AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: General

ISSN: 0096-3445

2025, Vol. 154, No. 1, 1–17
https://doi.org/10.1037/xge0001697

Illusory Facial Expressions Caused by Lighting Direction

Mahitha Ramanathan[1], Lindsay M. Peterson[1], and Colin J. Palmer[1, 2]
[1] School of Psychology, University of New South Wales
[2] Department of Psychology, National University of Singapore

Our daily interactions draw on a shared language of what facial expressions mean, but accurate perception of these signals may be subject to the same challenges that characterize visual perception in general. One such challenge is that faces vary in their appearance with the context, partly due to the interaction between environmental lighting and the characteristic geometry of the human face. Here, we examine how asymmetries in lighting across the horizontal and vertical axes of the face influence the perception of facial expressions in human observers. In Experiment 1, we find that faces with neutral expression appear to bear a negatively valenced expression and appear higher in emotional arousal when lit from below—an illusion of facial expression where none really exists. In Experiment 2, we find that faces performing common emotional expressions are more often miscategorized when lit from below compared to when lit from above, specifically for angry and neutral expressions. These data show that changes in facial appearance related to illumination direction can modify visual cues relevant to social communication—and suggest that facial expression recognition in humans is partially adapted to (naturalistic) environments in which light arrives predominately from overhead.

Public Significance Statement

The phenomenon that faces can appear sinister or uncanny when lit from below is one that resonates widely, traditionally exploited by children telling a ghost story around the campfire and by film makers when depicting a villain. Here, we investigate systematically how lighting direction contributes to the (apparent) emotional character of the human face. We find that illusory differences in facial expression can be perceived when comparing faces lit from above and below, and that certain facial expressions are less accurately recognized when lit from below. These results speak to the visual processes that underlie our ability to recognize another person's facial expression and the theory that our perceptual system is optimized for environments characterized by a tendency toward overhead lighting.

Keywords: social perception, face perception, emotion recognition, illumination tolerance, light from above

Supplemental materials: https://doi.org/10.1037/xge0001697.supp

From productions of Shakespeare to horror films to the music video for *Bohemian Rhapsody*, directional lighting is commonly used to dramatize the human face. An observation often made about stage lighting design (and around campfires) is that a sinister or otherworldly look can be created by lighting a face from below, while faces lit from overhead tend to appear more natural (Grodal, 2005; R. H. Palmer, 1994). It has been demonstrated empirically that face identity recognition is improved when we see others lit from above rather than below, either when matching between images of unfamiliar faces or when identifying people known to us (Hill & Bruce, 1996; Johnston et al., 1992). Indeed, the pattern of shading, shadows, and highlights that occur across face features when lit from above contributes to the prototypical look of the human face, drawing attention preferentially in newborns (Farroni et al., 2005) and facilitating face detection in adults (C. J. Palmer et al., 2022; Stein et al., 2011). This advantage for "light from above" in face perception aligns with the directional bias in lighting strength that characterizes natural environments, most plainly due to the sun and sky being located above us (Dror et al., 2004). Despite this bias toward overhead lighting, the directional strength of illumination is highly variable during the natural viewing of objects, and the contribution of this to the visual appearance of faces (and variability

Rachael E. Jack served as action editor.
Colin J. Palmer https://orcid.org/0000-0002-1058-3428
Data and code can be accessed at https://osf.io/rc7qf. Other research materials are available by emailing the corresponding author, Colin J. Palmer. The authors declare no conflicts of interest or prior dissemination of the data. This work was supported by Australian Research Council Discovery Project DP200100003 awarded to Colin J. Palmer.

Mahitha Ramanathan played a lead role in formal analysis, investigation, and writing–original draft, a supporting role in methodology, and an equal role in conceptualization. Lindsay M. Peterson played a supporting role in writing–review and editing and an equal role in methodology and software. Colin J. Palmer played a lead role in funding acquisition, methodology, supervision, and writing–review and editing, a supporting role in formal analysis, and an equal role in conceptualization and software.

Correspondence concerning this article should be addressed to Colin J. Palmer, Department of Psychology, National University of Singapore, 9 Arts Link, Singapore 117570, Singapore. Email: c.palmer@nus.edu.sg

therein) has been brought into focus partly by the challenge it poses to computerized face identification and expression recognition algorithms (Adini et al., 1997; O'Toole et al., 2018). The current article focuses on the role of illumination in the perception of facial expressions—can lighting direction affect how we perceive the emotional state of another person? While the relationship between illumination and facial expression recognition is little described in the experimental psychology literature, our informal observations suggest that asymmetries in lighting can contribute to the (perceived) emotional character of a face (Figure 1).

How is illumination relevant to the perception of facial expression? Expression recognition relies on inferences about face shape, as facial expressions are specific deformations of the facial surface brought about by muscular actions, particularly around the eyes and mouth. For example, anger involves the brows being lowered, eyelids raised, and lips tightened. Surprise involves eyebrows high and curved and the eyes stretching open, with (white) sclera visible between the iris and eyelid (Ekman, 1992; Ekman et al., 2002). In general, the perception of surface shape is tied closely to the effect of illumination on an object's appearance, which includes shading, shadows, and highlights. For example, shading gradients are produced across objects by gradual changes between surface normals and the angle of incident light, providing a fundamental visual cue to the 3D structure of objects (i.e., surface curvature), but one that is ambiguous without an estimate of lighting direction. Pertinently, the perception of shape from shading in human vision appears driven in part by an implicit assumption for overhead lighting (Morgenstern et al., 2011; Ramachandran, 1988; Sun & Perona, 1998), which in principle may lead to distortions in the perception of face shape when the veridical lighting direction is unfamiliar. This may help to explain why lighting direction interacts with face identity recognition (Johnston et al., 1992) and generally predicts that judgments that rely on recovering the 3D shape of the face may be sensitive to lighting direction. It is still unclear, however, whether any distortions of perceived face shape that occur across lighting conditions can be sufficient to either resemble a socially meaningful facial deformation (i.e., a facial expression) or alter the received meaning of an intentionally communicative facial signal. Interestingly, however, specific changes in appearance that can occur when a face is lit from below, such as highlighting of the sclera and shadowing above the eyebrows (illustrated in Figure 1), are localized to features involved in expressions including anger, fear, and surprise (Ekman, 1979; Stratou et al., 2011). In the present study, we test whether changes in the visual appearance of faces related to the illumination direction are sufficient to affect an observer's perception of facial expression.

Faces lit from below also have some resemblance to faces viewed as photographic negatives, that is, with the darker and lighter regions of the image reversed. For example, in Figure 1, darker and lighter sides of the nose are reversed depending on whether light arrives from above or below (though this inversion of light and dark is not the case for certain other face features, such as the irises). Recognizing a familiar face is strikingly more difficult when viewed as a photographic negative (Bruce & Langton, 1994; Galper, 1970). There are several different hypotheses regarding why this occurs: by disrupting the perception of shape from shading, by producing the sense of an unfamiliar pattern of surface pigmentation, and/or by disrupting ordinal contrast relationships across face regions that may be characteristic of a face (Gilad et al., 2009; Young & Bruce, 2024). The presence of familiar patterns of contrast across face features, such as darker regions around the eye sockets and below the nose, also appears important to face detection in primate vision (e.g., Farroni et al., 2005; Ohayon et al., 2012; C. J. Palmer et al., 2022; Stein et al., 2011). As described above, the visual cues that underlie expression recognition are often considered in terms of changes in the shape or configuration of face features related to specific muscular activations. Reversing the contrast polarity of an image maintains the spatial structure of edges that define the

Figure 1
Lighting Direction and the (Apparent) Emotional Character of a Face

Note. On the left, a 3D-scanned model of a man's face is rendered consistent with a light source positioned 45° above his face, while on the right, the identical model is lit from 45° below. The reader may find that the man appears angrier when lit from below and calmer when lit from above.

appearance of the face, and hence may retain shape-related cues important to distinguishing facial expressions even while disturbing contrast- or surface-based cues important to face detection and identification. Correspondingly, some studies have found relatively little effect of photographic negation on the perception of expression compared to the perception of identity (e.g., Harris et al., 2014; White, 2001), although other studies did find impaired expression recognition in contrast-reversed faces (Benton, 2009; Sormaz et al., 2016). Unlike the artificial contrast reversal that occurs in a photographic negative, illumination direction is a natural form of variability in the appearance of faces, with some comparable though nonidentical effects on the relative brightness of different face features (returned to in the Image Analysis section). The potential for such changes in the pattern of contrast across the face to affect expression recognition is unclear even if affecting the detection and identification of faces. One can expect, however, that if expression recognition relies partly on detecting surface- or contrast-based features of the face (e.g., Sormaz et al., 2016), a statistical bias toward overhead lighting during visual development may lead to an optimization of expression recognition for facial contrast patterns most typical of faces lit from above.

It is intrinsic to our everyday visual experience of faces that they are viewed under varying illumination conditions—from sun-washed beaches to dimly lit bars to harsh university ceiling lights. Within-person variability in facial appearance across contexts can significantly alter social evaluations (e.g., identity, attractiveness, friendliness; Jenkins et al., 2011; Røysamb et al., 2022; Todorov & Porter, 2014), though the effect of illumination on expression recognition, and the visual mechanisms that may help to compensate for this, are not well understood. Expression recognition can vary in accuracy and perceived intensity with the strength of lighting (Wisessing et al., 2020; Yang & Fotios, 2015), though a study that varied lighting direction for rendered cartoon characters found no significant effect on expression recognition (Wisessing et al., 2016), which could be due partly to the characters portraying stylized displays of emotion. Attaching shadows to images of wooden masks worn during traditional Japanese dramas ("Noh masks") can alter whether observers evaluate the masks as looking happier or sadder (Kawai et al., 2013). The present study adds to this literature by characterizing the effect of lighting direction on the perception of human facial expressions. Investigating the role of lighting direction in the perception of human faces may help elucidate the visual cues underlying expression recognition, the dependence of expression recognition on the context a face is viewed within, and the adaptation of high-level vision to sensory environments encountered in daily life.

In the present study, participants viewed faces presented on a computer monitor that differed in how they were illuminated. Faces were generated by rendering 3D-scanned models of human faces, which has the advantage that the identical face shape and surface reflectance properties can be rendered under varying, but precisely specified, illumination conditions (avoiding involuntary changes in expression related to fatigue, squint, pupil dilation, etc., that may occur when photographing an individual across different illumination conditions, for example). In Experiment 1, all faces had neutral expression, though this was not stated to participants for whom the task was to rate the emotional expression of each face in terms of valence and arousal. We tested whether changes in the visual appearance of faces related solely to the illumination direction are sufficient to cause systematic biases in how observers perceive the emotional expression of the face. Experiment 2 tested how the perception of faces performing (real) expressions is influenced by the lighting direction, including whether the influence of lighting is sufficient to cause judgments of another person's expression to shift between distinct categories of emotion.

Transparency and Openness

The choice of sample size for each experiment is noted in the corresponding Participants section. All data exclusions, manipulations, and measures are reported. The de-identified data and computer code can be accessed at https://osf.io/rc7qf (C. J. Palmer, 2024). Other research materials are available by emailing the corresponding author. Access to some research materials may require purchasing third-party software assets. The study was not preregistered.

