AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: General


ISSN: 0096-3445

2022, Vol. 151, No. 2, 302–308
https://doi.org/10.1037/xge0000927

# Unconscious Pupillometry: An Effect of "Attentional Contagion" in the Absence of Visual Awareness

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When looking at other people, we can readily tell how attentive (or distracted) they are. Some cues to this are fairly obvious (as when someone stares intensely at you), but others seem more subtle. For example, increased cognitive load or emotional arousal causes one's pupils to dilate. This phenomenon is frequently employed as a physiological measure of arousal, in studies of pupillometry. Here, in contrast, we employ it as a stimulus for social perception. Might the human visual system be naturally and automatically engaging in "unconscious pupillometry"? We demonstrate that faces rendered invisible (through continuous flash suppression) enter awareness faster when their pupils are dilated. This cannot be explained by appeal to differential contrast, differential attractiveness, or spatial attentional biases, and the effect vanishes when the identical stimuli are presented in socially meaningless ways (e.g., as shirt buttons or facial moles). These results demonstrate that pupil dilation is prioritized in visual processing even outside the focus of conscious awareness, in a form of unconscious "attentional contagion."

*Keywords:* pupil size, pupillometry, continuous flash suppression, attentional contagion, visual awareness

*Supplemental materials:* https://doi.org/10.1037/xge0000927.supp



A critical task for vision is determining what we should attend to, in what might otherwise be an overwhelming stream of sensory input. Often, of course, we simply make voluntary decisions about what to focus on. But attention is also more automatically attracted to certain categories of stimuli—especially other people (e.g., New et al., 2007; Ro et al., 2001). This may be an adaptive bias, insofar as other people are more likely than most other stimuli (e.g., trees or clouds) to act in a way that may directly impact our fitness. But this is not equally true for all people: Those who are actively attending (especially to us) may be much more likely to immediately influence our welfare, compared to people who are inattentive—and in fact, people spend a rather amazing amount of time being distracted (Killingsworth & Gilbert, 2010) or focusing internally rather than externally (Chun et al., 2011).

So how can we tell whether someone is attentive or distracted? Some of the cues seem obvious—as when someone turns to look in a particular direction (e.g., Milgram et al., 1969), is looking directly at us (von Grünau & Anston, 1995), or stops blinking or moving their eyes (e.g., Reichle et al., 2010; Smilek et al., 2010). But other cues seem more subtle. Perhaps the best example of this is pupil size: Our pupils dilate when we are attentionally engaged —for example, as the result of heightened interest (Hess & Polt, 1960), increased cognitive load (Kahneman & Beatty, 1966), emotional arousal (Bradshaw, 1967), or uncertainty (Lavín et al., 2013). Indeed, pupils dilate obligatorily upon excitation of the nervous system (Applegate et al., 1983; Reimer et al., 2016) and even unbeknownst to the subject (Prochazkova & Kret, 2017), thus rendering observers unable to control their own pupil size (e.g., Laeng & Sulutvedt, 2014)—which in turn makes this an especially honest and reliable signal of one's attentional state. As a result, this cue has been used in hundreds of recent studies (of everything from memory and decision making to language and emotion), in experiments employing pupillometry (for reviews, see Binda & Murray, 2015; Laeng et al., 2012; Sirois & Brisson, 2014).

An extensive body of research has thus employed pupil size as a dependent measure. Here, in contrast, we employ it as a stimulus for social perception. If the apprehension of pupil size is so helpful

