

# Categorical Perception of Fear and Anger Expressions in Whole, Masked and Composite Faces. --Manuscript Draft--

<b>Manuscript Number:</b>	PONE-D-15-09499R2
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<b>Full Title:</b>	Categorical Perception of Fear and Anger Expressions in Whole, Masked and Composite Faces.
<b>Short Title:</b>	Categorical Perception of Emotions in Face Parts.
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<b>Keywords:</b>	Faces; emotion; expression; categorical perception
<b>Abstract:</b>	<p>Human observers are remarkably proficient at recognizing expressions of emotions and at readily grouping them into distinct categories. When morphing one facial expression into another, the linear changes in low-level features are insufficient to describe the changes in perception, which instead follow an s-shaped function. Important questions are, whether there are single diagnostic regions in the face that drive categorical perception for certain pairings of emotion expressions, and how information in those regions interacts when presented together.</p> <p>We report results from two experiments with morphed fear-anger expressions, where (a) half of the face was masked or (b) composite faces made up of different expressions were presented.</p> <p>When isolated upper and lower halves of faces were shown, the eyes were found to be almost as diagnostic as the whole face, with the response function showing a steep category boundary. In contrast, the mouth allowed for a substantially lesser amount of accuracy and responses followed a much flatter psychometric function.</p> <p>When a composite face consisting of mismatched upper and lower halves was used and observers were instructed to exclusively judge either the expression of mouth or eyes, the to-be-ignored part always influenced perception of the target region. In line with experiment 1, the eye region exerted a much stronger influence on mouth judgements than vice versa. Again, categorical perception was significantly more pronounced for upper halves of faces.</p> <p>The present study shows that identification of fear and anger in morphed faces relies heavily on information from the upper half of the face, most likely the eye region. Categorical perception is possible when only the upper face half is present, but compromised when only the lower part is shown. Moreover, observers tend to integrate all available features of a face, even when trying to focus on only one part.</p>
<b>Order of Authors:</b>	<p>Martin Wegrzyn</p> <p>Isabelle Bruckhaus</p> <p>Johanna Kissler</p>
<b>Opposed Reviewers:</b>	
<b>Response to Reviewers:</b>	<p>Reviewer #1:</p> <p>The sigmoid (or S-shaped) function is not only a necessary condition for categorical perception but also a necessary condition for any noise limited perceptual functions. Thus, its absence only suggests a lack of noise in the system regardless what kind of perception it is. Here, I challenge the authors to find any example in any aspect of perception that has no s-shape logistic function (as long as the dependent variable is probability). My recommendation here is to drop the attempt to associate s-shape function and categorical perception and focus on the empirical results. The sigmoid function is too generic to derive any useful argument from its existence. Its slope, however, can be quite informative.</p> <p>We would like to thank the reviewer for helping us to improve our manuscript. We have given this point much thought and have carefully revised our manuscript.</p>

	<p>We have removed the linear function from our manuscript altogether, as well as direct comparisons of a linear and a logistic function. However, we would find it unfortunate to simply leave out a central point of our analysis without adequate substitute and thereby deny the readers a thorough and comprehensive picture of the data. Since the reviewer commented positively on the use of slope parameters, we have shifted the emphasis of our manuscript towards this aspect and provide more detailed descriptive statistics on this aspect.</p> <p>In our revised manuscript, we not only show the raw data of each participant, but also the fitted logistic function of each participant's data. In each logistic function, the threshold value (the point where the function is steepest) is additionally visualised. The computation of the threshold value has been performed in a slightly more elaborate way, so that threshold values on the x-axis (for which morphing grade is the function steepest?) as well as on the y-axis (on which level is performance at the steepest point?) are extracted. We also visualise the steepness of the function across its whole course (i.e. the first derivative of the function), so that the slope parameter and its relationship to the data can be better understood.</p> <p>These parameters are visualised both as hybrid violin/box-plots (showing the distribution of the data including median and quartiles) and as raw data (with lines indicating repeated measures of the same participant) and 95% confidence intervals. Using both types of visualisation back-to-back helps to get a quick and intuitive understanding of the data and in return has allowed to shorten the text of the manuscript. The parameters are also subjected to statistical tests, which are performed as ANOVAs (in accordance with the preferences of reviewer 2) and reported in tables, to ease readability.</p> <p>Also, the readers might ask whether fitting a logistic function is appropriate for the data in the first place. We briefly demonstrate this by using cross-validation, but instead of comparing a linear and logistic function, we compare the logistic function and the original raw data in their ability to fit the left-out half of the raw data. The superiority of the logistic function in the cross-validation provides a strong and unbiased indication that it is indeed well-suited to describe the participants' behavior.</p> <p>While the revised version now features more figures and two new tables, we were able to slightly shorten the text. We feel that the revised version of the manuscript is not only more methodologically sound, but also more readable. We hope that the reviewer and editor feel the same way.</p>
<b>Additional Information:</b>	
<b>Question</b>	<b>Response</b>
<p><b>Financial Disclosure</b></p> <p>Please describe all sources of funding that have supported your work. A complete funding statement should do the following:</p> <p>Include <b>grant numbers and the URLs</b> of any funder's website. Use the full name, not acronyms, of funding institutions, and use initials to identify authors who received the funding.</p> <p><b>Describe the role</b> of any sponsors or funders in the study design, data collection and analysis, decision to publish, or preparation of the manuscript. If they had no role in any of the above, include this sentence at the end of your statement: "<i>The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.</i>"</p> <p>If the study was <b>unfunded</b>, provide a</p>	<p>Research was funded by the Deutsche Forschungsgemeinschaft (DFG; <a href="http://www.dfg.de">www.dfg.de</a>), Cluster of Excellence 277 "Cognitive Interaction Technology", in form of a scholarship awarded to MW.</p> <p>The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.</p>

<p>statement that clearly indicates this, for example: <i>"The author(s) received no specific funding for this work."</i></p> <p>* typeset</p>	
<p><b>Competing Interests</b></p> <p>You are responsible for recognizing and disclosing on behalf of all authors any competing interest that could be perceived to bias their work, acknowledging all financial support and any other relevant financial or non-financial competing interests.</p> <p>Do any authors of this manuscript have competing interests (as described in the <a href="#">PLOS Policy on Declaration and Evaluation of Competing Interests</a>)?</p> <p>If <b>yes</b>, please provide details about any and all competing interests in the box below. Your response should begin with this statement: <i>I have read the journal's policy and the authors of this manuscript have the following competing interests:</i></p> <p>If <b>no</b> authors have any competing interests to declare, please enter this statement in the box: <i>"The authors have declared that no competing interests exist."</i></p> <p>* typeset</p>	<p>The authors have declared that no competing interests exist.</p>
<p><b>Ethics Statement</b></p> <p>You must provide an ethics statement if your study involved human participants, specimens or tissue samples, or vertebrate animals, embryos or tissues. All information entered here should <b>also be included in the Methods section</b> of your manuscript. Please write "N/A" if your study does not require an ethics statement.</p> <p><b>Human Subject Research (involved human participants and/or tissue)</b></p>	<p>The study was approved by the ethics board of Bielefeld University (Ethic Statement Nr. 2014-010). All participants gave oral informed consent before taking part in the experiments. Use of verbal informed consent was advised by the ethics board of Bielefeld University to ensure full anonymity.</p>

All research involving human participants must have been approved by the authors' Institutional Review Board (IRB) or an equivalent committee, and all clinical investigation must have been conducted according to the principles expressed in the [Declaration of Helsinki](#). Informed consent, written or oral, should also have been obtained from the participants. If no consent was given, the reason must be explained (e.g. the data were analyzed anonymously) and reported. The form of consent (written/oral), or reason for lack of consent, should be indicated in the Methods section of your manuscript.

Please enter the name of the IRB or Ethics Committee that approved this study in the space below. Include the approval number and/or a statement indicating approval of this research.

**Animal Research (involved vertebrate animals, embryos or tissues)**

All animal work must have been conducted according to relevant national and international guidelines. If your study involved non-human primates, you must provide details regarding animal welfare and steps taken to ameliorate suffering; this is in accordance with the recommendations of the Weatherall report, "[The use of non-human primates in research](#)." The relevant guidelines followed and the committee that approved the study should be identified in the ethics statement.

If anesthesia, euthanasia or any kind of animal sacrifice is part of the study, please include briefly in your statement which substances and/or methods were applied.

Please enter the name of your Institutional Animal Care and Use Committee (IACUC) or other relevant ethics board, and indicate whether they approved this research or granted a formal waiver of ethical approval. Also include an approval number if one was obtained.