Experiment 1

Method

Participants

The sample for this study included 40 university students, with a mean age of 19.3 years ($SD = 1.6$ years; range = 17–23 years). The sample included 30 females and 10 males. Thirty-nine participants were right-handed, and one was left-handed. Participants were recruited through a university platform for undergraduate students and given course credit for their participation. Each participant gave informed consent, and methods of data collection were approved by an ethics committee at the University of New South Wales (Human Research Ethics Advisory Panel C: Behavioural Sciences). No participants were excluded, but one participant's data were not saved correctly for the valence rating task; thus, the sample size used in the analysis was 40 for the arousal rating task and 39 for the valence rating task.

A target sample size of 40 participants was chosen prior to data collection, using the sample size of a previous study as an approximate guide (Sormaz et al., 2016; $n = 20$ per experiment). There is a lack of previous research investigating the effect of illumination direction on emotion recognition, preventing us from identifying a known effect size to base a power analysis on, but Sormaz et al. examined a related question of how manipulating feature locations and textural cues influence the perception of facial expressions. A sensitivity analysis performed using G * Power (Version 3.1.9.6) indicated that with 40 participants a repeated-measures t test would be sensitive to an effect size of Cohen's $d = 0.45$ or greater with 80% power ($\alpha = .05$, two-tailed).

Design

In Experiment 1, we took a relatively agnostic approach to characterizing the influence of lighting direction on the perception of facial expression. We tested the perception of faces across a range of both vertical and horizontal lighting directions and focused on measures of perceived expression that made relatively few assumptions about the changes in facial expression that observers might perceive. In particular, Experiment 1 consisted of two computer-based tasks that each utilized a 3×3 within-subjects design. Participants were presented images of faces on a screen and rated the emotional expression of each face in terms of either valence or arousal. There were two independent variables in each task: the vertical direction of illumination across the face and horizontal direction of illumination across the face. Each independent variable had three levels: light arrived from above, below, or directly in front of the face (for vertical illumination), and from the left, right or directly in front of the face (for horizontal illumination). The dependent variables were ratings of emotional valence and emotional arousal. These measures are commonly used for characterizing the perception of emotional responses in a dimensional way (Mauss & Robinson, 2009). In this context, emotional valence contrasts the pleasurable (positive) versus unpleasurable (negative) nature of the emotional state conveyed by a facial expression (e.g., happy vs. sad) while emotional arousal contrasts how relaxed versus stimulated a person appears based on their facial expression. Valence and arousal can be useful to consider together—for example, "angry" and "sad" emotional states might be similar in perceived valence (i.e., negative valence) but differ significantly in perceived arousal. Measuring emotion along a dimension may be more sensitive to subtle changes in perception compared to a categorical measure and avoids making an assumption about the specific emotional states that participants might attribute to the stimuli. We included valence and arousal scales together to provide a more comprehensive assessment of changes in perceived expression related to the lighting direction.

Stimuli

The stimuli were computer-generated images of faces produced using a combination of 3D scanning and scene-based graphical rendering. Accurate facial anatomy is important to the present study, because the influence of illumination on the appearance of an object is dependent on the interaction between lighting direction and the specific three-dimensional shape of the object. To this end, the face stimuli were generated using high-resolution 3D models of faces acquired from a 3D scanning company, Ten24 (https://ten24.info). The models were each created from photographic scanning of a real person using an extensive camera array, with the 3D shape of their face reconstructed using photogrammetry. There were six identities used in Experiment 1. The six models varied in gender, presenting as four men and two women, while varying also in race and age. Each face bore a neutral expression and direct eye gaze. Example images of each model can be found in Supplemental Figure S1.

Each model was rendered as a 2D image using the program Blender (Blender 3.2.2) and the Cycles rendering engine. The physically based process by which Cycles renders an image is designed to simulate how light interacts with objects in the real world, including the interaction between object shape and lighting direction that generates shading, shadows, and specular reflections. This allows for a realistic simulation of how the face models appear under different conditions of illumination. The reflectance properties of the face models were driven in part by high-resolution textures derived from the 3D photography described above, together with shaders that simulate diffuse and specular reflectance (such as specular reflections from the eye surface that produce eye glint). More details about the setup of face models in the rendering environment are described in C. J. Palmer et al. (2020). Image production via Blender was controlled using custom Python scripts (Version 3.5.3). The models were rendered in grayscale, with pixel intensities coded with a high-bit depth (32 bits) and a linear intensity scale.

The face models were rendered under nine illumination angle conditions. The nine illumination angles can be understood as a 3×3 matrix, where the position of the light source varies in 45° increments around the face along two axes (See Figure 2a and 2b). Along the horizontal axis across the face, light arrived at either −45°, 0°, or 45°, where negative angles indicate that the light source was positioned to the left of the face, and 0° indicates frontal lighting (with the light source centered between the two eyes of the face model). Along the vertical axis across the face, light arrived at either −45°, 0°, or 45°, where negative angles indicated that the light source was positioned below the face. The face models were rendered from the perspective of a virtual camera, stationed 70 cm away from the model and centered in between the eyes. There were 54 images: Six identities rendered under each of the nine illumination conditions. The same images were presented in both the valence and arousal tasks. Each image was presented three times during each task, for a total of 18 trials per illumination condition and 162 trials per task.

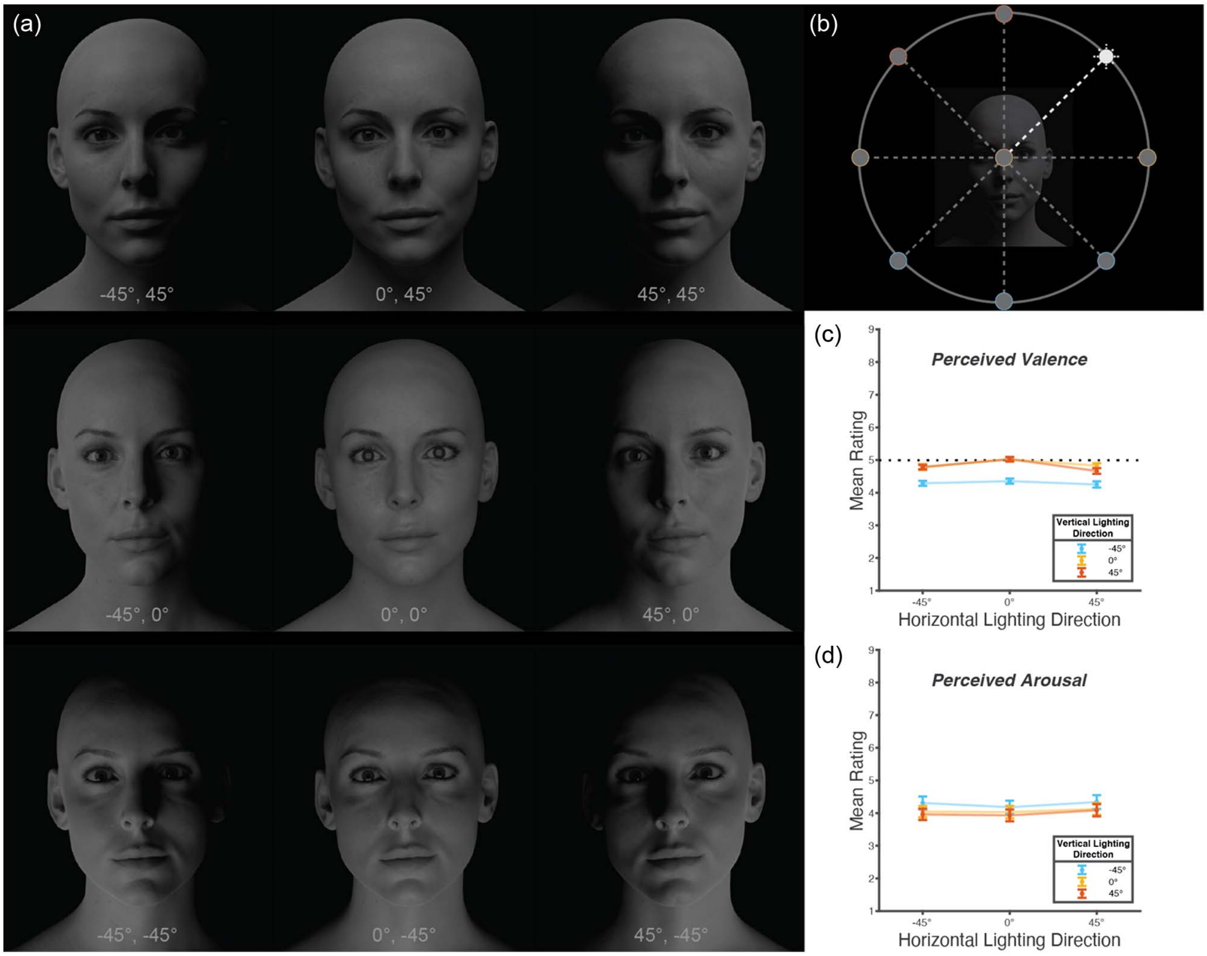
In each image, the face model was illuminated by a single square light source (60 cm × 60 cm), positioned 75 cm away from the face model within the virtual environment, and always angled toward a point in between the two eyes of the face model. This simple light source is comparable in size and shape to some light sources encountered in everyday environment such as ceiling lights, small windows, skylights, and "soft-box" lights used commonly in portrait photography. While illuminating an object with a single light source can lead to more pronounced shadowing compared to when additional ambient lighting is present, this is less pronounced for a plane-shaped light source than a point light source, due to the extended area that light is emitted from. Note that the face images presented in the figures of this article are necessarily compressed and γ-adjusted, which leads to a loss of information particularly in the darker regions of each image. The better reproduction of the rendered image data during the experiment (e.g., due to the bit depth of the display) meant that information in the darker regions was more visible compared to in the article figures.

Procedure

The stimuli were presented on a Cambridge Research Systems Display++ LCD monitor (1,920 × 1,080 pixels resolution, 28 pixels per cm, 120 Hz refresh rate), using the program MATLAB (version R2021a) with the Psychtoolbox extension (Version 3, PTB-3). This allowed images to be presented with linear light output and high-bit depth (14 bits), which is relevant to the present study in allowing the shading gradients produced across the face to be presented faithfully. Participants completed the experiment in a darkened testing cubicle. The face images were presented as approximately life-size on screen, defined by an interpupillary distance of 6.3 cm (Fesharaki et al., 2012). The face stimuli subtended a visual angle of 19° width and 25° height on average. The faces were presented against a black background, directly facing the participant. Participants were seated approximately 50 cm away from the monitor and were asked to adjust their seat height to be sitting directly in front of the stimuli.