This article was published Online First August 26, 2021.
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For helpful conversations and/or comments on previous drafts, we thank Ed Awh, Yi-Chia Chen, Molly Crockett, Pieter Moors, Jay Pratt, Nick Turk-Browne, and the members of the Yale Perception & Cognition laboratory. For helpful photogeny and permission to conduct digital eye surgery, we thank Cameron Ellis, Thomas O'Connell, Brynn Sherman, and Lena Skalaban. For help constructing the mirror haploscope, we thank Ben van Buren. This project was funded by ONR MURI N00014-16-1-2007 awarded to Brian J. Scholl. Preliminary results were presented at the 2019 meetings of both the Vision Sciences Society and the Object Perception, Attention, and Memory group. The preregistered methods and analyses for each experiment can be viewed at https://osf.io/wnqek/.
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to scientists, might it be similarly helpful to us in everyday life? Might the human visual system be naturally and automatically engaging in "unconscious pupillometry"? Past work has shown that when viewing faces, pupil dilation influences neural processing even when observers do not notice such differences: Faces with dilated pupils, for example, elicit greater amygdala activity (Amemiya & Ohtomo, 2012; Demos et al., 2008), although this phenomenon is not always observed (see Harrison et al., 2006). But might the detection of others' pupil size also influence awareness and behavior, even when we are not conscious of faces (much less eyes or pupils) in the first place? Here, in what is to our knowledge the first investigation of the perception of pupil size in social vision, we asked whether dilated pupils are automatically prioritized in visual processing, even outside of conscious awareness.

## Experiment 1: Pupils Versus Buttons

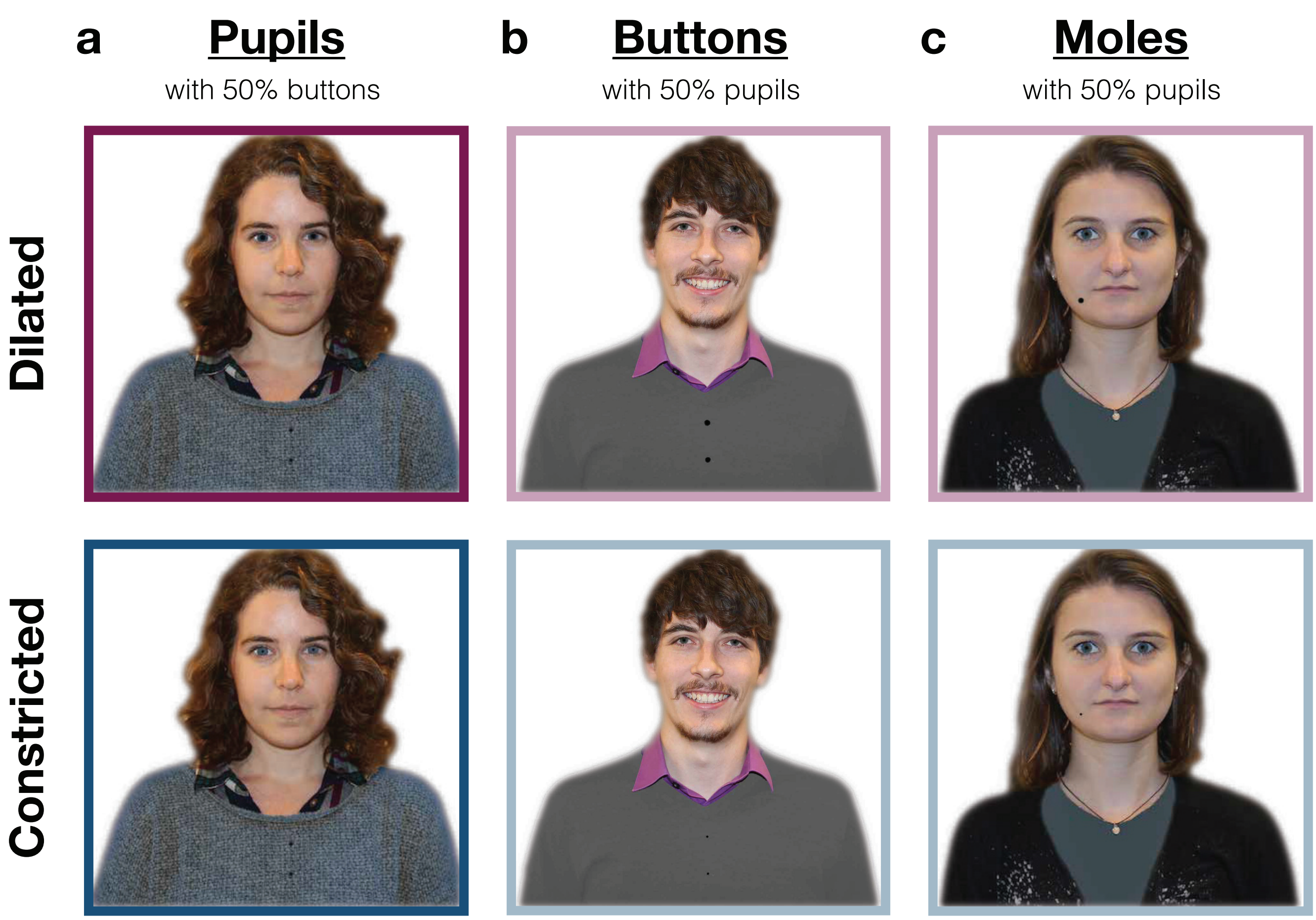
Observers viewed displays featuring faces whose pupils were artificially dilated or constricted, as depicted in Figure 1a. We used continuous flash suppression (CFS; Tsuchiya & Koch, 2005; for a review, see Stein, 2019) to render these faces invisible, and measured the time they took to break through interocular suppression (Figure 2a). To ensure that any difference between dilated and constricted pupils was due to the perception of others' attention, per se (rather than to lower-level physical differences between the stimuli), we employed a control condition in which the same physical manipulation (i.e., large vs. small black dots) was applied to identical stimuli that lacked social significance: buttons on the actors' shirts (as depicted in Figure 1b). Additional features of the experimental design further ruled out explanations that appeal to differences in contrast or spatial attentional biases.

