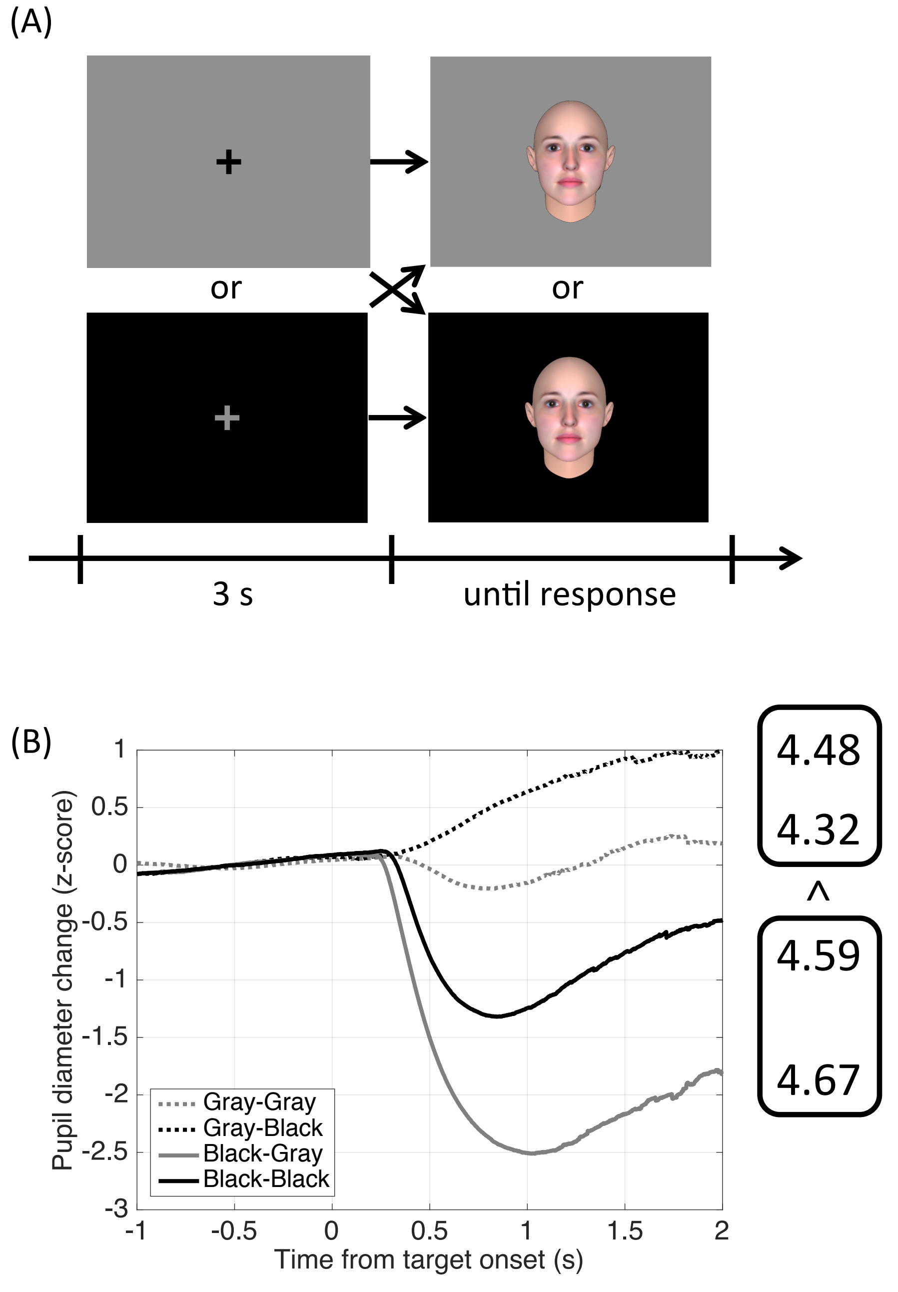
(A)
Face - Explicit Attractiveness
(B)
Geometric figure - Attractiveness
(C)
Face - Roundness
(D)
Face - Implicit Attractivness
1-2
3
4
5
6
7
8-9
Pupil diameter change (z-score)
Time from target onset (s)

Figure 1



(A)
Face - Explicit Attractiveness
(B)
Natural scene - Attractiveness
(C)
Face - Roundness
(D)
Face - Implicit Attractiveness
1-2
3
4
5
6
7
8-9
Pupil diameter change (z-score)
Time from stimulus onset (s)
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
1.5
2