<p><b>Field Permit</b></p> <p>Please indicate the name of the institution or the relevant body that granted permission.</p>	
<p><b>Data Availability</b></p> <p>PLOS journals require authors to make all data underlying the findings described in their manuscript fully available, without restriction and from the time of publication, with only rare exceptions to address legal and ethical concerns (see the <a href="#">PLOS Data Policy</a> and <a href="#">FAQ</a> for further details). When submitting a manuscript, authors must provide a Data Availability Statement that describes where the data underlying their manuscript can be found.</p> <p>Your answers to the following constitute your statement about data availability and will be included with the article in the event of publication. <b>Please note that simply stating 'data available on request from the author' is not acceptable. If, however, your data are only available upon request from the author(s), you must answer "No" to the first question below, and explain your exceptional situation in the text box provided.</b></p> <p>Do the authors confirm that all data underlying the findings described in their manuscript are fully available without restriction?</p>	<p>Yes - all data are fully available without restriction</p>
<p>Please describe where your data may be found, writing in full sentences. <b>Your answers should be entered into the box below and will be published in the form you provide them, if your manuscript is accepted.</b> If you are copying our sample text below, please ensure you replace any instances of <b>XXX</b> with the appropriate details.</p> <p>If your data are all contained within the paper and/or Supporting Information files, please state this in your answer below. For example, "All relevant data are within the paper and its Supporting Information files."</p> <p>If your data are held or will be held in a public repository, include URLs, accession numbers or DOIs. For example, "All <b>XXX</b> files are available from the <b>XXX</b> database (accession number(s) <b>XXX</b>, <b>XXX</b>)." If this information will only be available after acceptance, please indicate this by ticking the box below.</p>	<p>All relevant data are within the paper and its Supporting Information files.</p>

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Bielefeld, 6 July 2015

## Resubmission of Manuscript (PONE-D-15-09499)

Dear Editor,

enclosed please find the revised version of our manuscript entitled "*Categorical Perception of Fear and Anger Expressions in Whole, Masked and Composite Faces*".

Again, we would like to thank you and the reviewers for the helpful comments on our study. We have addressed all issues raised by the reviewers and have attached a point-by-point answer to their comments. The manuscript itself has been thoroughly revised, and all changes are marked in red color.

We feel that the suggestions have helped to greatly improve the manuscript and we hope that you and the reviewers feel the same way. We would appreciate a positive review and are looking forward to your reply.

Sincerely for the authors,



Martin Wegrzyn

# **Categorical Perception of Fear and Anger Expressions in Whole, Masked and Composite Faces.**

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# ABSTRACT

Human observers are remarkably proficient at recognizing expressions of emotions and at readily grouping them into distinct categories. When morphing one facial expression into another, the linear changes in low-level features are insufficient to describe the changes in perception, which instead follow an s-shaped function.

Important questions are, whether there are single diagnostic regions in the face that drive categorical perception for certain pairings of emotion expressions, and how information in those regions interacts when presented together.

We report results from two experiments with morphed fear-anger expressions, where (a) half of the face was masked or (b) composite faces made up of different expressions were presented.

When isolated upper and lower halves of faces were shown, the eyes were found to be almost as diagnostic as the whole face, with the response function showing a steep category boundary. In contrast, the mouth allowed for a substantially lesser amount of accuracy and responses followed a much flatter psychometric function.

When a composite face consisting of mismatched upper and lower halves was used and observers were instructed to exclusively judge either the expression of mouth or eyes, the to-be-ignored part always influenced perception of the target region. In line with experiment 1, the eye region exerted a much stronger influence on mouth judgements than vice versa. Again, categorical perception was significantly more pronounced for upper halves of faces.

The present study shows that identification of fear and anger in morphed faces relies heavily on information from the upper half of the face, most likely the eye region.

Categorical perception is possible when only the upper face half is present, but

compromised when only the lower part is shown. Moreover, observers tend to integrate all available features of a face, even when trying to focus on only one part.

# 1. INTRODUCTION

Facial expressions are a powerful means of conveying information about the emotional state of an individual. Recognizing and correctly interpreting these non-verbal signs is of vital importance for successful social interaction [1].

Faces are not only complex stimuli, but their expressions can often be subtle and ambiguous. Despite this, human observers can readily recognize expressions of emotions and assign them distinct labels. A large body of research suggests that there are a number of basic emotions which are correctly recognized by most observers [2], although their exact number is under debate [3]. Even when the expressions' intensity varies continuously, as in manipulated faces where one expression is gradually morphed into another, human observers readily group them into distinct categories with a high level of confidence [4].

Such categorical perception is demonstrated by identification tasks where linear changes in low-level features (e.g. basic visual properties like colour or shape) lead to non-linear changes in perception, which are best described by a sigmoid function with a steep category boundary. In general, categorical perception refers to the phenomenon that objects from the same category will be perceived as more similar than objects from different categories [5], despite being equally far apart from each other on a given physical dimension. One example is human colour perception, where two different wavelengths will only be perceived as two different colours when a category boundary is crossed [6]. For facial expressions, categorical perception has been demonstrated in a number of seminal studies [7–9].

Faces are inherently multidimensional stimuli, and in face processing categorical perception can relate to different dimensions (identity, age, attractiveness, gender, emotion), which in turn may depend on different facial features. Regarding emotion, each

expression of a basic emotion can be described in terms of a number of muscle groups that are active when a person shows that particular emotion [10]. For example, fear will most frequently be expressed in the face by the brows raised and drawn together, the upper eyelids raised, the lower eyelids tensed, the lips stretched back and, in some cases, the mouth opened [11,12]. Furthermore, masking studies have demonstrated that each basic emotion is recognized through different diagnostic areas of the face [13]. For example, fear can be best recognized when the eyes are visible, while happiness is best inferred from the mouth region. On the other hand, eye tracking studies have shown that for all six basic expressions, including ones of low intensity, people focus primarily on the eyes [14]. While eye tracking studies shed light on how observers usually inspect faces under free viewing conditions, masking studies help to understand what information is indispensable in order to make a correct decision. Therefore a masking approach helps to make causal inferences about the diagnostic value of each facial feature.

To understand categorical perception of facial expressions, it is essential to know which information in the face is used to make a categorical decision and how facial features are integrated into a perceptive whole, so that successful categorization can occur.

The term 'holistic processing' refers to the fact that faces are preferentially processed as a whole [15–17]. Findings from the composite face illusion, where complementary upper and lower face halves are combined into a whole face, serve to illustrate this mechanism: It is considerably more difficult to make a decision about the properties of either half in such composites than it is to judge each part in isolation [18]. For example, it may be more difficult to recognize a person's identity from a lower face half when it has been combined with the upper face half of another person, while the same task is easy when each half is presented in isolation [18]. Using happy and angry faces, interference from composites with mis-matching expressions have been found reflected in slower reaction times [19,20].

So far, both masking studies [13] and composite face paradigms [19] used full-blown facial expressions instead of gradually morphed faces. Chen and Chen [21] have used morphed happy-sad expressions in a composite face, but always asked to judge the whole face and not its parts, therefore making it difficult to draw inferences on how the perception of one facial feature is influenced by another one.

Masking or composite face studies with morphed faces however allow to better describe human behaviour in psychophysical terms, as the subjective perception dissociates from the changes in low-level features. They also allow to better understand how we process subtle and ambiguous expressions, which are arguably most relevant in daily life.

Therefore, it is useful to investigate the relationship of categorical perception and featural (i.e. focusing on single parts) or configural (i.e. integrating parts into a whole) face processing with masked and composite faces. Main questions are, whether there are diagnostic regions in the face that are sufficient to allow for categorical perception, and whether multiple features need to be integrated when making categorical judgements.

Therefore, to better understand mechanisms of categorical perception of facial expressions, a promising approach is to break down the face into its features and understand how each contributes to identifying a certain expression. In a second step, the features can be re-assembled into a whole and one can investigate how they are integrated to infer an expression from a whole face.

To address these questions, two experiments with faces morphed from fear to anger were performed. Beginning with the seminal work by Ectoff and Magee [9], fear-anger pairings have been frequently used for investigating categorical perception (e.g. [7,8] ; cf. [5]).

Previous masking studies with full-blown fear and anger expressions have shown that both expressions are mainly recognized from the eye region [13] and studies with neurological patients also point to a special role of the eyes for recognizing fear [22]. Therefore, one can hypothesize that categorical perception of fear and anger will rely mostly on the features in

the upper half of the face. In line with research on the composite face illusion [19,20], the more informative half of the face should also dominate the perception of a full face.