### Method

#### *Observers*

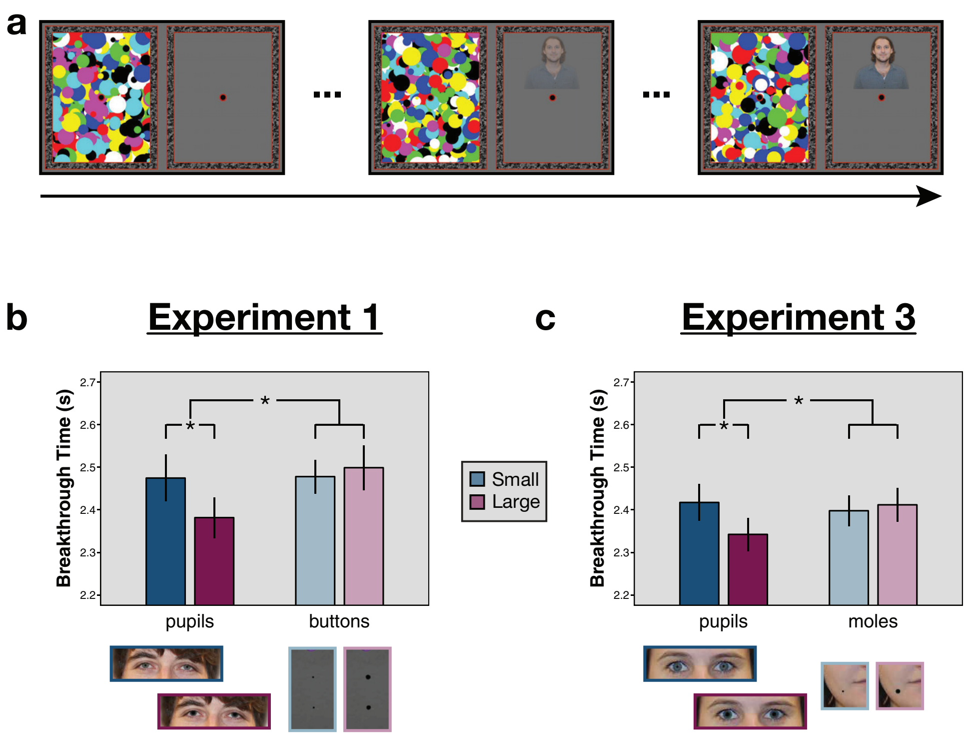
Thirty members of the Yale/New Haven community (21 females; average age = 21.93 years, *SD* = 3.99 years) participated in exchange for course credit or monetary compensation. Since to our knowledge, no previous studies have employed pupil size in