The experiment consisted of two main tasks in which the face images were presented one at a time. The same face stimuli were presented in both tasks. In each trial of the valence task, participants were asked to judge whether the facial expression they saw conveyed a positive, negative or neutral emotional state, by rating the face on a 9-point Likert scale ranging from *very negative* (1) to

Figure 2
Face Images and Results for Experiment 1



Note. (a) and (b) Face models with neutral expressions were rendered under nine lighting conditions, varying in the horizontal and vertical angle of a light source relative to the face. These images depict one of six face models used in the experiment. (c) The lighting angle tended to alter the perceived emotional valence of the faces. Faces lit from below were perceived as more negatively valenced on average. The dotted line indicates the point of "neutral" valence on the scale. Error bars indicate ±1 SEM. (d) Faces lit from below were also perceived as having slightly higher emotional arousal on average compared to faces lit from above. SEM = standard error of the mean. See the online article for the color version of this figure.

neutral (5) to *very positive* (9). Participants were instructed that examples of positive-valence facial expressions include happy and excited, while examples of negatively valence facial expressions include angry and upset. In other words, valence was conceptualized as a bipolar characteristic of the emotional states of an individual that can be conveyed by their facial expression, reflecting the qualitative difference between pleasurable emotional states (e.g., happiness, excitement) and unpleasurable emotional states (e.g., anger, sadness, disgust). The valence scale also captures the apparent absence of an emotional state (i.e., a neutral expression reflecting the relative absence of either a positive or negative emotional state). Participants were reminded in each trial that their task was to rate the emotional expression of the face they saw. In the arousal task, participants were instructed to rate the expression of each face they saw in terms of emotional arousal, using a 9-point Likert scale ranging from *very relaxed* (1) to *very stimulated* (9). It was explained to participants that emotional arousal refers to how energized or stimulated a person is, such that a face with low-emotional arousal could appear more calm, relaxed or sleepy, and a face with high-emotional arousal could appear stimulated, energetic, excited, agitated, or nervous. There was no explicit midpoint label in the arousal scale, reflecting how arousal can be conceptualized as a unipolar rather than bipolar characteristic of emotion. In other words, an absence of arousal would correspond to the lowest point of the scale (as opposed to the midpoint) and can only increase from there. Hence, one might expect a truly "neutral" face expression (i.e., an apparent absence of any emotional state) to be rated at the midpoint of the valence scale and rated lowly on the arousal scale. The use of a 9-point scale followed previous research measuring perceived valence and arousal of facial expressions or other stimuli (e.g., Aviezer et al., 2012; Bliss-Moreau et al., 2020).

Prior to each task, participants completed 10 practice trials consisting of 10 randomly selected images. In each trial, a fixation cross was presented for 1 s, followed by a face image for 2 s. After each face image, the 9-point Likert scale appeared on screen. Participants gave their response by pressing with their mouse the number on the scale that best corresponded with their perception. There was no limit on response time for each trial, and the next trial would start as soon as participants selected a number on the scale. Participants were instructed to take breaks if needed after completing 25%, 50%, and 75% of each task. Whether the valence or arousal task was given first was counterbalanced for each participant, and the order of trials within each task was randomized for each participant.

Statistical Analysis

Statistical analysis was conducted with the program Jamovi (Jamovi 2.2.5). For each participant, we calculated the mean valence and arousal ratings across the 18 trials of each illumination condition. Each dependent measure was compared across illumination conditions using a separate two-way repeated measures analysis of variance (ANOVA), with the two factors being the horizontal and vertical lighting direction. Bonferroni-adjusted thresholds are reported for simple main effects and post-hoc *t* tests where appropriate to control the Type I error rate.

Results

Valence Ratings

The perceived emotional valence of the faces depended on the angle of illumination, illustrated in Figure 2c. Faces lit from above or in front tended to be perceived as having a neutral emotional valence. The same faces lit from below were perceived as having more negative emotional valence. This trend was reflected in a significant main effect of vertical lighting direction on mean valence ratings, $F(2, 76) = 55.19$, $p < .001$, $\eta_p^2 = .59$. Post-hoc *t* tests comparing mean valence ratings across the three vertical illumination conditions confirmed that valence ratings for faces lit from −45° below were significantly lower on average than for faces lit from 45° above, $t(38) = 8.06$, $p < .001$, and faces lit from in front, $t(38) = 8.03$, $p < .001$. Both comparisons survive Bonferroni correction with an adjusted significance threshold of .017 (correcting for three comparisons). In contrast, valence ratings did not differ significantly between faces lit from 45° above and faces lit from in front, $t(38) = -1.30$, $p = .20$. Together, these results indicate that faces perceived with a neutral expression when seen lit from 45° above or in front tend to be instead perceived with a more negative emotional valence when lit from below.

A more subtle trend in the data apparent in Figure 2c is that faces illuminated by a light source positioned centrally in the horizontal axis were perceived as having a lack of emotional valence (i.e., a "neutral" expression) compared to when illumination arrived from the left or right. This was reflected in a significant main effect of horizontal lighting direction on valence ratings, $F(2, 76) = 11.34$, $p < .001$, $\eta_p^2 = .23$. Post-hoc *t* tests comparing valence ratings across the three horizontal illumination conditions demonstrated that valence ratings for faces lit from 45° to the right and 45° to the left were both significantly lower on average than for faces lit frontally, $t(38) = -3.69$, $p < .001$; $t(38) = 3.42$, $p = .001$. Both comparisons survive Bonferroni correction with an adjusted significance threshold of .017 (correcting for three comparisons). In contrast, mean valence ratings for faces lit from 45° to the right and 45° to the left did not differ significantly from each other, $t(38) = -1.23$, $p = .23$. This indicates that faces can be perceived as having a more negative expression when lit from either the left or right compared to when lit centrally.

There was also a significant interaction between vertical lighting direction and horizontal lighting direction on valence ratings, $F(4, 152) = 3.2$, $p = .015$, $\eta_p^2 = .08$. The trends illustrated in Figure 2c suggest that changing illumination direction horizontally may have a more pronounced effect on perceived valence for faces that are lit from above or directly in front compared to those lit from below. Simple main effects were computed to compare mean valence ratings across horizontal lighting conditions separately for each of the three vertical lighting conditions. There was a simple main effect of horizontal lighting direction on mean valence ratings for faces lit from 45° above, $F(2, 37) = 9.59$, $p < .001$, $\eta_p^2 = .34$. A similar trend was seen for faces lit centrally in the vertical axis—$F(2, 37) = 3.57$, $p = .038$, $\eta_p^2 = .16$—though this did not reach significance when compared to a Bonferroni-adjusted significance threshold of .017 (correcting for three comparisons). There was no simple main effect of horizontal lighting direction on mean valence ratings when faces were lit from 45° below, $F(2, 37) = 1.41$, $p = .26$, $\eta_p^2 = .07$. For faces lit from above, post-hoc *t* tests indicated that mean valence ratings were slightly more negative for faces lit from the upper left compared to faces lit from the upper center (mean difference = 0.25, $t(38) = 3.59$, $p < .001$) and slightly more negative for faces lit from the upper right compared to faces lit from the upper center (mean difference = 0.36, $t(38) = 4.44$, $p < .001$). Mean valence ratings did not differ significantly between faces lit from the upper left and upper right (mean difference = 0.12, $t(38) = 2.34$, $p = .03$) when compared to a Bonferroni-adjusted threshold of .017 (correcting for three comparisons). This indicates that horizontally noncentral illumination tends to make a facial expression appear more negatively valenced when the position of the light source is overhead, more so than when the face is illuminated from below (for which neutral faces are perceived with more negative valence across horizontal angles of illumination).

Arousal Ratings

The perceived emotional arousal of the faces also depended on the angle of illumination. As depicted in Figure 2d, faces were perceived as having slightly greater emotional arousal when lit from below. This trend was reflected in a main effect of vertical lighting direction on arousal ratings, $F(2, 78) = 6.54$, $p = .002$, $\eta_p^2 = .14$. Post-hoc *t* tests indicated that perceived arousal was significantly higher for faces lit from below compared to faces lit from above, $t(39) = 3.3$, $p = .002$. Given that the arousal scale varied from 1 = *very relaxed* to 9 = *very stimulated* (with no midpoint label), this result indicates that faces with neutral expression tend to appear slightly more stimulated (or agitated, etc.) when lit from below. Perceived arousal did not differ significantly on average between faces lit from below and faces lit from in front, $t(39) = 2.17$, $p = .036$, nor between faces lit from above and faces lit from in front $t(39) = 1.33$, $p = .192$, when compared to a Bonferroni-adjusted significance threshold of .017 (correcting for three comparisons). The main effect of horizontal lighting direction on arousal ratings was not significant $F(2, 78) = 2.13$, $p = .13$, $\eta_p^2 = .05$, nor was the interaction between horizontal and vertical lighting direction, $F(4, 156) = 0.59$, $p = .67$, $\eta_p^2 = .02$.

Experiment 2

In Experiment 1, we found that faces with a neutral expression tend to be perceived with negative emotional valence and greater emotional arousal when illuminated from below. The dependent measures that were used (valence and arousal) were chosen partly, because (a) they do not require making an assumption about the category of expressions that an observer might perceive, and (b) they may be sensitive to changes in the (perceived) emotional complexion of a face that are not easy for an observer to categorize or label. Experiment 2 builds on this by investigating the categorization of facial expressions across lighting directions and by testing whether the perception of emotional facial expressions (rather than just neutral expressions) is influenced by the lighting direction. In this regard, our informal observations suggest that emotional facial expressions can appear distorted when lit from below (Figure 3).

Experiment 2 employed two tasks: an emotion categorization task and a valence rating task. The emotion categorization task was included to test whether accuracy in identifying the emotional expression of a face varied depending on the illumination direction. Moreover, this task gave insight into the type of errors that observers made (e.g., whether the perception of faces lit from below trended toward a specific type of facial expression). The valence ratings task was included partly so that changes in perceived valence associated with illumination direction could be compared in their magnitude to changes in valence that occur when there is a (real) change in facial expression. The valence ratings task was also included to test for changes in the perception of emotional expressions that may be perceptually salient but insufficient to cause errors in categorization.

Method

Participants

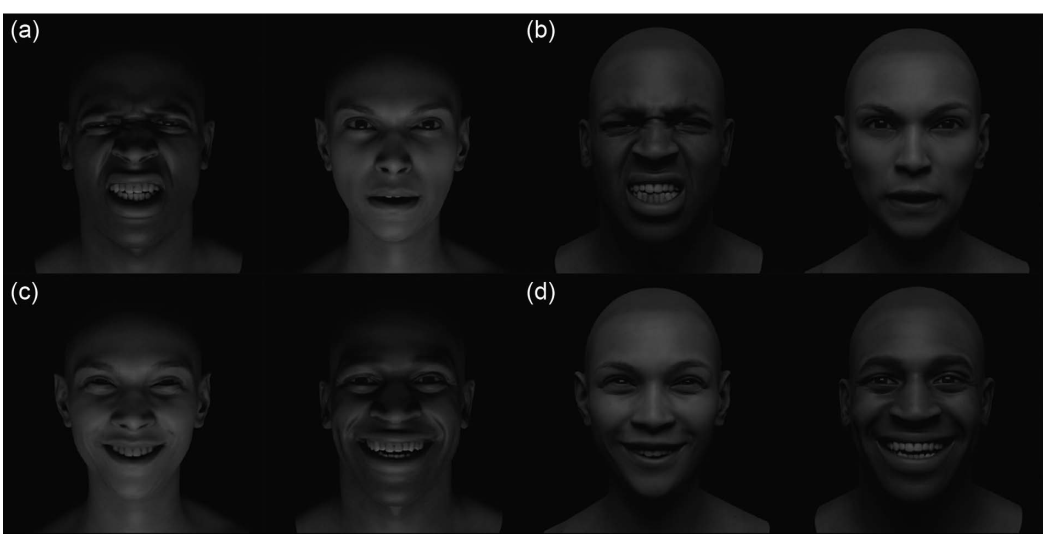
The sample for this study included 41 university students, with a mean age of 19.7 years (*SD* = 3.1 years; range = 17–34 years). The sample included 32 females and nine males. Thirty-seven participants were right-handed, and four were left-handed. Participants were recruited through a university platform for undergraduate students or word of mouth. Each participant gave informed consent and methods of data collection were approved by an ethics committee at the University of New South Wales (Human Research Ethics Advisory Panel C: Behavioural Sciences). The target sample size was chosen prior to data collection for consistency with Experiment 1. No participants were excluded, but one participant's data were not saved correctly for the categorization task, thus the sample size used in the analysis was 41 for the valence rating task and 40 for the categorization task.