In the present study, the first experiment was carried out to investigate how observers make categorical decisions from morphed faces when only a limited amount of features is present. In this experiment, an upper face half, a lower face half, or an intact face were shown and observers were asked to categorize each morph as being either angry or fearful. The second experiment investigated how this relates to performance in a composite face task, when participants have to ignore one half of the face to make an optimal decision. In this experiment, a face assembled of an upper and lower half was presented. The observers had to judge only one half at a time, while the distractor half was showing either full-blown anger or fear. Together, these experiments aim to elucidate the psychophysics of recognizing facial expressions.

## **2. EXPERIMENT 1**

### **2.1 Participants**

30 participants took part in the experiment (22 female). Mean age of participants was 25 years (range: 18-32). Participants received course credit or 5 EUR for participation.

Participants reported no history of neurological or psychiatric illness and had normal or corrected-to-normal vision. The study was approved by the ethics board of Bielefeld University (Ethic Statement Nr. 2014-010). All participants gave oral informed consent before taking part in the experiments.

Two participants showed performance close to guessing for all conditions combined with exceptionally fast reaction times, indicative of non-compliance. Their data were excluded, leaving 28 participants for further analysis.

### **2.2 Material**

Anger and fear pictures of 20 identities (10 male, 10 female) were selected from the KDEF [23] and NimStim [24] databases. The pictures were used to generate morphs in 9 steps with Gimp 2.6 ([www.gimp.org](http://www.gimp.org)) and the GAP toolbox, resulting in 11 morphing grades including the original images. Faces were divided into an upper and lower half, with the border defined as being above the nostrils at the bridge of the nose of the middle morph. This border was defined for each face identity and subsequently applied to all of its morphs.

In Experiment 1 there were three visibility conditions (whole face, upper half, lower half). The half of no interest was blurred with a very broad Gaussian filter, preserving only a rough outline of the face, thereby conveying a feeling of wholeness, while rendering the masked features invisible (cf. Fig 1).



**[Figure 1. Design of Experiment 1.** Illustration of a face morphed from the original fearful (outer left) to the original angry expression (outer right) in 9 intermediary steps, resulting in a total of 11 face morphs; a, whole face; b, upper half intact ('eyes' condition); c, lower half intact ('mouth' condition); due to copyright restrictions, the depicted example is an in-house generated face which was not used in the present experiment.]

### **2.3 Design**

A two-alternatives forced choice identification task was used, in which participants had to decide for each face whether its expression was 'angry' or 'fearful'. Each of the 20 identities was presented in 11 morphing grades. The experiment consisted of two runs with a total of 40 trials per cell, resulting in a resolution of 2.5% for identification performance. The first run was repeated after a short break, to allow for analyses of intra-subject stability. This resulted in a total of 440 trials per masking condition (11 morphs x 20 identities x 2 runs). Pictures were shown with no time limit until a response was given, after which the next stimulus was shown directly, to allow for smooth work-flow. Participants were able to monitor their progress on a status bar presented at the bottom of the screen. Order of stimuli was randomized, the only constraint being that two subsequent trials never contained the same face identity.

Participants had to press the left or right mouse button to indicate whether the target face part showed an angry or fearful expression (button assignment counterbalanced between participants). Experiments were performed using Presentation software (Version 17.1, [www.neurobs.com](http://www.neurobs.com)). All experiment files, including raw data, can be found in supplementary files S7 Code and S8 Dataset.

### **2.4 Analysis**

To characterise the participants' performance, a logistic function was fitted to their data. The logistic function ( $F_{\text{logistic}}(x; \alpha, \beta) = 1 / [1 + \exp(-\beta(x - \alpha))]$ ) is well-suited to describe observers' performance in psychometric terms [25, p. 82]. An s-shaped logistic function with a steep slope is indicative of high precision in distinguishing between two categories and little uncertainty [25, p. 20]. If categorical perception occurs, the steepest point in the psychometric curve corresponds to the category boundary, as this is the point where two stimuli will be discriminated best [5]. However, it should be noted that the logistic function might occur for any linear system limited by Gaussian noise [26], including decisions based on simple image features such as contrast [27].

To derive the point of steepest increase, the limits of the logistic function were always defined by the lowest and highest value of the raw data, so that it provided an optimal fit even in cases when responses never crossed 50% guessing (cf. Experiment 2). Functions were fitted using an iterative optimization strategy, employing a non-linear least-squares procedure to derive the best-fitting function for the raw data. The steepest point of each curve was defined by computing the first derivative of the function. The position of this point on the x- and y-axis (threshold) as well as its value (slope) were then compared between conditions.

Furthermore, for cross-validation, data from one half of the experiment were used to predict the other half of the data. Since each participant performed every trial twice, data from the first half of the experiment were used to predict the data from the second half (and vice versa). For each condition, one half of the participants' data was compared to all conditions of the other half using sums of squared errors ( $ss^2$ ). This allowed assessing whether results were stable across experiment repetitions. The more similar two conditions are, the smaller the  $ss^2$  should be. Using sums of squared errors has the advantages of being an intuitive measure of similarity and being virtually assumption-free [28, p. 106].

We also investigated whether left-out data can be better predicted by using raw data or by a logistic function fitted to these data. If a logistic function provides a superior fit to left-out raw data (smaller  $ss^2$ ), this should indicate that the simplifying assumption made by the psychometric function are sensible and add to our understanding of the underlying perceptual mechanisms.

Data analysis was performed with Python 2.7.9 ([www.python.org](http://www.python.org)) using NumPy, SciPy, Pandas, Matplotlib, and the IPython Notebook, all as provided with Anaconda 2.2.0 (Continuum Analytics; [docs.continuum.io/anaconda](http://docs.continuum.io/anaconda)). Full code and output for all analyses can be found in the online supplement. Refer to S1 Code and S2 Code for data import and restructuring; S3 Code for main data analysis; S4 Code for fitting psychometric functions; S5 Code for cross-validation; and to S6 Code for analyses of single face identities.

Analyses of Variance (ANOVA) for repeated measure designs were additionally carried out using IBM SPSS 22.

## 2.5 Results

### 2.5.1 Comparison of response curves for different masking types

Identification performance was compared across all 11 morphing grades for the three masking conditions (full face, upper face half, lower face half). Participants' performance is illustrated in Fig 2. A 3x11 repeated-measures ANOVA showed a significant main effect of morphing grade, reflecting that anger responses increase as the faces are morphed towards this expression ( $F_{(10,270)}=620.7, p<0.001, \eta_p^2=0.96$ ). There was no main effect of masking condition ( $F_{(2,54)}=2.3, p=0.112, \eta_p^2=0.08$ ), indicating that there is no bias that would shift the responses between conditions. A significant condition-by-morphing grade interaction ( $F_{(20,540)}=63.5, p<0.001, \eta_p^2=0.70$ ) indicated that the shape of the response curve differs between conditions. Paired t-tests for repeated measures and the Wilcoxon signed rank test as its non-parametric equivalent were carried out to test differences between conditions for all morphing grades. Results were only considered significant if the p-value for both metrics fell below  $\alpha=0.05$ .

Identification performance was best (i.e. significantly farthest from guessing) for the whole face, compared both to the upper (all  $ps<0.05$ , except 50% angry morphs) and lower half (all  $ps<0.05$ , except 60% angry morphs). Furthermore, performance was significantly better for the upper than for the lower half (all  $ps<.05$  except for 50% and 60% angry morphs). This indicates that observers were able to make the most accurate decisions when presented with a whole face, followed by face halves containing only the eye region.

Performance was worst when only the mouth region was visible.

Judgements of the eye region closely resembled the whole face responses, as indicated by a significantly smaller difference between upper and whole face decisions compared to lower and whole face decisions (all  $ps<0.05$  for pairwise comparisons of differences, except for 50% and 60% morphs).

[ **Figure 2. Main Results Experiment 1.** Percent angry responses (y-axis) across the 11 morphing grades morphed from fear to anger (x-axis) for the three different visibility conditions (coloured lines); 'whole face', whole face is visible (no masking); 'lower half', lower face half is visible (upper half is masked); 'upper half', upper face half is visible (lower half is masked).]

### **2.5.2 Cross-validation of conditions**

If differences between conditions are genuine and stable, each condition should be able to predict itself best, e.g. the whole face condition of the first half of the experiment should be most similar to the whole face condition of the second half.