**Figure 1**
*Stimuli From Experiments 1, 2, and 3*




*Note.* (a) Sample face with constricted and dilated pupils used in Experiments 1 and 2. (b) Sample face with constricted and dilated buttons used in Experiment 1. (c) Sample face with constricted and dilated moles used in Experiment 3. Permission has been received from the photographed individuals. See the online article for the color version of this figure.

**Figure 2**
*Methods and Results From Experiments 1 and 3*




*Note.* (a) Depiction of the Continuous Flash Suppression paradigm (see text for details). (b) Stimuli closeup and average breakthrough times for dilated versus constricted pupils and buttons (Experiment 1). (c) Stimuli closeup and average breakthrough times for dilated versus constricted pupils and moles (Experiment 3). Error bars indicate 95% confidence intervals, subtracting out the shared variance. Permission has been received from the photographed individuals. * $p < .05$. See the online article for the color version of this figure.

measures of visual awareness, this sample size was determined arbitrarily—but this was done before data collection began, was preregistered, and was fixed to be identical in both of the CFS experiments reported here. An additional two observers whose average accuracy was below 80% were removed from further analyses and replaced, per the preregistered exclusion criteria. All experimental methods and procedures were approved by the Yale University Institutional Review Board.

### *Apparatus*

Stimuli were presented on a Dell 2208WFPT monitor with a 60-Hz refresh rate, using custom software written in Python with the PsychoPy libraries (Peirce et al., 2019). Observers placed their head in a chinrest and viewed the display through a custom-made mirror haploscope. The display was 90 cm away and subtended approximately 29.51° × 18.68° (with all extents reported below based on this distance).

### *Stimuli*

As in the examples depicted in Figure 1, photographs of four individuals (two males and two females) were taken, and each was further modified according to the following procedure: The background was removed, the silhouette was feathered, the iris was lightened and/or pigmented (e.g., blue or green), and the shirt color was modified to roughly match the iris color. The pupils were then manipulated to be small (approximately .05° × .05°), medium (approximately .09° × .09°), or large (approximately .13° × .13°). The ensemble of the two pupils was then rotated 90° and pasted on the shirt to create buttons of the same size. As a result, several different versions of these images were created featuring (a) medium pupils with medium buttons, (b) small pupils with medium buttons, (c) large pupils with medium buttons, (d) medium pupils with small buttons, and (e) medium pupils with large buttons (see Figures 1a and 1b; for additional sample stimuli, see the online supplemental materials).

The functional part of the display consisted of two vertically centered 11.99° × 15.87° regions centered 7.53° to the left and right of the screen center. Each had a gray (#6E6E6E) background and a centered fixation dot (radius = .32°) with a black (#000000) inside and a red (#C72819) outline (stroke width = .14°) and was surrounded by a frame filled with static noise to support binocular alignment (.81° stroke) and an outer red border (#C72819; .09° stroke).

Eighty Mondrian masks were created, each consisting of 1,500 circles positioned randomly within the left-hand region (as depicted in Figure 2a), each with a different radius (randomly selected from .18° to 1.26°) and color (randomly selected between white [#FFFFFF], yellow [#FFFF00], fuchsia [#FF00FF], red [#FF0000], lime [#00FF00], aqua [#00FFFF], blue [#0000FF], and black [#000000]).

### *Procedure*

At the beginning of each trial, observers saw the frames and fixation dots and (if necessary) adjusted the haploscope mirrors until the left and right regions were binocularly fused. They then pressed a key to start the trial, after which the Mondrian masks immediately began flashing at 10 Hz on a randomly selected side. The face (7.18° × 6.87°, 7.18° × 7.01°, 7.18° × 7.15°, or 7.18° × 7.22°) was shown on the other side (horizontally centered within the frame and vertically displaced 4.22° either above or below the center of the frame), with its opacity linearly increased from 0% to its maximum opacity over the course of the first second. As soon as observers saw any part of the image emerge into their awareness, they immediately indicated its position with respect to the fixation dot by pressing either the up or down arrow key. The trial ended after a response or after 8 s had elapsed—at which point the next trial immediately began.