Design

The two computer-based tasks each utilized a 2 × 7 within-subjects design. In each task, participants were presented with a set of faces under different illumination conditions and asked to either rate the emotional expression of each face in terms of perceived valence or categorize the facial expression according to the emotion label that best represented it. In both tasks, the independent variables were vertical lighting direction (45° above or 45° below the face)

Figure 3

Expressive Faces Lit From Above and Below



Note. The top row of the figure depicts two faces posed to display an angry expression illuminated by a light source positioned either 45° below the face (a) or 45° above the face (b). The bottom row of the figure depicts two faces posed to display a happy expression lit from either below (c) or above (d). The reader may find that the facial expressions appear distorted when lit from below.

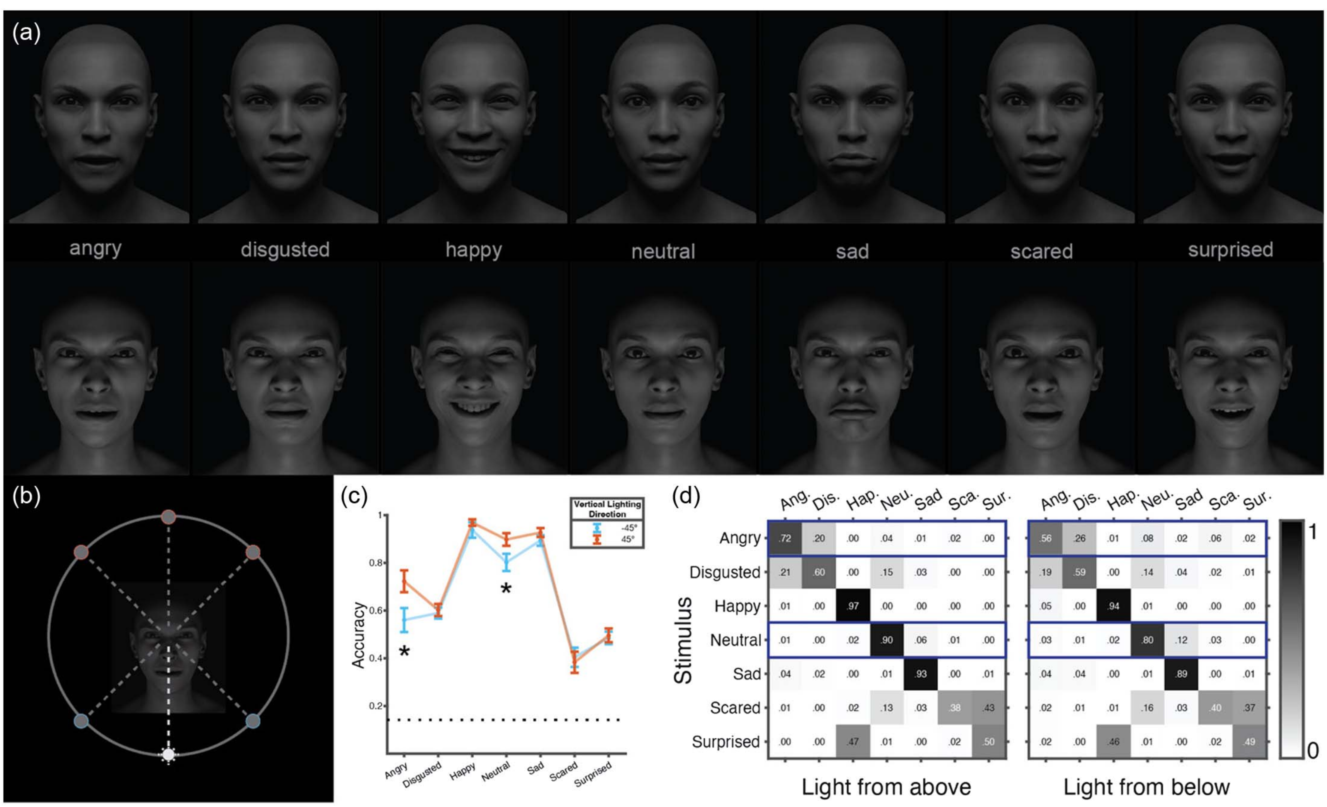
and stimulus emotion category (happy, sad, angry, scared, disgusted, surprised, and neutral). The dependent variables were the mean valence ratings and categorization accuracy, calculated as the proportion of trials in each stimulus emotion category for which the participant gave the correct response.

Stimuli

The stimuli were computer generated images of faces of two new identities, produced using similar methods as Experiment 1 (Figure 4a). The two identities were one man and one woman, each scanned to create a 3D model of their face shape while being asked to display seven facial expressions: happy, sad, angry, fearful, disgusted, surprised, and neutral. These seven expressions were selected to reflect Ekman's taxonomy of basic emotions (Ekman, 1992; Ekman & Cordaro, 2011). Neutral expressions were included to test whether the influence of lighting direction on the visual appearance of a neutrally composed face is sufficient to produce the impression of a well-defined facial expression. The face models were produced by the 3D scanning company, Ten24. We rendered the face models under controlled lighting conditions using Blender, with a similar rendering setup as described for Experiment 1.

The face models were rendered under six illumination conditions varying in the horizontal and vertical angle of the light source relative to the face (Figure 4b). To accommodate the seven categories of facial expression used for each face model while keeping the task to a practical duration, we reduced the number of lighting directions that were included in the analysis compared to Experiment 1. Given that the most pronounced difference in perceived expression in Experiment 1 occurred between faces lit from above and below, we designed Experiment 2 to focus on this comparison. The vertical angle of the light source was either 45° above or below the face. For each vertical angle of illumination, we included three horizontal angles of illumination (−45°, 0°, and 45°) in our image set but performed no

Figure 4
Face Images and Results for Experiment 2



Note. (a) Face models for a single identity with varying expression. Each face is rendered under the illumination of a light source positioned 45° above the face (top row) or 45° below the face (bottom row). (b) The full image set included six lighting conditions, varying in the horizontal and vertical angle of the light source relative to the face. (c) Accuracy in categorizing certain facial expressions is reduced when lit from below compared to when lit from above. The dotted line indicates chance performance for the 7AFC task. Error bars indicate ±1 SEM. (d) Response matrices illustrating the errors in categorization that participants tended to make for each expression type, separately for faces lit from above and faces lit from below. The rows indicate the facial expressions of the stimuli, while the columns indicate the response options that participants selected between. The mean proportion of each response type across participants is shown in each cell, indicated by the listed values and cell shading. Values on the diagonal correspond to accuracy, while off-diagonal cells indicate errors. The blue rectangles highlight response proportions for facial expressions that were associated with significantly lower categorization accuracy when lit from below. SEM = standard error of the mean. See the online article for the color version of this figure.
* $p < .007$ (adjusted threshold).

analyses to compare across these. Rather, different horizontal angles of illumination were included, like the different identities, for the sake of variety in the image set and to avoid limiting the stimuli to a specific horizontal lighting angle that is chosen arbitrarily. Thus, the trials within each vertical lighting condition consisted of face stimuli that varied in appearance due to their identity and horizontal lighting angle but were all consistent in the vertical angle of lighting.

There were 84 images rendered in total: two identities, six angles of illumination, and seven emotional expressions. These images were presented in both the emotion categorization task and the valence rating task. Each image was presented twice in each task for a total of 168 trials. This results in 12 trials per emotion category and vertical lighting condition. In the emotion categorization task, we included an additional 24 trials, which were images of the six identities with neutral facial expression used in Experiment 1, lit from above or below (with central lighting in the horizontal axis), with each image presented twice. These stimuli were included as a supplementary test of whether the shift in perceived valence away from neutral for the set of identities observed in Experiment 1 when lit from below was sufficient to cause their facial expression to be miscategorized.

Procedure

Experiment 2 followed a similar procedure to Experiment 1. The experiment consisted of two main tasks in which the faces were presented on screen at approximately life size, subtending a visual angle of 18° width and 24° height on average under the testing conditions of 50 cm viewing distance. In the valence task, participants were asked to determine whether each face presented bore an emotional facial expression with more positive or negative valence, by rating the face on a 9-point Likert scale ranging from *very negative* (1) to *neutral* (5) to *very positive* (9). In the categorization task, participants were asked to categorize the emotional expression of the faces by selecting from a list of seven categories of emotional expression: happy, sad, angry, disgusted, scared, surprised, and neutral. The order of category labels presented on screen differed randomly between participants. While there is a limitation in restricting participants' responses to a set of seven categories, these categories are each thought to represent families of related states (e.g., variations of anger) that are relatively universal and distinguishable in their physical expression (Ekman & Cordaro, 2011); thus, we expected the 7AFC task to capture a significant range of variation in the facial expressions that participants are likely to perceive. This point is returned to in the Discussion section.

For both tasks, participants underwent 10 practice trials before undertaking the main task. In each trial, participants were presented with a fixation cross for 1 s before the presentation of a face, which was presented for 2 s, followed by either the 9-point Likert scale (for the valence task) or the list of seven emotions (for the categorization task). Participants clicked on the corresponding scale number or emotion category to make their response. There was no limit on response time in each trial. Whether the valence or emotional categorization task was given first was counterbalanced across participants, and the order of trials within each task was randomized for each participant.

Statistical Analysis

To analyze the categorization task, we calculated the proportion of accurate responses for each participant across the 12 trials of each stimulus emotion category and each illumination condition. The influence of lighting direction on categorization accuracy was assessed using a 2 × 7 repeated measures ANOVA. To analyze the valence rating task, for each participant, we calculated the mean valence rating across the 12 trials for each emotion category and illumination condition. Mean valence ratings were compared across conditions using a 2 × 7 repeated measures ANOVA. For each ANOVA, the factors were the vertical lighting direction (−45° or 45°) and stimulus emotion category (happy, sad, scared, disgusted, surprised, angry, and neutral). Bonferroni-adjusted thresholds are reported for simple main effects and post-hoc t tests where appropriate to control the type I error rate. Cohen's d for paired samples t tests was calculated as the mean difference divided by the standard deviation of difference scores.