This was confirmed by split-half cross-validation with each half of the experiment used once as test and as training set, within each participant. Each condition was significantly closest to its analogue from the other half of the experiment, as expressed in significantly smallest  $ss^2$  for these pairings (all  $p < 0.01$  for pairwise comparisons).

Furthermore, the upper and whole face conditions were significantly more similar to each other than to the lower half condition ( $p < 0.01$ ). This stronger similarity of the eye region to the whole face ratings further corroborates that the upper half carries more information about fear and anger expressions than does the mouth region.

### **2.5.3 Comparison of thresholds and slopes of the logistic function between conditions**

When fitting a logistic function to each participant's data for each condition, the steepness of the slopes can be compared as measure for the presence of a category boundary, with a steep slope indicating stronger categorical perception (Fig 3).

Results show that the logistic functions for all conditions had their thresholds close to 50% guessing, with no significant differences between conditions (Table 1, Fig 4). There was a

clear effect for the slope, which was steepest for the whole face condition, followed by the upper and lower half (Table 1, Fig 4; all  $ps < 0.001$  for pairwise comparisons), indicating a more abrupt shift from fear to anger responses when the whole face is visible and more smooth shifts in responses when viewing the lower face half.

[ **Figure 3. Data on single participant level.** Each line represents a participant; each row of the figure indicates a masking condition, as illustrated by the example stimulus on the left-hand side. Each column indicates a different metric describing the data: 'raw data', the original data for each participant; 'logistic function', the best-fitting logistic function for each individual participant, with point of steepest slope indicated by a dot; 'derivative of function', the slope of the fitted logistic function, with the highest value indicated by a dot.]

[**Figure 4. Parameters of logistic function for different masking conditions.**

a, violin plots with width indicating density of values, inner lines indicating median and 25% and 75% quartiles; b, red bars indicate 95% confidence intervals of the mean for each condition; line graphs in the background depict the raw data of each participant; black lines indicate that the participant's value for the left-hand condition is numerically bigger than the right-hand value; blue line indicates that the value is smaller for the left-hand compared to right-hand condition; 'whole face', whole face is visible (no masking); 'upper half', upper face half is visible (lower half is masked); 'lower half', lower face half is visible (upper half is masked).]

Table 1. Comparison of curve parameters for experiment 1						
condition	mean (SD)			F	p	np <sup>2</sup>
	whole face	upper half	lower half			
x-threshold	0.53 <sup>a</sup> (0.04)	0.53 <sup>a</sup> (0.06)	0.51 <sup>a</sup> (0.08)	1.83	0.180	0.064

<b>y-threshold</b>	0.53 <sup>a</sup> (0.05)	0.53 <sup>a</sup> (0.05)	0.55 <sup>a</sup> (0.11)	0.77	0.415	0.028
<b>slope</b>	2.17 <sup>a</sup> (0.53)	1.64 <sup>b</sup> (0.47)	0.96 <sup>c</sup> (0.38)	105.30	<b>&lt;0.001</b>	0.796

Results of a repeated measures ANOVA for the different curve parameters; means in the same row sharing the same superscript letter do not differ significantly from one another at  $\alpha=0.05$ ; degrees of freedom (df) for x-threshold: 1.5,41.6 (Greenhouse-Geisser corrected); df for y-threshold : 1.3, 33.9 (Greenhouse-Geisser corrected) ; df for slope: 2,54.

#### 2.5.4 Cross-validation of response curves for different masking types

Left-out data from one half of the experiment were predicted using data from the other half of the experiment with the two runs of the experiment used for cross-validation. Each condition was modelled for one half of the experiment using raw data or logistic function fitted to these data. These training sets were then compared to the left-out half of the experiment to check how the models compare to each other in predicting new data. The results of the cross-validation analysis show that in fact the logistic function fits left-out raw data significantly better than the raw data does ( $p<0.001$  for all conditions), indicating its suitability for describing the participants' performance.

## 3. EXPERIMENT 2

### 3.1 Methods

Mean age of participants was 24 years (range 19-29). Of the 30 participants, 24 were female. Participants received course credit or 7EUR for participation and gave oral informed consent before starting the experiment.

The same boundary to divide faces into lower and upper halves as in experiment 1 was used and design choices were identical to experiment 1, with the following exceptions: This time 100% fearful or 100% angry expression halves were combined with the morphed pictures to create the composite face illusion. There were four conditions: 'lower half 100% angry' (Fig 5a), 'lower half 100% fearful' (Fig 5b), 'upper half 100% angry' (Fig 5c) and 'upper half 100% fearful' (Fig 5d). The complementary half was presented in 11 morphing steps, and was the part which the observers were asked to identify as either angry or fearful. This part was always framed by a red square (cf. Fig 5). Participants were explicitly instructed to focus only on the framed face half and to ignore the other half. Unlike experiment 1, order of conditions was blocked, to make it easier for the participants to focus on the part of interest. Each block required either always judging the upper half or always judging the lower half, and consisted of 440 trials, with block order counterbalanced between participants. Within blocks, order of the 20 face identities, the 11 morphed face halves and whether the to-be-ignored half was fearful or angry were randomised.

[ **Figure 5. Design of Experiment 2 (Composite Face).** Illustration of a face morphed from the original fearful (outer left) to the original angry expression (outer right) in 9 intermediary steps, resulting in a total of 11 face morphs; a, eye judgements with 100% angry lower face half; b, eye judgements with 100% fearful lower half; c, mouth



judgements with 100% angry upper face half; d, mouth judgements with 100% fearful upper half; conditions a and b or conditions c and d were always presented in one block, to aid participants in focusing on one face half only; due to copyright restrictions, the depicted example is an in-house generated face which was not used in the present experiment. ]

One participant reported to have only focused on the mouth region throughout the experiment, ignoring which face half was currently framed. These data were excluded, leaving 29 data sets for analysis.

## **3.2 Results**

### **3.2.1 Comparison of response curves for different composite faces**

Depending on the viewing condition, responses for the attended face half were biased in the direction of the to-be-ignored face half (Fig 6, Fig 7).

A 2x2x11 ANOVA with the factors upper/lower face half, anger/fear distractor and morphing grade (fear to anger) revealed a main effect of morphing grade ( $F_{(10,280)}=213.7$ ,  $p<0.001$ ,  $\eta_p^2=0.88$ ), a main effect of emotion ( $F_{(1,28)}=109.6$ ,  $p<0.001$ ,  $\eta_p^2=0.80$ ) and significant interactions between all factors (all  $ps<0.001$ ). The main effect of emotion in the distractor half reflects that responses for the eye region were shifted towards anger when the lower face half was angry, and towards fear when the lower half was fearful ( $p<0.01$  for all 11 morphing grades). The same bias occurred for the judgements of the mouth region, when the upper half was either angry or fearful (Fig 6; all  $p<0.001$ ).

The interaction effect between emotion and face half ( $F_{(1,28)}=26.0$ ,  $p<0.001$ ,  $\eta_p^2=0.48$ ) reflects that the bias was significantly stronger for mouth judgements than for eye judgements, indicating that the upper face half exerts a stronger influence on the lower half than vice versa. Across all 11 morphing grades, fearful and angry distracting halves led to

bigger differences in mouth judgements, compared to the differences in eye judgements (all  $p < 0.001$ , for pairwise comparisons of differences).

[ **Figure 6. Main Results for Composite Faces.** Percent angry responses (y-axis) across the 11 morphing grades morphed from fear to anger (x-axis) for the four different composite face conditions (coloured lines); 'lower fearful', observers judge the upper half, while the lower half is always 100% fearful; 'lower angry', observers judge the upper half, while the lower half is always 100% angry; 'upper fearful', observers judge the lower half, while the upper half is always 100% fearful; 'upper angry', observers judge the lower half, while the upper half is always 100% angry. ]

[**Figure 7. Data on single participant level.** Each line represents a participant; each row of the figure indicates a composite face condition, as illustrated by the example stimulus on the left-hand side. Each column indicates a different metric describing the data: 'raw data', the original data for each participant; 'logistic function', the best-fitting logistic function for each individual participant, with point of steepest slope indicated by a dot; 'derivative of function', the slope of the fitted logistic function, with the highest value indicated by a dot.]

### 3.2.2 Cross-validation of conditions

Split-half cross-validation with each half of the experiment used once as test and as training set showed that each condition was significantly closest to its analogue from the other half of the experiment (all  $p < 0.01$  for pairwise comparisons), indicative of reliable differences between conditions.