### *Design*

Observers completed two blocks of 96 trials each (2 sizes [small/large] × 2 items [pupils/buttons] × 2 positions within the frames [up/down] × 4 identities × 3 repetitions), for a total of 192 trials. The trial order was randomized for each observer, and there were four self-paced breaks evenly spaced throughout the experiment. The experimental trials were preceded by 16 trials featuring different stimuli (license plates). The first 4 were practice trials, the results of which were not recorded. The remaining 12 functioned as a pretest: Observers were excluded from moving on to the experimental trials if their accuracy was below 75% or if their average reaction time was below 1.0 s. Following these 16 practice trials, observers completed a staircasing procedure aimed at determining their optimal fade-in opacity. These trials featured the same faces as in the main experiment, but with medium-sized pupils and buttons. The opacity was initially 50% and was updated on each trial (in steps of 20%, 10%, 10%, and 5%) until observers responded accurately and within 3 s on two of the last four trials.

## Results and Discussion

Trials were removed from further analyses according to the following preregistered criteria: (a) missed (4.97/192 on average), (b) inaccurate (3.33/192 on average), and (c) more than 2 *SD* away from each observer's mean (9.83/192 on average). The average breakthrough times for small and large items are depicted in Figure 2b, separately for pupils and buttons. Inspection of this figure reveals that breakthrough times were faster for large versus small pupils, but not for large versus small buttons. Statistical analyses confirmed a reliable difference between large and small pupils (2.38 vs. 2.47 s, $t(29) = 2.50$, $p = .018$, $d_z = .46$), no difference between large and small buttons (2.50 vs. 2.48 s, $t(29) = .70$, $p = .490$, $d_z = .13$), and a reliable interaction ($t(29) = 2.45$, $p = .020$, $d_z = .45$). Thus, faces with dilated pupils enter awareness faster than faces with constricted pupils, and this difference vanishes when the same stimuli are presented in a socially meaningless way (as shirt buttons).

# Experiment 2: Pupil Dilation and Attractiveness?

The effects obtained in Experiment 1 demonstrate that faces with dilated pupils gain preferential access into visual awareness, even controlling for lower-level visual factors. Although we were motivated to test such effects by the well-established connection between pupil dilation and heightened attention, past work has also uncovered links between dilated pupils and other overt social impressions. Perhaps most notoriously, pupil dilation has been associated with perceived attractiveness: Adult male observers have been reported to judge female faces to be more attractive when their pupils are dilated (Gründl et al., 2012; Hess, 1965, 1975; for a review, see Laeng & Alnæs, 2019). Might the prioritization for faces with dilated pupils observed in Experiment 1 thus be mediated by their increased attractiveness, rather than perceived attention per se? This possibility is supported, in principle, by prior results indicating that more attractive faces gain preferential access into visual awareness (Hung et al., 2016; Jiang et al., 2006; Nakamura & Kawabata, 2018). To find out, we tested whether the same faces used in Experiment 1, presented under the same viewing conditions, would be perceived as differentially attractive depending on pupil dilation. If these stimuli were to be rated as more attractive with dilated (vs. constricted) pupils, then that would be consistent with the possibility that the results of Experiment 1 might have reflected an "attractiveness effect" rather than the perception of heightened attention.

## Method

### *Observers*

In total, 1,304 new observers (649 females; average age = 35.73 years, *SD* = 13.66 years) were recruited through Prolific Academic (www.prolific.co), and each completed a single trial in a 1- to 2-min session in exchange for monetary compensation. (All observers resided in the United States, had at least a 95% Prolific approval rate, had previously completed at least 100 Prolific tasks, and had normal or corrected-to-normal acuity.) This sample size was determined and preregistered before data collection began based on an a priori power analysis, which suggested that 1,302 observers would suffice to achieve 95% power to detect a conventionally small effect size (Cohen's $d = .20$) with a .05 alpha level. This number was then rounded up to 1,304 in order to have an equal number of observers for each image.