Results

Categorization of Emotional Facial Expressions

Accuracy across the seven categories of facial expressions is shown in Figure 4c. Participants performed well above the chance level of ∼.14 accuracy in all conditions. There was a trend toward lower accuracy when categorizing the emotional expression of faces lit from below, particularly for the face models with angry or neutral facial expressions. To assess the statistical significance of this trend, we compared accuracy in categorizing the seven facial expressions between the two lighting conditions using a 2 × 7 repeated-measures ANOVA. There was a significant main effect of stimulus emotion category—$F(6, 234) = 56.3$, $p < .001$, $\eta_p^2 = .59$—with higher accuracy being apparent for some facial expressions compared to others as illustrated in Figure 4c. Accuracy was also slightly lower on average for faces lit from below (mean accuracy = .67, $SE = .02$) compared to the same faces lit from above (mean accuracy = .71, $SE = .01$), $F(1, 39) = 26.3$, $p < .001$, $\eta_p^2 = .40$. This effect of lighting varied depending on the facial expression of the stimulus, reflected in a significant interaction effect, $F(6, 234) = 6.29$, $p < .001$, $\eta_p^2 = .14$. Simple main effects were computed to compare accuracy across the two lighting conditions for each facial expression separately. These indicated that accuracy was significantly lower for faces lit from below compared to faces lit from above specifically for faces with angry expressions, $F(1, 39) = 22.6$, $p < .001$, $\eta_p^2 = .37$, or neutral expressions, $F(1, 39) = 11.4$, $p = .002$, $\eta_p^2 = .23$. These comparisons were significant compared to a Bonferroni-adjusted threshold of .007 (correcting for seven comparisons), while accuracy did not differ significantly between faces lit from above and below for the other five facial expressions (all $p > .05$).

The categorization errors that participants made are illustrated in Figure 4d, separately for faces lit from above and faces lit from below. The blue rectangles in this figure highlight the type of categorization errors that underlie lower accuracy in recognizing angry and neutral expressions when lit from below. Neutral faces lit from below are most often miscategorized as sad, while angry faces lit from below are most often miscategorized as disgusted. However, the increased errors for faces lit from below are spread somewhat across response categories, particularly toward negative facial expressions (e.g., sadness, scared, angry) for the neutral faces.

In the response matrices presented in Figure 4d, one can also see that there was lower accuracy across lighting conditions in categorizing scared and surprised faces, reflecting a tendency for scared faces to be categorized as surprised, and surprised faces to be categorized as happy. This appears partly to reflect the specific stimuli used, that is, that the "surprised" face models used to generate our image set are posed as "pleasantly surprised" rather than "unpleasantly surprised," for example. However, previous studies with different face stimuli also found categorization errors like those evident in our data, including confusions between fear and surprise (e.g., Jack et al., 2009) and varying accuracy in recognizing different categories of expression (e.g., Schurgin et al., 2014).

Valence Ratings Across Emotional Facial Expressions

The influence of vertical lighting direction on the perceived emotional valence of facial expressions is illustrated in Figure 5. As expected, the perceived emotional valence varied strongly with changes in the (intended) facial expression. Subtler differences in the perceived emotional valence of facial expressions were induced by changes in the vertical lighting direction for faces with angry and neutral expressions.

To test the statistical significance of these trends, a 2 × 7 repeated-measures ANOVA was used to compare mean valence ratings across stimulus facial expressions (angry, disgusted, happy, neutral, sad, scared, surprised) and vertical lighting direction (45° above or below the face). There was a main effect of stimulus facial expression, $F(6, 240) = 577$, $p < .001$, $\eta_p^2 = .94$. As can be seen in Figure 5, the valence ratings varied with the expression of the face in a predictable way, with the mean valence around the "neutral" midpoint of the scale for faces posed with a neutral facial expression, strongly positive valence ratings for faces posed with a "happy" expression, and negative valence ratings for faces posed with "angry," "disgusted," "sad" or "scared" expressions. The "surprised" expressions were also rated as positively valenced on average, that is, these expressions tended to be perceived as "pleasantly surprised" or the like.

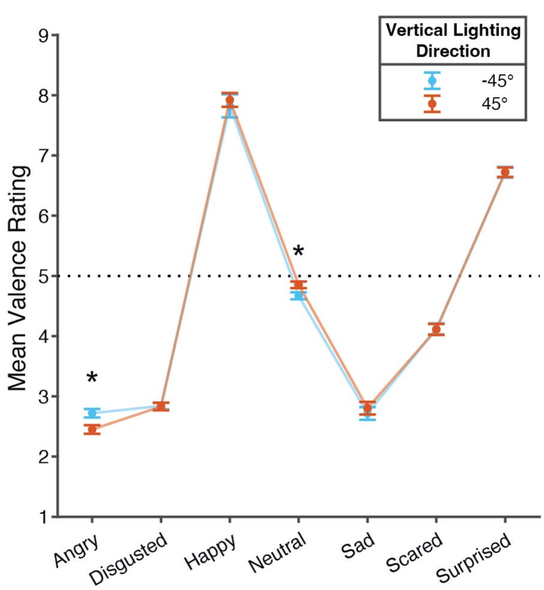
The main effect of vertical lighting direction was not significant, $F(1, 40) = 0.17$, $p = .68$, $\eta_p^2 < .01$. However, there was a significant interaction effect, suggesting that the influence of the vertical lighting direction on perception depended on the (intended) facial expression of the stimulus, $F(6, 240) = 4.51$, $p < .001$, $\eta_p^2 = .10$. To shed light on this interaction effect, simple main effects were computed to compare mean valence ratings across the two lighting conditions for each facial expression separately. Consistent with Experiment 1, the perceived emotional valence of faces with a neutral expression was significantly more negative on average when lit from below compared to when lit from above, $F(1, 40) = 14$, $p < .001$, $\eta_p^2 = .26$, mean difference = −0.2. In contrast, faces with an angry expression were perceived with significantly *less* negative valence when lit from below compared to when lit from above, $F(1, 40) = 23.3$, $p < .001$, $\eta_p^2 = .37$, mean difference = 0.3. Both comparisons survive Bonferroni correction with an adjusted significance threshold of .007 (correcting for seven comparisons). Mean valence ratings did not differ significantly between lighting conditions for faces belonging to the other five stimulus expression categories (all $p > .05$).

These results are consistent with the effect of lighting direction on emotion categorization. The perception of neutral and angry expressions was most sensitive to the lighting direction in both the valence-rating and categorization tasks. The more negative valence rating for neutral faces when lit from below is consistent with the trend toward categorization errors made toward negative expressions (e.g., sad; Figure 4d). The less negative valence rating for angry faces when lit from below is consistent with the trend toward categorizations that participants generally rated as less negatively valenced compared to anger (e.g., disgust).

It is clear from Figure 5 that the effect of changing the vertical lighting direction on mean valence ratings was much smaller in this task than the effect of changing the intended facial expression itself. When using a rating scale, the set of stimuli used in the experiment may help to anchor the endpoints of the scale in the observers' mind. For the current task, the stimuli consisted of a set of distinct expressions posed by human models that are intended to capture a significant range in the variation of human expression (i.e., based on the notion of there being a limited number of distinct families of basic emotions; Ekman, 1992; Ekman & Cordaro, 2011). Clearly, the difference in perceived emotional valence between these basic expressions is much greater than the effect of vertical lighting direction. However, these seven basic categories of expression are of course not capturing the full subtlety of meaningful expressions that we encounter in everyday life. When interacting with another person, a small change in the perceived emotional valence of their expression, whether caused by a small adjustment of the face muscles or a contextual factor like lighting direction, might be meaningful or not to the observer depending on the context. The fact that the small shifts in perceived valence in the current experiment for angry and neutral expressions correspond to a (larger) drop in accuracy in the emotion categorization task for these expressions suggests that the change in

Figure 5

Mean Valence Ratings for Faces With Varying Expressions (Experiment 2)



Note. Faces were rendered under the illumination of a light source positioned 45° above the face or 45° below the face. The dotted line indicates the point of "neutral" valence on the scale, while a rating of 1 corresponds to "very negative" emotional valence and a rating of 9 corresponds to "very positive" emotional valence. Error bars indicate ±1 SEM. SEM = standard error of the mean. See the online article for the color version of this figure.
* $p < .001$.

appearance of the face due to lighting direction can be meaningful-enough to shift the broad category of emotion that an observer attributes to the face (e.g., the angrily posed expressions were categorized as angry 72% of the time when lit from above but 56% of the time when lit from below, corresponding to a 16% drop in accuracy caused only by a shift in the vertical angle of lighting from 45° above the face to 45° below; Figure 4c).

Categorization of Neutral Faces

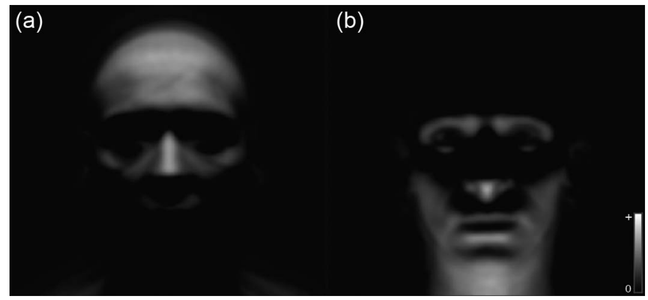
As a supplementary task-within-a-task, the categorization task included a subset of the face images used in Experiment 1. These were six identities that differed from the other faces presented in the categorization task and were presented with neutral facial expressions only. These additional images were analyzed separately from the rest of the task, that is, trials for the "neutral" condition described previously in this section did not include data for these additional face identities. The purpose of including these additional neutral faces was to test whether the shift in perceived emotional valence of facial expressions away from neutral for the set of identities observed in Experiment 1 when lit from below was sufficient to cause their facial expression to be miscategorized. For this set of identities with neutral face expression, the accuracy of categorization judgments was similar when the faces were lit from below (mean accuracy = .67, SD = .21), compared to when lit from above (mean accuracy = .69, SD = .19), $t(39) = 0.59$, $p = .56$, Cohen's $d = 0.09$. We also compared whether the proportion of each response type in the categorization task for these neutral faces varied across lighting conditions using a 2 × 7 repeated-measures ANOVA. There was a significant interaction effect in the ANOVA, $F(6, 234) = 2.51$, $p = .022$, $\eta_p^2 = .06$. Simple main effects were computed to compare the proportion of responses for the neutral faces across the two lighting conditions for each response type separately. There was a significant difference between lighting conditions for only one response type: Neutral faces lit from above were more often judged as happy when lit from above (mean proportion = .05, SD = .08) compared to when lit from below (mean proportion = .002, SD = .01), $F(1, 39) = 14.4$, $p < .001$, $\eta_p^2 = .27$. In other words, the neutral faces were miscategorized as happy in ~5% more trials on average for faces lit from above. This aligns with the tendency for these same faces to be judged as having a more negatively valenced facial expression when lit from below compared to when lit from above (Experiment 1). This comparison survived Bonferroni correction with an adjusted significance threshold of .007 (correcting for seven comparisons), while the proportion of all other response types did not differ significantly between the two lighting conditions for the neutral faces (all $p > .05$).

Image Analysis

Visualizing the Influence of Vertical Lighting Direction on Facial Appearance. Figure 6 provides a visual summary of how luminance is distributed differently across the face images when the models are lit from above compared to when lit from below. These images were created by averaging the face images with neutral expression used in Experiments 1–2 to capture differences in appearance caused by the vertical lighting direction that were consistent across identities and horizontal lighting directions. The images were averaged separately for faces lit from 45° above and 45° below. The mean pixel intensities in each image set were smoothed with a 2D Gaussian filter (SD = 5 pixels), then subtracted across the lighting conditions to visualize the areas of the face exhibiting greater luminance when lit from above compared to when lit from below (Figure 6a) and the regions of the face exhibiting greater luminance when lit from below compared to when lit from above (Figure 6b). For faces lit from above, greater luminance tends to occur across the forehead, nose, and upper cheeks. For faces lit from below, greater luminance tends to occur across the lower surface of the brow (above the eyes), the upper sclera, the bottom of the nose, and the lower lip. Note that the image sets used in the present study are particularly suitable for averaging because they were produced in a controlled rendering environment. Across the comparison between lighting directions, the images were generated using the identical position and 3D shape of the faces, strength of lighting, reflectance properties, and (virtual) camera perspective. The identities differed in face morphology, but the interocular distance and position of the eyes in the 3D environment were closely matched between identities, such that there was consistency in the position of face features across images.