### 3.2.3 Comparison of thresholds and slopes of the logistic function between conditions

As in experiment 1, the steepest point of the psychometric function was located around the intermediary morph (50% fear/50% anger). However, responses were significantly shifted on the y-axis for the different viewing conditions, indicating that there was a response bias towards fear or anger, depending on the expression of the to-be-ignored half (Table 2).

When the to-be-ignored half was more fearful, the threshold was shifted towards fear, and when that half was more angry, responses were shifted towards anger. This main effect was accompanied by a significant interaction, reflecting that this bias was much strongest when the lower face half had to be rated and the upper face was the distractor (Fig 7, Fig 8, Table 2). Also, when judging the lower face half, the psychometric functions were almost flat, while they had a steep slope when the upper half had to be judged (Fig 7, Table 2).

**[Figure 8. Parameters of logistic function for different composite face conditions.**

a, violin plots with width indicating density of values, inner lines indicating median and 25% and 75% quartiles; b, red bars indicate 95% confidence intervals of the mean for each condition; line graphs in the background depict the raw data of each participant; black lines indicate that the participant's value for the left-hand condition is numerically bigger than the right-hand value; blue line indicates that the value is smaller for the left-hand compared to right-hand condition.]

Table 2. Comparison of curve parameters for experiment 2													
Condition	Mean (SD)				Contrast								
	rating of upper half		rating of lower half		face half			emotion			interaction		
	lower angry	lower fearful	upper angry	upper fearful	F <sub>(1,28)</sub>	p	$\eta_p^2$	F <sub>(1,28)</sub>	p	$\eta_p^2$	F <sub>(1,28)</sub>	p	$\eta_p^2$
x-threshold	0.53 <sup>a</sup> (0.06)	0.56 <sup>b</sup> (0.06)	0.55 <sup>a,b</sup> (0.19)	0.51 <sup>a,b</sup> (0.18)	0.77	0.389	0.03	0.01	0.939	<0.01	1.44	0.241	0.05
y-threshold	0.57 <sup>a</sup> (0.07)	0.50 <sup>b</sup> (0.06)	0.67 <sup>c</sup> (0.13)	0.41 <sup>d</sup> (0.14)	0.22	0.624	0.01	100.23	<0.001	0.78	24.67	<0.001	0.47
slope	1.29 <sup>a</sup> (0.61)	1.23 <sup>a</sup> (0.47)	0.40 <sup>b</sup> (0.43)	0.39 <sup>b</sup> (0.31)	69.31	<0.001	0.71	0.18	0.178	0.06	0.54	0.542	0.01

Results of a repeated measures ANOVA for the different curve parameters of experiment 2; means in the same row sharing the same superscript letter do not differ significantly from one another at  $\alpha=0.05$ ; 'face half', main effect of face half which is rated; 'emotion', main effect of whether the to-be-ignored half is fearful or angry; 'interaction', interaction between the two factors

### **3.2.4 Cross-validation of response curves for different masking types**

Analogous to experiment 1, results of the cross-validation analysis show that the logistic function was better able to fit left-out raw data than the raw data it was based on ( $p < 0.001$  for all conditions), indicating that fitting a logistic function to the present data is suitable. Again, this might indicate that the fitting of a logistic function reduces irrelevant noise in the raw data and is therefore better able to generalize to new measurements.

## **4. RESULTS FOR SINGLE FACE IDENTITIES**

Since 20 different face identities were used as stimuli in the experiments, the present results may underestimate or blur the sigmoid shape of the response functions, due to averaging over a heterogeneous set of stimuli with shifted thresholds.

Therefore, data of both experiments were re-analysed by fitting a logistic function to the responses to each of the 20 individual face identities, averaged across participants.

Subsequently, the thresholds were shifted to be uniformly at the mean value of the respective condition, so that all curves share the x- and y-threshold and only differ in their (unchanged) slopes. The necessary shift determined from the fitted logistic functions was then applied to the underlying raw data, allowing to compare how the curves would be shaped, given equal thresholds for all face identities. The results are illustrated in Fig 9 and are described in-depth in S6 Code. Visual inspection of the data suggests that a sigmoid function clearly emerges only for whole faces and upper halves in experiment 1 and for upper halves in experiment 2 when accounting for potential variability between faces, thereby closely replicating the above results and demonstrating their generalizability across many stimuli.

[ **Figure 9. correction for different thresholds between face identities.** Main analyses for both experiments after modelling responses to each face identity individually and shifting the thresholds to be at the respective group mean; a, results for experiment 1 (masking); b, results for experiment 2 (composite faces); note that a different number of data points is available for each bin on the x-axis, as functions may be partly shifted out of the displayed range, rendering estimates at the extremes less reliable; also, variability is modelled at the stimulus level, not at participant level; please refer to Supplement S6 for more details on the analysis procedure.]

## 5. DISCUSSION

The present study set out to investigate what part of the face is most diagnostic for categorical perception of fear-anger morphed expressions, and how this information is integrated when presented in a composite face.

Experiment 1 showed that the upper face half is more diagnostic than the lower half for deciding between fearful and angry expressions in an identification task. The upper half alone was sufficient for high identification performance, closely reflecting the whole face condition. Its perception could also be well-described by a logistic function with a steep category boundary, providing converging evidence for categorical perception based on the upper face half alone. When viewing the lower half, responses were significantly closer to chance, were less s-shaped and had a comparably shallower slope.

In experiment 2, it was expected that the to-be-ignored halves of the face would bias performance, and that regions that have proven most diagnostic in experiment 1 should exert a stronger biasing influence over complementary face parts than vice versa.

Accordingly, results indicated that both eye and mouth regions bias judgements on the respective other face half, with strongest influences exerted by the eyes, leading to what might be considered a breakdown of performance for mouth judgements. This effect is noteworthy, as information in the mouth region is equally present in both experiments. Nevertheless, when instructed to evaluate the mouth and ignore the eyes in a composite face, the participants' ratings reflect the expression of the eyes numerically more strongly than they reflect mouth judgements. This means that a cue that is reasonably useful for expression recognition in isolation, will be of almost no use when exposed to the influence of a strongly diagnostic cue.

The influence of the mouth on eye judgements should be considered equally striking, since it illustrates that even a very diagnostic cue that allows for recognition levels almost as

high as a whole face, can be subject to significant bias from a substantially weaker cue.

This suggests that even when analytical processing of a single feature is sufficient to allow for categorical perception, human observers seem to integrate features into a whole whenever possible.

The dominance of the eye region in the present experiments is well in line with masking studies which point towards its prominent role for both fear and anger recognition [13].

Studies with neurological patients also indicate a specific importance of the eyes in fear detection [22]. Also, when asked to evaluate expressions of emotion, observers most readily fixate the eyes [14], irrespective of the emotion in question

Regarding identity recognition, there are many studies that demonstrate the importance of the eyes. For example, when a face has to be learned in a training run and later distinguished from distractors differing in one feature, it is easier to recognize identity changes due to differences in the eyes, compared to nose or mouth changes [29]. Masking out the eyes may even represent a legal requirement in some contexts for ensuring anonymity. Although the scientific basis for the effectiveness of this procedure is equivocal at best [cf. 30], it illustrates the paramount importance we intuitively place on the eye region. Regarding mental states, it is also commonly assumed that they can be assessed best from the eye region, as reflected for example in the 'reading the mind in the eyes' test [31]. Accordingly, one must ask whether the eye advantage reported in the present study can be generalised to other features and other expressions of emotion.

Even though the eyes may be most likely fixated when judging emotions from intact faces [14], this does not necessarily imply that most information is coded in the eye region. This becomes obvious when considering the studies carried out with patient SM, who exhibits major difficulties at recognizing fear from faces, due to a failure to fixate the eyes [22].

Nevertheless, she is virtually unimpaired at recognizing all other basic emotions. This indicates that it must be possible to recognize those emotions utilising other diagnostic

features. Accordingly, masking studies [13] and coding systems for basic emotion expressions [10], suggest that each expression can be best recognized from a set of features specific to that emotion and that focusing on the eyes cannot be the optimal strategy in all cases.

Therefore, regarding the results of the present experiments, we would predict that the basic mechanisms outlined here will be replicated with other facial expressions, but perhaps not for the same features. For example, happy-surprised pairings should be best recognized from the mouth, as both involve mainly muscles of the lower face half [10,13,32].

Interestingly, eye-tracking studies found that increased fixating of the eye region correlates with improved emotion recognition for all expressions [14,33] and argue that fixating the eyes reflects a holistic processing strategy. One could test this assumption using happy-surprise pairings and the composite face task from experiment 2. If holistic processing is associated with fixating the eyes, then eye judgements should be easier in a composite face task, even if a strongly diagnostic distracting lower face half is present.