### *Apparatus*

After agreeing to participate, observers were redirected to a website where stimulus presentation and data collection were controlled via custom software written in HTML, JavaScript, PHP, and CSS. (Since the experiment was rendered on observers' own web browsers, viewing distance, screen size, and display resolutions could vary dramatically, so we report stimulus dimensions below using pixel [px] values.)

### *Stimuli*

Observers viewed the same stimuli employed in Experiment 1 in the constricted and dilated pupil conditions (small pupils with medium buttons, and large pupils with medium buttons; see Figure 1a). The functional part of the display consisted of a 430-px × 420-px region centered in their browser window and with a gray (#6E6E6E) background, thus matching the image background in Experiment 1.

### *Procedure and Design*

Each observer viewed a photograph of a single person (one of four possible identities; 230 × 220 px, 230 × 225 px, 230 × 229 px, or 230 × 232 px; roughly 7.2° × 6.9°, 7.2° × 7.0°, 7.2° × 7.2°, or 7.2° × 7.2°) centered in their browser window and within the functional part of the display. These sizes were chosen to match those of Experiment 1: (a) Average viewport size was approximated using a sample of 400 participants from another online study conducted a few months prior (Colombatto et al., 2020; Experiment 3b; median viewport width = 1,350 px), (b) average distance from the monitor was approximated using the average arm's length (~60 cm), and (c) average display size was approximated using a standard 20-in. diagonal and a 16:9 aspect ratio. Observers' browser windows were automatically put in full-screen mode at the beginning of the experiment, and observers were asked to sit at arm's length from the monitor. They were then instructed to view the image as carefully as possible, as it would be displayed only once. The photograph was displayed upon a keypress and after a 0.5-s delay. To match the viewing conditions from Experiment 1, the image was presented with its opacity linearly increased from 0% to its maximum opacity over the course of the first second (with the maximum opacity set at 53%, which was the average fade-in opacity from observers in Experiment 1 as determined by the staircasing procedure they completed prior to beginning the experiment). The image was then displayed at full opacity for an additional 1.4 s (such that the total presentation time was 2.44 s, matching the average response time in Experiment 1). After a 0.5-s delay, observers were then asked to rate how attractive that person looked. To respond, they simply clicked on one of nine buttons, numbered 1 through 9, with 1 labeled as *definitely not attractive* and 9 labeled as *definitely attractive*. They then answered questions that allowed us to exclude observers (according to the preregistered criteria) who encountered technical problems ($n$ = 14; e.g., reporting that "my trackpad accidentally got clicked and it went to the next page" during the instructions) or who misremembered the instructions as indicated on a multiple-choice question ($n$ = 39; e.g., misreporting that they were supposed to rate the photograph on its perceived trustworthiness or competence, rather than its attractiveness). We also removed observers whose browser windows were smaller than 500 × 500 px ($n$ = 4). The resulting unique excluded observers ($n$ = 55, some of whom triggered multiple criteria) were replaced without ever analyzing their data. This design resulted in a total of 8 images (2 pupil sizes [small/large] × 4 identities), and each was viewed by 163 unique observers.