Figure 2



(A)
or
or
3 s
until response
(B)
Pupil diameter change (z-score)
Time from target onset (s)
Gray-Gray
Gray-Black
Black-Gray
Black-Black
4.48
4.32
^
4.59
4.67

Figure 3

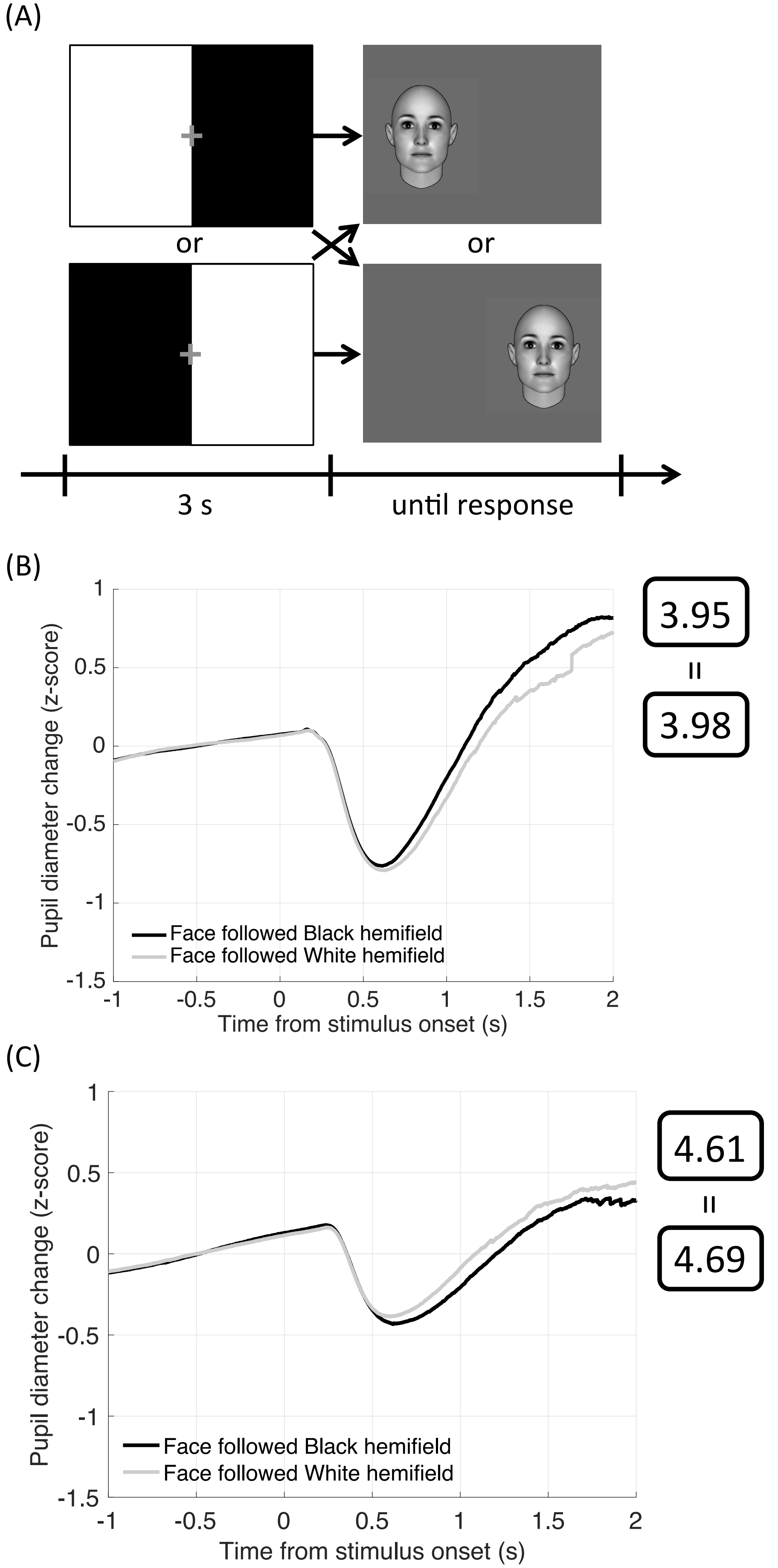

(A)
or
or
3 s
until response
(B)
Pupil diameter change (z-score)
Time from stimulus onset (s)
Face followed Black hemifield
Face followed White hemifield
3.95
=
3.98
(C)
Pupil diameter change (z-score)
Time from stimulus onset (s)
Face followed Black hemifield
Face followed White hemifield
4.61
=
4.69

Figure 4