The present findings should not only be extended to investigate other expressions, but also further elaborated for the currently used fear-anger pairing, to shed light on the basic perceptual mechanisms at work. The employed identification task could be complemented by a discrimination task. There, it should be easier to discriminate two images when they are on opposing sides of the category boundary, compared with being both sampled from within the same category [5,6]. Thus, the sigmoid curves from the present experiments could be used to predict the discrimination performance in a follow-up experiment. As differences in slope between conditions can reflect differences in variance of the underlying noise distribution or the uncertainty of the observer [34,35], it would be important to establish that a between-category advantage [5] is indeed present at the point where the psychometric function is steepest in the identification task.



On the basis of the present data from experiment 1, we would therefore predict that discrimination performance at the category boundary should be higher for eye than mouth judgements.

In the composite face task, the peak of the discrimination function might be shifted to the right and left, respectively, when judging the eyes, in accordance with the shifts of the psychometric curve due to the mouth expressions. Finally the discrimination function should be almost flat when judging the mouth in a composite face, as there is virtually no crossing of a category boundary in the present data.

To further generalise the present findings regarding fear-anger pairings, averaged faces could be used, which have the advantage that idiosyncrasies would average out while expressions prototypical for a certain emotion would be emphasized [36, p. 76]. While studies on categorical perception are often performed with a very limited number of identities ( $\leq 4$ ; [cf. 4,7,8,21]), the 20 different faces used in the present experiments should be considered a valuable step towards greater generalisability. However, the fact that the mouth provided so little diagnostic information might be partly due to the fact that 12 out of the 20 face identities expressed the emotions with a closed mouth. While this might have reduced variance in the expressiveness of the lower face half, both the pressing of the lips as well as the baring of the teeth are valid anger expressions [10,12]. Of the two, lip pressing is probably much more frequent in everyday life. Also, when making statements about the importance of either eyes or mouth for recognizing an expression, it should be kept in mind that these features were rather crudely operationalised as the upper and lower face half, respectively. While such a division is standard practice in the field [18,21,37], the muscles around the nose have likely contributed to the judgements of both face halves, and the eyebrows [38] and forehead [11] might have contributed to judgements of the upper face half. While the sclera of the eyes seems crucial for fear

detection [39], anger judgements might depend more on the surrounding muscles of the eyes and the eyebrows [13,38], especially since patient SM shows no difficulty at recognizing anger [22].

Another interesting question is to what degree the failure to concentrate on one half of a composite face can be voluntarily overridden, especially since previous work has shown that emotion recognition improvements are associated with increased fixation of the eyes [33]. This could be investigated by introducing training blocks before the experiment proper, a forced minimum exposure time to discourage spontaneous responses, biofeedback from an eye-tracking device helping to fixate on a specific face part, and rewards for correct responses.

To summarise, the present studies show that identification of fear and anger in morphed faces relies heavily on the eye region, corroborating previous research [10,13,14,19].

Expanding previous work, the study shows that observers can perform categorical perception even when viewing only a single face part. For the employed fear-anger pairings, the eye region was sufficient to allow for decisions with a high degree of certainty. This demonstrates that categorical perception can emerge based on single features only, adding to our understanding of how categorization works in complex stimuli such as faces.

Even though the eye region was almost as diagnostic as the whole face, it was not immune to biasing influences in a composite face task. When a full face with conflicting expressions was shown, the psychometric curves for eye judgements were shifted in accordance with the expression in the lower half of the face. For the first time, we can therefore show that holistic perception of a full face can be explained based on the diagnostic value of its constituent parts. In addition, given that observers were aware that a holistic processing strategy impaired their performance, this illustrates that humans

involuntarily process faces as a gestalt when trying to make categorical decisions about its expression.

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## **SUPPLEMENT**

**S1 Code.** Data import for experiment 1

**S2 Code.** Data import for experiment 2

**S3 Code.** Main analysis and plotting

**S4 Code.** Fitting of logistic function

**S5 Code.** Cross-validation of data

**S6 Code.** Additional analyses for face identities

**S7 Code.** Complete analysis code from S1-S6 in executable IPython Notebook format

**S8 Code.** Complete code for experiment presentation in Neurobs Presentation format

**S9 Dataset.** Complete raw data of all participants



Fig1

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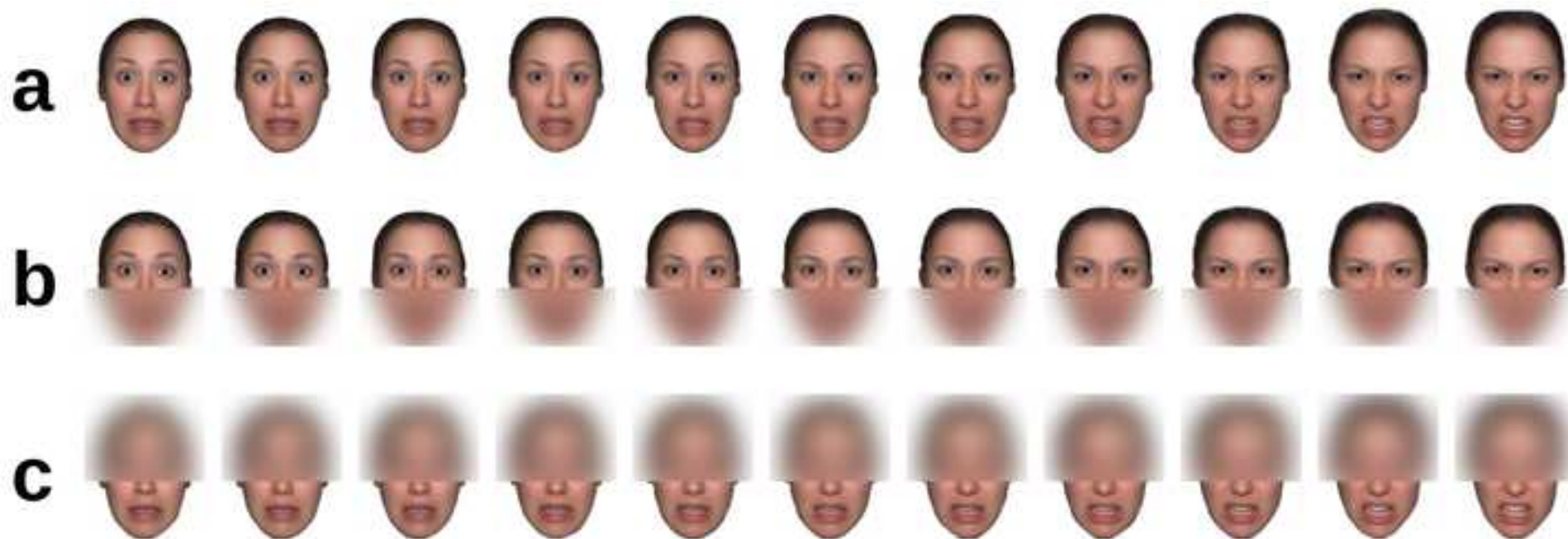