## Results

Pupil dilation did influence attractiveness judgments, but not in the predicted direction: Faces with large pupils were reliably judged as *less* attractive than those same faces with small pupils (4.81 vs. 5.03, $t(1{,}302) = 2.37$, $p = .018$, $d = .13$). Because prior reports of increased perceived attractiveness for pupil dilation were mostly based on male observers only (e.g., Hess, 1965), we also conducted an additional exploratory analysis testing whether the effect of pupil dilation on attractiveness judgments might be modulated by observers' gender. For the purposes of this analysis, we only analyzed data from observers who identified as "female" ($n$ = 649) or "male" ($n$ = 632), excluding those who selected "other" ($n$ = 20) or "I'd rather not say" ($n$ = 3). A two-way between-subjects analysis of variance on the attractiveness ratings from the remaining 1,281 observers revealed a main effect of pupil size ($F(1, 1{,}277) = 4.51$, $p = .034$, $\eta_G^2 = .004$), no main effect of observer gender ($F(1, 1{,}277) = .39$, $p = .533$, $\eta_G^2 < .001$), and no interaction ($F(1, 1{,}277) = .03$, $p = .860$, $\eta_G^2 < .001$).

## Discussion

This experiment was designed to investigate an alternative explanation for the results of Experiment 1—namely, that prioritization into visual awareness might be driven by higher perceived attractiveness of faces with dilated pupils—rather than an effect of heightened perceived attention. On the contrary, however, the results revealed a small yet reliable effect wherein faces with dilated pupils in this stimulus set were rated as less attractive, and an additional analysis confirmed that this effect did not interact with participant gender. Far from providing an alternate explanation for the results observed in Experiment 1, the current results thus suggest that the previous experiment may even have been underestimating the effect of perceived attention—since the slight (if robust) attractiveness difference due to pupil dilation observed here was in the opposite direction from that consistent with the initial experiment's results (while previous CFS studies have consistently found that more attractive faces are prioritized for entry into visual awareness, as cited above). We did not find this reversed effect to be especially surprising, however. In fact, despite the long-held belief that faces with dilated pupils are perceived as more attractive by adult men (Hess, 1965), many studies have repeatedly failed to observe this purported effect (e.g., Amemiya & Ohtomo, 2012; Demos et al., 2008; Hicks et al., 1967) or have observed it only inconsistently (e.g., Tombs & Silverman, 2004).

# Experiment 3: Pupils Versus Moles

The buttons employed as a control stimulus in Experiment 1 were identical to the pupils while lacking social significance—but of course they also differed in their location (i.e., appearing on the shirt instead of the face). In this experiment, we thus employed a control stimulus that also appeared on the face (often very near to the eyes or mouth) yet lacked social meaning: moles (as depicted in Figure 1c).

## Method

This experiment was identical to Experiment 1 except as noted here. Thirty new observers (18 females; average age = 21.27 years, $SD$ = 3.67 years) were recruited, with this preregistered sample size chosen to exactly match that of Experiment 1. An additional two observers whose average accuracy was below 80% were removed from further analyses and replaced.

The stimuli employed in Experiments 1 and 2 were modified such that all buttons were removed, and one of the pupils was instead pasted onto the person's face (at a different location for each distinct person, always slightly above or below the eyes or mouth) to create (what appeared to be) a high-contrast mole of the same size. (These "moles" were placed near to the eyes and mouth since those are the regions that observers tend to fixate during free viewing, although recall that in this study, the faces were rendered invisible.) As a result, several different versions of these images were created featuring (a) medium pupils with a medium mole, (b) small pupils with a medium mole, (c) large pupils with a medium mole, (d) medium pupils with a small mole, and (e) medium pupils with a large mole.

### Results and Discussion

Trials were removed from further analyses according to the following preregistered criteria: (a) missed (7.80/192 on average), (b) inaccurate (3.37/192 on average), and (c) more than 2 *SD* away from each observer's mean (10.20/192 on average). The average breakthrough times for small and large items are depicted in Figure 2c, separately for pupils and moles. Inspection of this figure reveals that breakthrough times were faster for large versus small pupils, but not for large versus small moles. Statistical analyses confirmed a reliable difference between large and small pupils (2.34 vs. 2.42 s, $t(29) = 2.21$, $p = .035$, $d_z = .40$), no difference between large and small moles (2.41 vs. 2.40 s, $t(29) = .47$, $p = .645$, $d_z = .08$), and a reliable interaction ($t(29) = 2.58$, $p = .015$, $d_z = .47$).