Figure 6

Image Analysis Summarizing the Varying Distribution of Luminance When Face Models Are Illuminated by a Light Source Positioned 45° Above or Below Eye Level

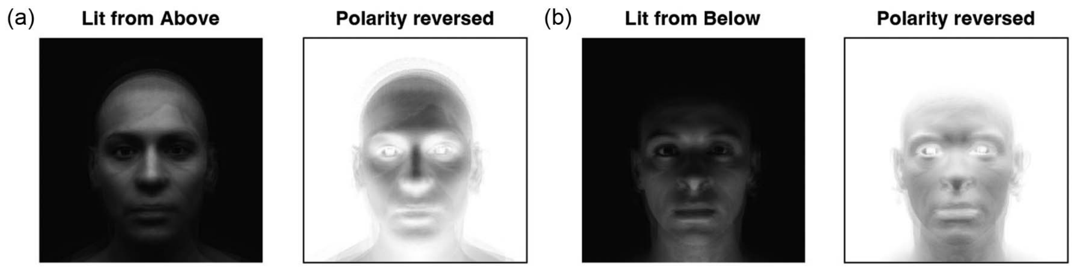


Note. (a) Regions exhibiting greater intensity on average when the faces are lit from above compared to when lit from below. (b) Regions exhibiting greater intensity on average when the faces are lit from below compared to when lit from above. Note that these images represent differences between lighting conditions rather than the appearance of faces in either lighting condition per se.

As noted in the introduction, the effect of varying the illumination direction of a face from above to below is comparable in some respects to reversing the contrast polarity of the image. This is visualized in Figure 7, which presents averaged face images lit from 45° above or below eye level, together with polarity-reversed images. If one compares the (original) images lit from below to images lit from above then polarity-reversed, there are similarities in the distribution of luminance across the face. For example, lighter regions tend to occur below the nose and the underside of the brows in both types of images, while darker regions tend to occur on top of the nose and above the brow. However, there are also notable differences. For example, features of the face that have lower reflectance due to their differing material properties compared to the surrounding skin (e.g., irises, eyebrows) appear dark when lit from either above or below but appear light in polarity-reversed images.

Figure 7

Reversing the Contrast Polarity of Face Images When Lit From Above and Below

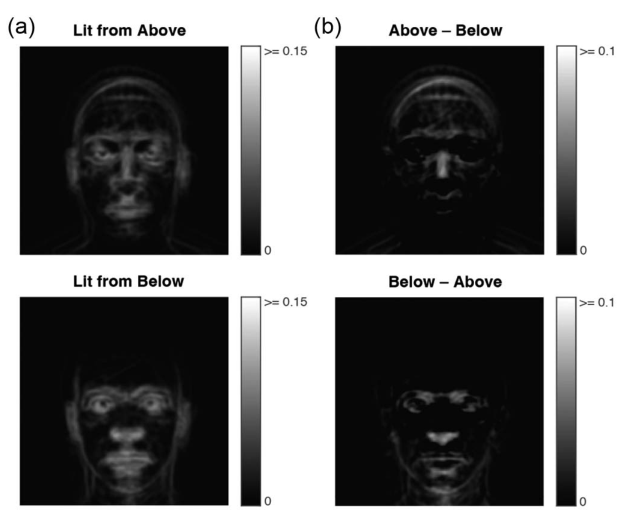


Note. (a) The summary image on the left illustrates the mean pixel intensities when face models were illuminated by a light source positioned 45° above eye level. On the right is the same for images with inverted pixel intensity, such that the lightest parts of the original image become the darkest and vice versa. (b) Summary images for face models illuminated by a light source positioned 45° below eye level, with original and inverted pixel intensities. These summary images were created using face images with neutral expression from Experiment 1 and 2 that varied in identity and horizontal lighting direction. Prior to averaging, pixel intensities for each face image were rescaled to a proportion of the maximum intensity in the image.

Unlike contrast polarity reversal, varying the vertical lighting direction also alters the structure of edges in the face images. To visualize this, we extracted edges in the face images with neutral expression from Experiment 1 and 2, averaging across images that varied in identity and horizontal lighting direction. Pixel intensities in each image were smoothed with a 2D Gaussian filter ($SD = 3$ pixels), then the location of edges in each image was determined using the Sobel method implemented in MATLAB. Summary images for faces lit from above and below are shown in Figure 8. By comparing the two images in Panel a, one can see that the density of edges that tends to occur around the eye region, nose, and mouth depends on the vertical lighting direction. For example, greater edge density tends to occur around the upper portion of the eyes when faces are lit from below compared to when lit from above (illustrated further in the subtraction images presented in Panel b). Similar to the varying distribution of luminance across the face illustrated in Figure 6, this edge analysis highlights how changes in the appearance of the eye region are a plausible explanation for the effect of vertical lighting direction on the perception of facial expression.

Figure 8

Image Analysis Summarizing the Density of Edges in the Face Images When Face Models Were Illuminated by a Light Source Positioned 45° Above or Below Eye Level



Note. The summary images in (a) illustrate the proportion of face images containing an edge for each pixel, computed separately for faces lit from 45° above and 45° below, and smoothed with a 2D Gaussian filter ($SD = 5$ pixels). In (b), these summary images have been subtracted across lighting conditions to visualize areas of the face that have greater edge density when lit from above compared to when lit from below or vice versa.

Image Statistics Across Lighting Directions. Changes in lighting direction can alter the brightness and contrast of faces. For example, in Figure 2a, one can see that the central illumination (0°, 0°) produces relatively uniform luminance across the face, while the noncentral illumination produces greater luminance contrast across the face and across individual face features. As noted above, the consistency of the rendering environment across lighting conditions means that any differences in the contrast or mean luminance of the face images result naturalistically from the change in lighting direction. One might wonder, however, whether differences in the perceived emotional valence of facial expressions observed in Experiment 1 vary together with changes in image contrast produced by the lighting angle. Supplemental Figure S2 illustrates the mean luminance and contrast of faces images presented in Experiment 1. One can see that contrast is lowest on average when faces are lit centrally (0°, 0°) but differs little between faces when lit from above versus below (red and blue lines; Supplemental Figure S2c). The difference in perceived valence across vertical lighting conditions illustrated in Figure 2c is therefore difficult to explain in terms of the overall contrast of the face images. Another effect of lighting angle on perceived valence observed in Experiment 1 was slightly more negative valence ratings for faces lit from the left or right compared to faces lit centrally in the horizontal axis. This effect of horizontal lighting direction was observed for faces lit from above but not for faces lit from below (Figure 2c). While the contrast of face images tends to be lower when faces are lit centrally in the horizontal axis compared to when lit from the left or right (e.g., Figure 2a, comparing across columns), the magnitude of this change varied between the vertical lighting conditions (Supplemental Figure S2c) in a way that does not correspond well with the contrasting effects of horizontal lighting on perceived valence across each vertical lighting direction.

Discussion

These experiments show that the pattern of illumination that falls across a person's face can influence a viewer's sense of their emotional state. In Experiment 1, we found that faces with neutral expressions appear to bear an expression that is negatively valenced and more highly stimulated when lit from below. This indicates an illusion of expression where none really exists, occurring most prominently when faces are lit from a (putatively) less familiar angle. The perceived emotional valence of facial expressions also varied with asymmetries in lighting along the horizontal axis of the face, though to a lesser extent compared to the vertical axis. In principle, changes in the (apparent) emotional complexion of a face might be perceptually salient without aligning with any well-defined category of emotion. For example, the happily posed faces pictured in Figure 3c and 3d may look rather ghoulish when lit from below while still appearing part of the same broad family of facial expressions as when lit from above. Nevertheless, in Experiment 2, we found that differences in the appearance of a face lit from above and below can be sufficient to shift how observers categorize its facial expression among basic emotion groupings, specifically when posed to display an angry or neutral facial expression.

Why Does Illumination Influence the Perception of Face Expression?

Previous empirical research has illustrated the increased familiarity that observers tend to display with faces lit from above, reflected primarily in face identification performance (e.g., Hill & Bruce, 1996; Johnston et al., 1992) and face detection (e.g., C. J. Palmer et al., 2022; Stein et al., 2011). It is well known that the perception of shape from shading can be influenced by an apparent assumption for overhead lighting (e.g., Ramachandran, 1988; Sun & Perona, 1998), suggesting that the accuracy at which an observer perceives the structural configuration of a face may be susceptible to how well the veridical lighting direction matches with that assumption. The results of the present study go beyond these observations by revealing specific effects of lighting direction on perceived facial expression, including the induction of perceived emotional expression in neutrally composed faces lit from below and a reduced ability of observers to identify the intended meaning of certain expressions when lit from below. This indicates an interaction between the changes in facial appearance that occur across lighting directions and the visual cues that underlie face expression recognition (which necessarily vary in part from those used for face detection and identification; Tsao & Livingstone, 2008).

The visual cues underlying expression recognition in humans can be described at various levels of analysis, including as visible configurations of facial actions (Ekman et al., 2002) or image-based landmark and textural cues (Sormaz et al., 2016; Young, 2021). Here, it is useful to delineate between visual features that result from the interaction between 3D shape and lighting direction (namely, shading gradients, shadows, and specular highlights) and features related to the reflectance properties of the face (i.e., the visual patterns caused by the sclera, eyebrows, and skin reflecting light to differing extent due to their different material properties). Both factors change with facial expression. For example, raising the eyebrows can both expose more high-reflectance sclera to an observer and alter the pattern of shading across the facial surface due to the change in geometry. The visual system faces a fundamental challenge in determining the combination of surface geometry, reflectance, and illumination that explains the pattern of light falling on the retina; the current results indicate that these perceptual inferences can vary sufficiently with the (veridical) lighting direction to impact the identification of facial expressions.