Fig2

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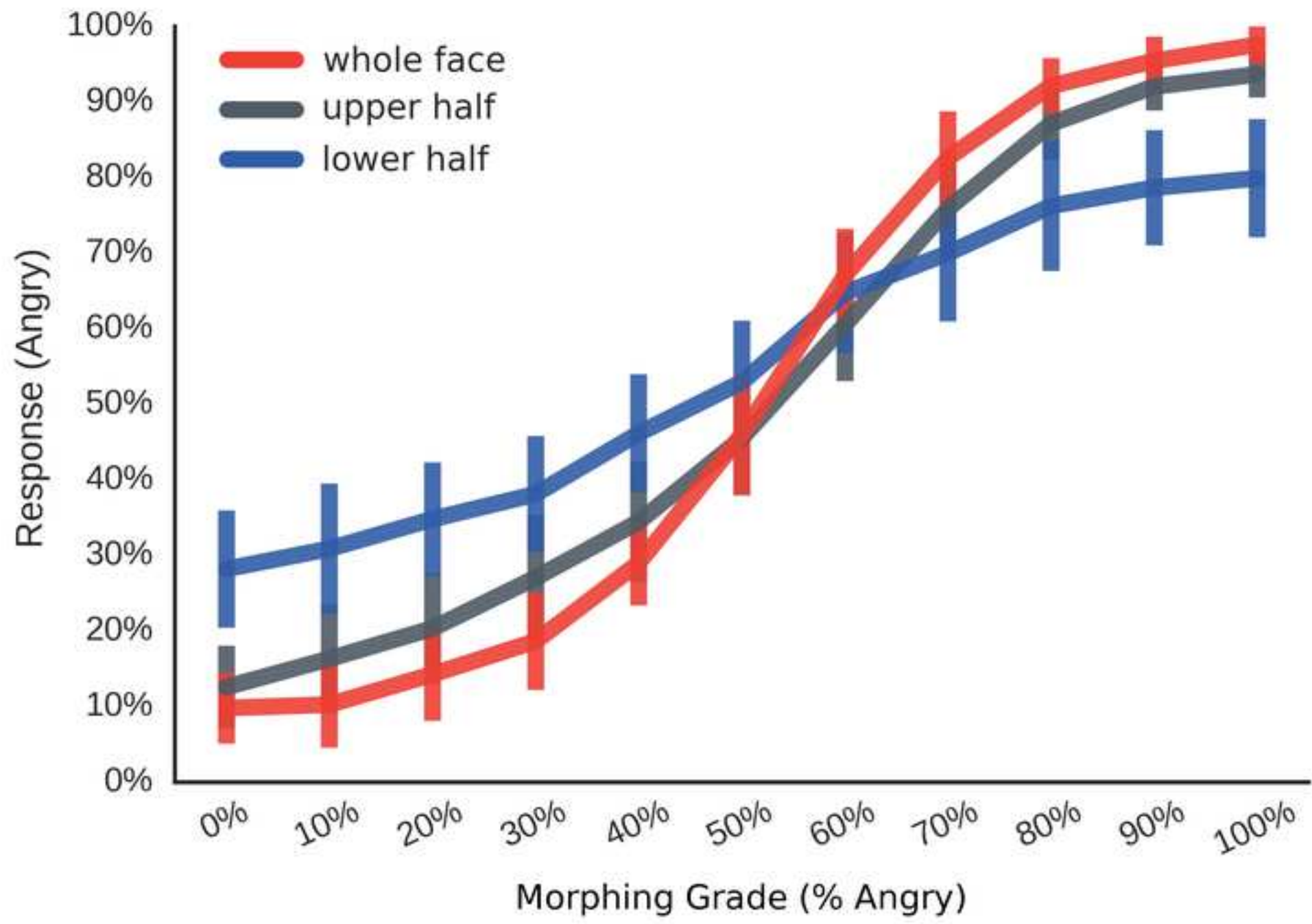


Fig3

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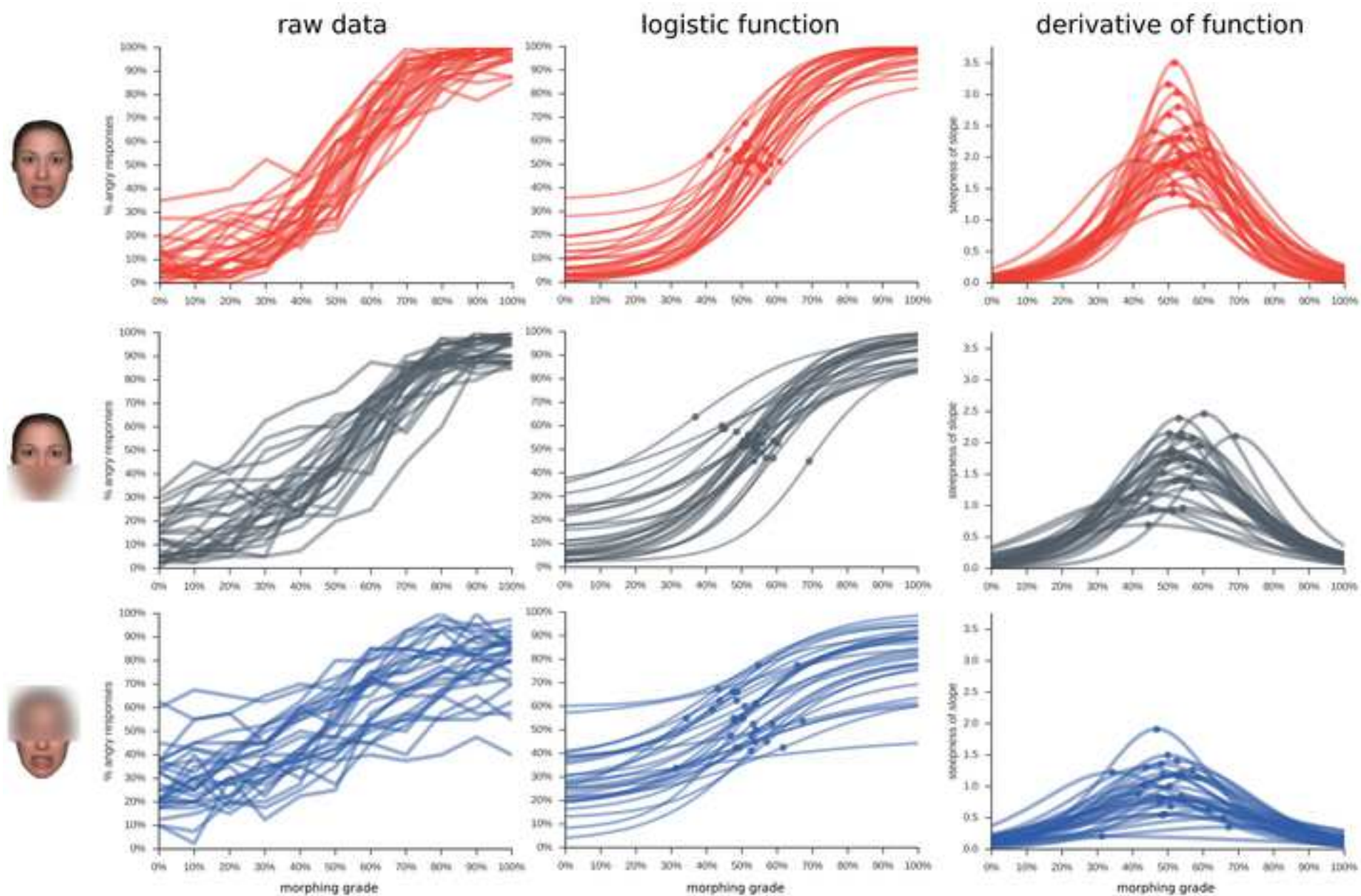


Fig4

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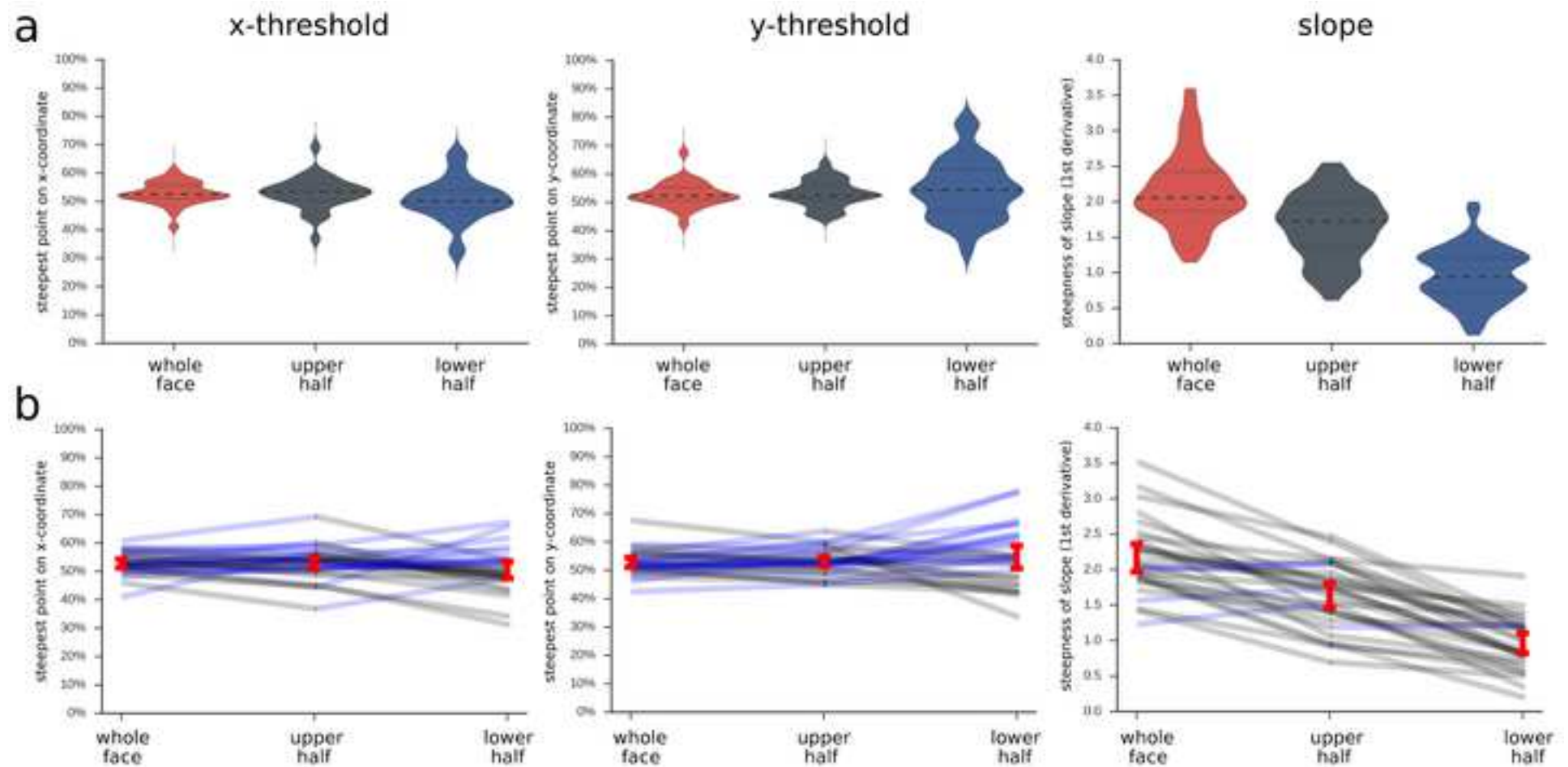