These results thus fully replicated the advantage for dilated pupils found in Experiment 1, while also confirming that this difference does not depend on the specific contrast with shirt buttons. This absence of unconscious prioritization for "mole dilation" (i.e., when the dilated stimuli were deprived of social meaning) seems especially remarkable given that the "dilated" moles were visually more salient than the "constricted" moles (and to a degree that went beyond the contrast in the pupil stimuli); for example, they had an especially high contrast with the background skin, and they made the faces less symmetrical. As discussed below in the General Discussion, other aspects of these experiments also rule out potential explanations based on differential contrast or spatial attentional biases.

## General Discussion

Despite its social significance, pupil dilation is an exceptionally visually subtle signal—since dilated versus constricted pupils differ by just a fraction of a degree of visual angle. (You might notice that the two faces in Figure 1a look rather remarkably—if somewhat ineffably—different, despite differing by only a few pixels.) Indeed, this difference was so subtle that the observers in our experiments almost never even overtly noticed the variations in pupil size, despite each seeing 192 images in Experiments 1 and 3. (In postexperiment debriefing, only 2 of the 60 observers [1 in each experiment] reported any awareness of this manipulation—one referring to a difference in eye color and the other mentioning that "Some people['s eyes] looked more intense.") This degree of subtlety makes the key results of this study all the more striking: These few pixels of difference—only when seen as dilated pupils—automatically facilitated the entry of faces into visual awareness.

This effect cannot be explained by appeal to a greater degree of visual contrast between the irises and the pupils, for two reasons. First, the shirts in Experiment 1 were modified to roughly match the color of the iris. Second, the contrast between the clear skin and the moles in Experiment 3 was actually considerably higher than that between the pigmented irises and the pupils—such that a contrast-based explanation would have to predict a greater dilated-versus-constricted effect for moles compared to pupils.

This effect also cannot be explained by appeal to biases of spatial attention (e.g., if observers are generally biased to attend to the positions in which eyes appear) for three reasons. First, the positions of the faces were randomized so that on each trial, they could appear on the top or bottom of the display—such that there was no single region where the eyes appeared. Second, the positions in which the eyes appeared actually differed dramatically (by up to 28 px, or $.38° \times 0.32°$) across the four separate identities featured in the experiments. Third, an explanation that appealed to spatial biases (relating to where the eyes were expected to appear) would predict that the effects should be greater when the same identity (and thus the identical eye positions) happened to repeat from one trial to the next—but if anything, the opposite was the case. (Collapsing across Experiments 1 and 3, the constricted-versus-dilated effect was unreliable for repeated identities [$t(59) = 1.07$, $p = .290$, $d_z = .14$] but was robust for different identities [$t(59) = 2.51$, $p = .015$, $d_z = .32$], with no reliable interaction [$t(59) = .44$, $p = .658$, $d_z = .06$].)

The results of Experiment 2 further suggest that the influence of pupil dilation on visual awareness is not mediated through differences in perceived attractiveness. Rather, we suggest that these results reflect a more direct form of unconscious "attention to attention"—such that faces that seem to have heightened attention are prioritized in visual awareness. This is consistent with the fact that pupil dilation has been associated not only with attractiveness (inconsistently!) but with many other forms of heightened attention and arousal—including those due to emotionally arousing pictures (Bradley et al., 2008) and to difficult decisions (Lavín et al., 2013). In this way, the current results complement other recent findings that faces looking directly at (or turned toward) the observer break into awareness faster than do faces looking (or turned) away (Chen & Yeh, 2012; Gobbini et al., 2013; Stein et al., 2011). Whereas those previous studies can be interpreted as demonstrations that human visual processing is especially sensitive to *whether* others are attending to us (as signaled by directed gaze), the results of the current study indicate that visual processing is also sensitive to far subtler degrees of perceived attention (as signaled by pupil size), even with direct gaze.

In short, the current results suggest that the perceived attentional state of others can in turn cause us to attend to them—a novel form of "attentional contagion."

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Received May 20, 2020
Revision received April 10, 2021
Accepted April 12, 2021 ■