Figure 6 provides a visual summary of how the vertical lighting direction tends to alter the appearance of the human face. Lighting a face from above increases luminance across the forehead, cheekbones, and nose. Lighting a face from below tends to highlight the sclera and the underside of the brow, nose, and lips. Changes in vertical lighting direction also alter the edge information present around the eye region, nose, and mouth (Figure 8). The changes in appearance of the sclera and brows in particular can help to explain why neutral faces appear more negatively valenced (and more stimulated) when lit from below, as they align with featural characteristics that define emotions such as anger, fear, and surprise (i.e., exposed sclera, raised eyebrows; Ekman, 1992; Ekman et al., 2002). For example, when we express fear, we tend to widen our eyes, exposing more of the sclera (eye whites) to those around us. Correspondingly, the exposed sclera serves as a salient cue to fear in others, even when presented as a visual cue in isolation from the rest of the face (Whalen et al., 2004). The perception of fear does not typically rely on the scleral cue alone, however, but also draws on other face features (Asghar et al., 2008), and hence, the effect of highlighting the sclera (e.g., by lighting a face from below) is likely to depend on the conjunction of this cue with the prevailing state of other face features. Similarly, our data suggest that the impact of vertical lighting direction on the perception of facial expressions depends on the veridical (or intended) expression of the face—for example, neutral expressions appeared more negatively valenced when lit from below, angry expressions appeared slightly more positively valenced on average, while other facial expressions were relatively unaffected. The potential role of the eye and brow region in the results of the present study is also supported by the findings of a computer vision study of illumination tolerance in automated expression classification (Stratou et al., 2011). In their analysis, images of neutral faces increased estimates of an algorithm designed to detect eyebrow movement when lit from below compared to uniform lighting. While the visual cues used by computer vision algorithms for expression recognition may differ from human perception, these results at least suggest that light from below can change the image characteristics of the eyebrow region in a way that partially resembles a change in facial expression. More generally, there is evidence that the eye region is particularly informative for identifying certain negative facial expressions, reflected, for example, in a tendency for observers to fixate the eye region longer (rather than the mouth region) when viewing angry or fearful expressions compared to happy or disgusted expressions, and the varying effects of covering the eye region versus mouth region on categorization accuracy for these expressions (Schurgin et al., 2014).

The changes in shadow and highlights across the face surface that occur when reversing the vertical angle of lighting is similar in some respects to reversing the contrast polarity of an image. As outlined in the introduction, artificially reversing the contrast polarity of face images can significantly disrupt aspects of face processing, particularly face identity recognition (e.g., Bruce & Langton, 1994; Galper, 1970) but also face detection (e.g., Farroni et al., 2005; Stein et al., 2011) and expression recognition (e.g., Benton, 2009; Sormaz et al., 2016). There has been some debate regarding the latter, however, driven in part by findings of weaker effects of contrast reversal on expression recognition compared to face identification (e.g., Harris et al., 2014; White, 2001), together with the view that facial shape information retained in contrast-reversed images is likely to be a dominant visual cue to facial expression (discussed in Young & Bruce, 2024). However, there are also notable differences in the effect of vertical lighting direction on the visual appearance of faces compared to contrast polarity reversal. For example, features of the face that have lower reflectance due to their differing material properties compared to the surrounding skin (e.g., irises, eyebrows) appear dark when lit from either above or below but appear light in polarity-reversed images (Figure 7). Similarly, while reversing the contrast polarity of an image maintains the spatial configuration of edges in the image, the presence of edges can be altered when reversing the vertical angle of illumination, including around the eyes, nose, and mouth (Figure 8). It is also worth noting that faces are rarely if ever viewed with reversed contrast polarity in natural environments, whereas variability in the direction of illumination is intrinsic to the everyday visual experience of faces. In this sense, our greater familiarity with faces lit from above is statistical rather than absolute, and the influence of lighting direction of the perception of expression that we report here is one that persists despite the opportunity for evolution and development to furnish the visual system with mechanisms for dealing with this naturalistic source of stimulus variability. Interestingly, one explanation offered for how photographic negation impacts face perception is by disrupting ordinal contrast relationships across specific face features (Gilad et al., 2009). There is evidence, for example, that face identification relies partly on local brightness differences around the eye region (Gilad et al., 2009) and that face-selective neurons in the primate visual system are sensitive to simple contrast relationships between select regions of the face (Ohayon et al., 2012). Thus, at a mechanistic level, the detection and analysis of faces may rely partly on the visual system matching local contrast patterns to internal templates characteristic of a face. If these internal templates are shaped by the lighting statistics of natural environments (e.g., the tendency for faces lit from above to exhibit darker regions around the eye sockets, lighter regions above the brow; C. J. Palmer et al., 2022), this may be another mechanism through which directional lighting can impact on processes like expression recognition.

Varying Effects of Illumination Direction on the Perception of Different Facial Expressions

Experiment 2 tested the effect of vertical lighting direction on the perception of facial expressions across seven basic categories. A drop in the accuracy of expression categorization (relative to the intended expression) was found specifically for angry and neutral expressions when these faces were lit from below compared to when lit from above. In contrast, categorization accuracy did not vary with the vertical lighting direction for the other basic expressions tested (e.g., disgust, fear, etc.). The same pattern of results was found in a separate task in which participants rated the emotional valence of facial expressions, with differences in perceived emotional valence of faces across vertical lighting directions occurring specifically for angry and neutral facial expressions but not the other expressions tested.

Why are some facial expressions more susceptible than others to the effects of lighting direction on the visual appearance of the face? One possibility is that facial signals differ in how clear they are for an observer to interpret, with more ambiguous facial expressions being more susceptible to misinterpretation due to contextual factors like lighting direction. However, we saw little evidence of this in the present experiments, as the facial expressions influenced most by the vertical lighting direction (angry and neutral expressions) were among the more-accurately categorized expressions when lit from above (Figure 4c). A better explanation may be the relative dependence of these expressions on signals transmitted by different regions of the face. For example, happy and sad expressions in our image set entail distinct changes in the configuration of the mouth, more so than some other expressions (Figure 4). As noted earlier, while facial expressions are holistic in nature, there is evidence that the most diagnostic features of the face vary between different categories of expression. For example, Schurgin et al. (2014) find that the duration of fixations to the eye region versus the mouth vary depending on the facial expression viewed, with more time spent fixating the eyes when viewing certain negative expression like anger and fear, or when observers are viewing neutral faces but tasked with identifying the presence or absence of these specific emotions. In contrast, happy and disgusted facial expressions tended to draw visual attention toward the mouth rather than the eyes. Correspondingly, Schurgin and colleagues also found differences in the accuracy of expression categorization when the eye region or the mouth were occluded, with the identification of angry expressions relying more on visibility of the eyes, while the identification of happy or disgusted expressions relied more on visibility of the mouth. Smith et al. (2005) found comparable evidence about the role of the eyes versus the mouth in signaling different expressions by using a windowing technique to vary the visibility of different face features while measuring expression categorization. If the effects of light from below on the perception of facial expressions is mediated in significant part by changes in the appearance of the eye region (as discussed above), this may help to explain why the perception of angry expressions is more susceptible to these effects compared to the perception of expressions that may rely more on signals from the mouth like happiness and disgust. While there is evidence that detecting fearful expressions also relies on the eye region, the eye region cues related to fear may be enhanced by light from below rather than disrupted, as noted in the previous section.

It is also worth highlighting that the vertical direction of illumination may alter the perceived shape of face features beyond the eye region. The perception of surface depth across regions of an object can be influenced partly by luminance contrast following a "darker is deeper" heuristic (Hibbard et al., 2023). Interestingly, illuminating a face from above tends to increase the brightness of the upper cheeks compared to faces lit from below, and hence, these may tend to be perceived as more elevated than when lit from below (Figure 6). Given that elevated cheeks are consistent with a smile, this type of effect might also contribute to differences in the perceived emotional valence of facial expressions when seen across different vertical lighting directions. Similarly, there is evidence that lighting direction can influence the perceived 3D orientation of objects like faces. Specifically, under certain conditions, a horizontally offset light source can bias the apparent horizontal orientation of a face away from the position of the light source (Troje & Siebeck, 1998). It seems plausible when considering the faces in Figure 4a that this effect may extend to the vertical axis, namely that lighting a face from above may induce the sense of a slight tilt forward of the head, while lighting from below may induce a sense of a slight tilt backward, and that this in turn could sway an observer's sense of whether a facial expression is conveying anger versus disgust, for example.

The "Light From Above Prior" in High-Level Vision and Contextual Cues to Lighting Direction

Our results are consistent with the notion that human vision is optimized in some respects for the bias toward overhead lighting that characterizes natural environments. It may be that greater exposure to faces lit from overhead has shaped the link between visual signals and perceived expression in a way that is less valid for faces lit unconventionally. (Our results suggest this primarily for faces with neutral or angry expression.) This parallels previous findings that face recognition and detection are facilitated when we see others lit from above (e.g., Hill & Bruce, 1996; C. J. Palmer et al., 2022). In general, perception of surface shape from shading relies partly on an implicit assumption for overhead lighting (Ramachandran, 1988; Sun & Perona, 1998), and hence, perception of face shape may be distorted when there is misalignment between the assumed and veridical lighting of the face. However, the perception of shape from shading is also driven by cues to the lighting direction available in the visual context rather than relying inflexibly on an assumption for light from above (Morgenstern et al., 2011). Recently, we found that perception of another person's gaze direction draws on cues to lighting direction available in the pattern of shading, shadows, and highlights visible across the face; in particular, this allows the observer to (partially) disambiguate luminance changes within the eye region related to lighting direction from those related to eye position (C. J. Palmer et al., 2020). This suggests that biases in perceived expression measured in the present study are those that persist following the action of visual mechanisms that partially compensate for lighting direction when estimating the state of facial features. This raises a question of whether the identification of facial expressions is disturbed further in contexts where cues to lighting direction are scarce or misleading, such as in video calls, in which the local illumination of each participant is likely to mismatch.

Constraints on Generality

The current article investigated the perception of face expressions in two samples of undergraduate students studying at an Australian university. A key debate in the study of emotion concerns whether facial expressions are universal across cultures, both in terms of how emotional states are signaled and how those signals are recognized. The face expressions presented in Experiment 2 were based on the six categories of emotional expression that are often referred to as "basic emotions" due in part to consideration of their biological origins as well as empirical data that partly supports their crosscultural significance (e.g., Ekman & Cordaro, 2011). However, systematic cultural variability in the recognition of these emotion categories has also been observed (Jack, 2013; Nelson & Russell, 2013). For example, in some studies, expressions typically recognized as conveying "fear" and "disgust" by Western Caucasian observers were not as consistently recognized as such by East Asian observers (Jack et al., 2009). Interestingly, such differences in categorization may be explained partly in terms of differences in the face regions that are visually sampled by participants when viewing faces. Hence, while we expect that the conclusions of our experiments may generalize beyond our sample to many other adult populations, future research might profitably examine whether cultural differences in expression recognition lead also to varying effects of environmental factors (e.g., lighting direction) on perception. Similarly, while the face images used in the present experiments varied in appearance (e.g., in the apparent gender and ethnicity of the face), further research would be needed to determine whether individual differences in facial appearance can render a particular person's face more robust (vs. susceptible) to variations in lighting direction, in terms of how others interpret their facial expression.

Conclusion

Illumination is a source of variability in facial appearance that is not only a challenge for computer vision but also appears to systematically influence facial expression recognition in human observers. Future research might investigate the interaction of lighting direction with individual differences in face shape, dynamic and spontaneous facial expressions, and other social judgments (e.g., dominance; Mattavelli et al., 2022). Our results also raise a question of identifying visual mechanisms that facilitate illumination tolerance (e.g., Jiang et al., 2009) in the relatively fine-grained featural distinctions that underlie the perception of facial expression.

References

Adini, Y., Moses, Y., & Ullman, S. (1997). Face recognition: The problem of compensating for changes in illumination direction. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *19*(7), 721–732. https://doi.org/10.1109/34.598229

Asghar, A. U., Chiu, Y. C., Hallam, G., Liu, S., Mole, H., Wright, H., & Young, A. W. (2008). An amygdala response to fearful faces with covered eyes. *Neuropsychologia*, *46*(9), 2364–2370. https://doi.org/10.1016/j.neuropsychologia.2008.03.015

Aviezer, H., Trope, Y., & Todorov, A. (2012). Body cues, not facial expressions, discriminate between intense positive and negative emotions. *Science*, *338*(6111), 1225–1229. https://doi.org/10.1126/science.1224313

Benton, C. P. (2009). Effect of photographic negation on face expression aftereffects. *Perception*, *38*(9), 1267–1274. https://doi.org/10.1068/p6468

Bliss-Moreau, E., Williams, L. A., & Santistevan, A. C. (2020). The immutability of valence and arousal in the foundation of emotion. *Emotion*, *20*(6), 993–1004. https://doi.org/10.1037/emo0000606

Bruce, V., & Langton, S. (1994). The use of pigmentation and shading information in recognising the sex and identities of faces. *Perception*, *23*(7), 803–822. https://doi.org/10.1068/p230803

Dror, R. O., Willsky, A. S., & Adelson, E. H. (2004). Statistical characterization of real-world illumination. *Journal of Vision*, *4*(9), Article 11. https://doi.org/10.1167/4.9.11

Ekman, P. (1979). About brows: Emotional and conversational signals. In M. von Cranach, K. Foppa, W. Lepenies, & D. Ploog (Eds.), *Human ethology* (pp. 169–248). Cambridge University Press.

Ekman, P. (1992). An argument for basic emotions. *Cognition and Emotion*, *6*(3–4), 169–200. https://doi.org/10.1080/02699939208411068

Ekman, P., & Cordaro, D. (2011). What is meant by calling emotions basic. *Emotion Review*, *3*(4), 364–370. https://doi.org/10.1177/1754073911410740

Ekman, P., Friesen, W. V., & Hager, J. C. (2002). *The facial action coding system: A technique for the measurement of facial movement*. Consulting Psychologists Press.

Farroni, T., Johnson, M. H., Menon, E., Zulian, L., Faraguna, D., & Csibra, G. (2005). Newborns' preference for face-relevant stimuli: Effects of contrast polarity. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(47), 17245–17250. https://doi.org/10.1073/pnas.0502205102

Fesharaki, H., Rezaei, L., Farrahi, F., Banihashem, T., & Jahanbkhshi, A. (2012). Normal interpupillary distance values in an Iranian population. *Journal of Ophthalmic & Vision Research*, *7*(3), 231–234.

Galper, R. E. (1970). Recognition of faces in photographic negative. *Psychonomic Science*, *19*(4), 207–208. https://doi.org/10.3758/BF03328777

Gilad, S., Meng, M., & Sinha, P. (2009). Role of ordinal contrast relationships in face encoding. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(13), 5353–5358. https://doi.org/10.1073/pnas.0812396106

Grodal, T. (2005). Film lighting and mood. In J. D. Anderson & B. F. Anderson (Eds.), *Moving image theory: Ecological considerations* (pp. 152–163). Southern Illinois University Press.

Harris, R. J., Young, A. W., & Andrews, T. J. (2014). Brain regions involved in processing facial identity and expression are differentially selective for surface and edge information. *NeuroImage*, *97*, 217–223. https://doi.org/10.1016/j.neuroimage.2014.04.032

Hibbard, P. B., Goutcher, R., Hornsey, R. L., Hunter, D. W., & Scarfe, P. (2023). Luminance contrast provides metric depth information. *Royal Society Open Science*, *10*(2), Article 220567. https://doi.org/10.1098/rsos.220567

Hill, H., & Bruce, V. (1996). Effects of lighting on the perception of facial surfaces. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(4), 986–1004. https://doi.org/10.1037//0096-1523.22.4.986

Jack, R. E. (2013). Culture and facial expressions of emotion, *Visual Cognition*, *21*(9–10), 1248–1286. https://doi.org/10.1080/13506285.2013.835367

Jack, R. E., Blais, C., Scheepers, C., Schyns, P. G., & Caldara, R. (2009). Cultural confusions show that facial expressions are not universal. *Current Biology*, *19*(18), 1543–1548. https://doi.org/10.1016/j.cub.2009.07.051

Jenkins, R., White, D., Van Montfort, X., & Mike Burton, A. (2011). Variability in photos of the same face. *Cognition*, *121*(3), 313–323. https://doi.org/10.1016/j.cognition.2011.08.001

Jiang, F., Blanz, V., & O'Toole, A. J. (2009). Three-dimensional information in face representations revealed by identity aftereffects. *Psychological Science*, *20*(3), 318–325. https://doi.org/10.1111/j.1467-9280.2009.02285.x

Johnston, A., Hill, H., & Carman, N. (1992). Recognising faces: Effects of lighting direction, inversion, and brightness reversal. *Perception*, *21*(3), 365–375. https://doi.org/10.1068/p210365

Kawai, N., Miyata, H., Nishimura, R., & Okanoya, K. (2013). Shadows alter facial expressions of Noh masks. *PLOS ONE*, *8*(8), Article e71389. https://doi.org/10.1371/journal.pone.0071389

Mattavelli, G., Gorrino, I., Cesana, E., De Angelis, J., & Ricciardelli, P. (2022). Illumination and gaze effects on face evaluation: The Bi-AGI database. *Frontiers in Psychology*, *13*, Article 948142. https://doi.org/10.3389/fpsyg.2022.948142

Mauss, I. B., & Robinson, M. D. (2009). Measures of emotion: A review. *Cognition and Emotion*, *23*(2), 209–237. https://doi.org/10.1080/02699930802204677

Morgenstern, Y., Murray, R. F., & Harris, L. R. (2011). The human visual system's assumption that light comes from above is weak. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(30), 12551–12553. https://doi.org/10.1073/pnas.1100794108

Nelson, N. L., & Russell, J. A. (2013). Universality revisited. *Emotion Review*, *5*(1), 8–15. https://doi.org/10.1177/1754073912457227

O'Toole, A. J., Castillo, C. D., Parde, C. J., Hill, M. Q., & Chellappa, R. (2018). Face space representations in deep convolutional neural networks. *Trends in Cognitive Sciences*, *22*(9), 794–809. https://doi.org/10.1016/j.tics.2018.06.006

Ohayon, S., Freiwald, W. A., & Tsao, D. Y. (2012). What makes a cell face selective? The importance of contrast. *Neuron*, *74*(3), 567–581. https://doi.org/10.1016/j.neuron.2012.03.024

Palmer, C. J. (2024). *Supporting data for "Illusory facial expressions caused by lighting direction"*. https://osf.io/rc7qf

Palmer, C. J., Goddard, E., & Clifford, C. W. G. (2022). Face detection from patterns of shading and shadows: The role of overhead illumination in generating the familiar appearance of the human face. *Cognition*, *225*, Article 105172. https://doi.org/10.1016/j.cognition.2022.105172

Palmer, C. J., Otsuka, Y., & Clifford, C. W. G. (2020). A sparkle in the eye: Illumination cues and lightness constancy in the perception of eye contact. *Cognition*, *205*, Article 104419. https://doi.org/10.1016/j.cognition.2020.104419

Palmer, R. H. (1994). *The lighting art: The aesthetics of stage lighting design* (2nd ed.). Prentice-Hall.

Ramachandran, V. S. (1988). Perception of shape from shading. *Nature*, *331*(6152), 163–166. https://doi.org/10.1038/331163a0

Røysamb, A., van der Kleij, B., Bhusal, P., & Pont, S. (2022). Context-robust influences of illumination on perceived friendliness of faces. *Journal of Vision*, *22*(14), Article 3724. https://doi.org/10.1167/jov.22.14.3724

Schurgin, M. W., Nelson, J., Iida, S., Ohira, H., Chiao, J. Y., & Franconeri, S. L. (2014). Eye movements during emotion recognition in faces. *Journal of Vision*, *14*(13), Article 14. https://doi.org/10.1167/14.13.14

Smith, M. L., Cottrell, G. W., Gosselin, F., & Schyns, P. G. (2005). Transmitting and decoding facial expressions. *Psychological Science*, *16*(3), 184–189. https://doi.org/10.1111/j.0956-7976.2005.00801.x

Sormaz, M., Young, A. W., & Andrews, T. J. (2016). Contributions of feature shapes and surface cues to the recognition of facial expressions. *Vision Research*, *127*, 1–10. https://doi.org/10.1016/j.visres.2016.07.002

Stein, T., Peelen, M. V., & Sterzer, P. (2011). Adults' awareness of faces follows newborns' looking preferences. *PLOS ONE*, *6*(12), Article e29361. https://doi.org/10.1371/journal.pone.0029361

Stratou, G., Ghosh, A., Debevec, P., & Morency, L.-P. (2011). *Effect of illumination on automatic expression recognition: A novel 3D relightable facial database* [Conference session]. 2011 IEEE International Conference on Automatic Face & Gesture Recognition (FG)., Santa Barbara, CA, United States.

Sun, J., & Perona, P. (1998). Where is the sun? *Nature Neuroscience*, *1*(3), 183–184. https://doi.org/10.1038/630

Todorov, A., & Porter, J. M. (2014). Misleading first impressions: Different for different facial images of the same person. *Psychological Science*, *25*(7), 1404–1417. https://doi.org/10.1177/0956797614532474

Troje, N. F., & Siebeck, U. (1998). Illumination-induced apparent shift in orientation of human heads. *Perception*, *27*(6), 671–680. https://doi.org/10.1068/p270671

Tsao, D. Y., & Livingstone, M. S. (2008). Mechanisms of face perception. *Annual Review of Neuroscience*, *31*(1), 411–437. https://doi.org/10.1146/annurev.neuro.30.051606.094238

Whalen, P. J., Kagan, J., Cook, R. G., Davis, F. C., Kim, H., Polis, S., McLaren, D. G., Somerville, L. H., McLean, A. A., Maxwell, J. S., & Johnstone, T. (2004). Human amygdala responsivity to masked fearful eye whites. *Science*, *306*(5704), Article 2061. https://doi.org/10.1126/science.1103617

White, M. (2001). Effect of photographic negation on matching the expressions and identities of faces. *Perception*, *30*(8), 969–981. https://doi.org/10.1068/p3225

Wisessing, P., Dingliana, J., & McDonnell, R. (2016). Perception of lighting and shading for animated virtual characters. *SAP'16:*

Proceedings of the ACM symposium on applied perception (pp. 25–29). Association for Computing Machinery. https://doi.org/10.1145/2931002.2931015

Wisessing, P., Zibrek, K., Cunningham, D. W., Dingliana, J., & McDonnell, R. (2020). Enlighten me: Importance of brightness and shadow for character emotion and appeal. *ACM Transactions on Graphics*, *39*(3), 1–12. https://doi.org/10.1145/3383195

Yang, B., & Fotios, S. (2015). Lighting and recognition of emotion conveyed by facial expressions. *Lighting Research & Technology*, *47*(8), 964–975. https://doi.org/10.1177/1477153514547753

Young, A. (2021). Face perception. *Oxford research encyclopedia of psychology*. Oxford University Press. https://doi.org/10.1093/acrefore/9780190236557.013.844

Young, A., & Bruce, V. (2024). *Face perception* (2nd ed.). Routledge.

Received August 3, 2023
Revision received September 27, 2024
Accepted October 4, 2024 ■