Fig5

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Fig6

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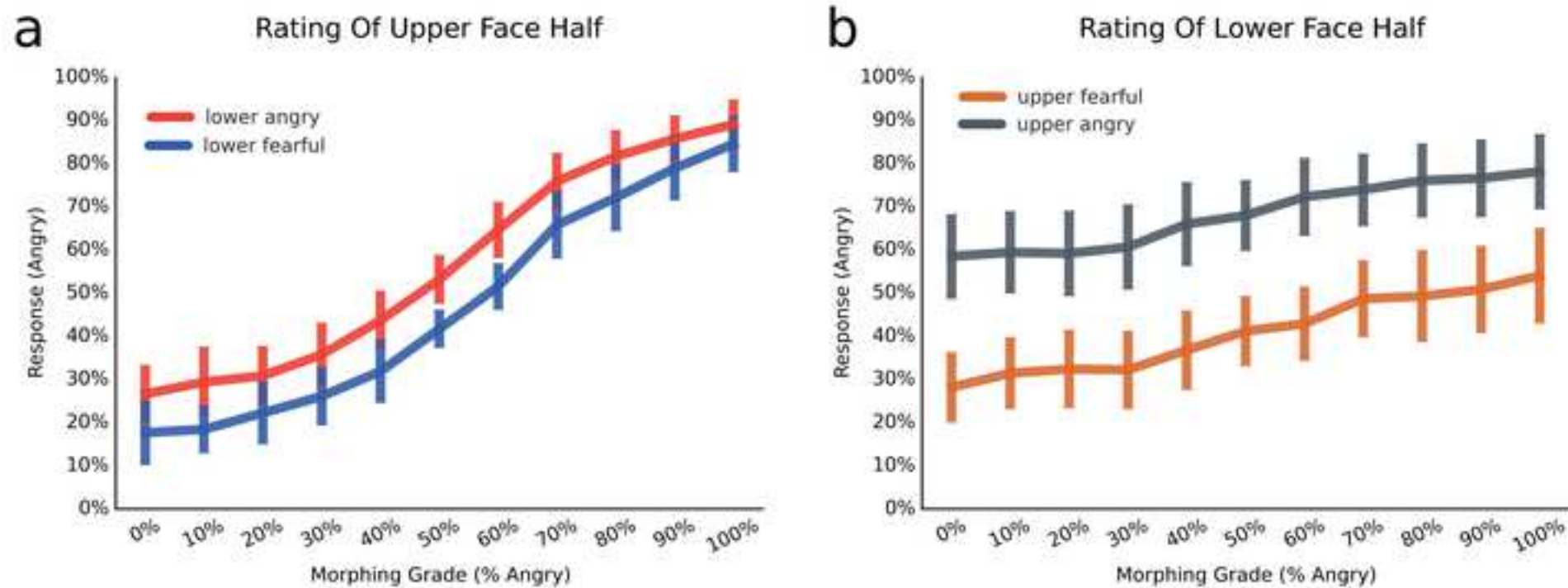


Fig7

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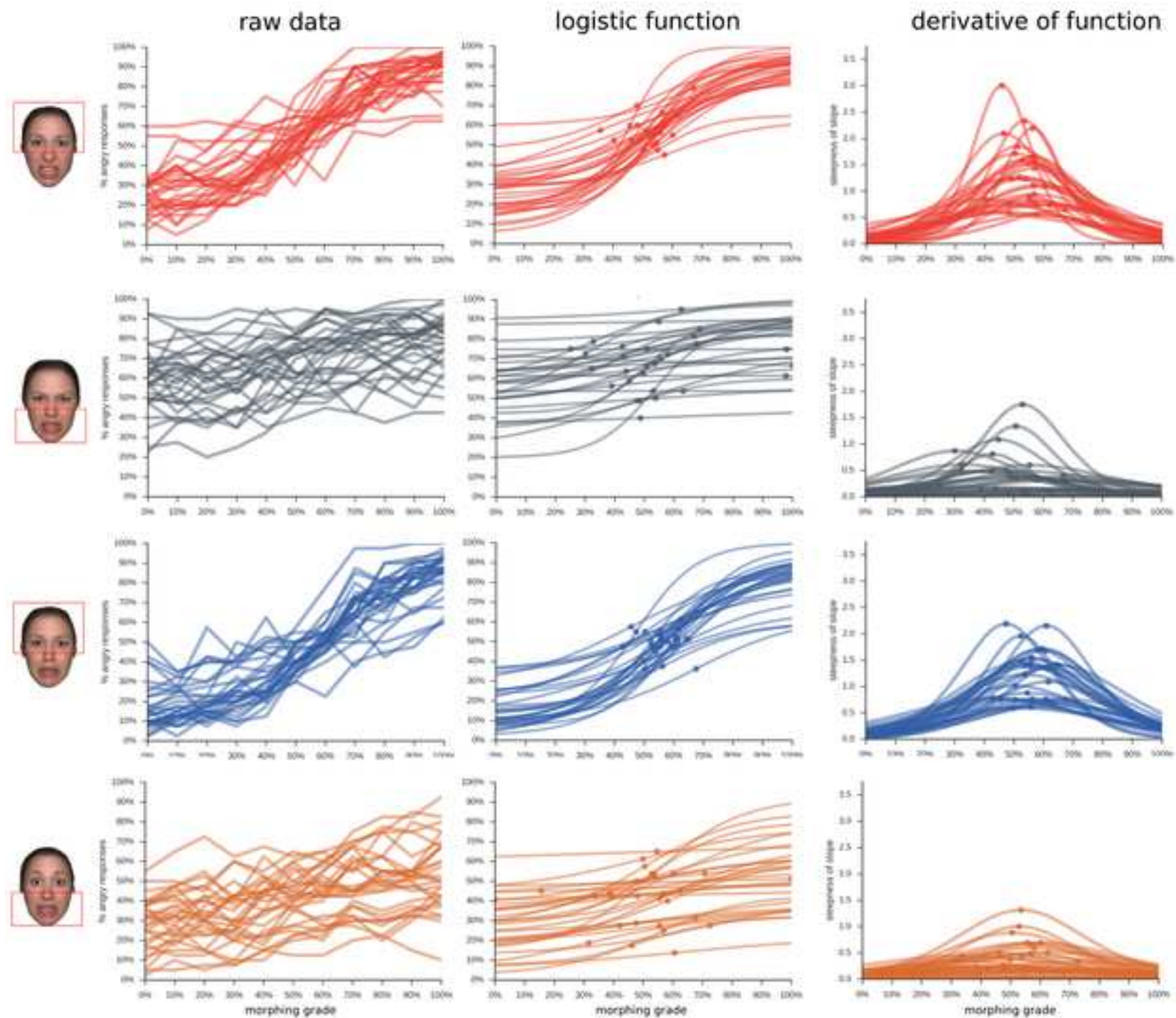




Fig8

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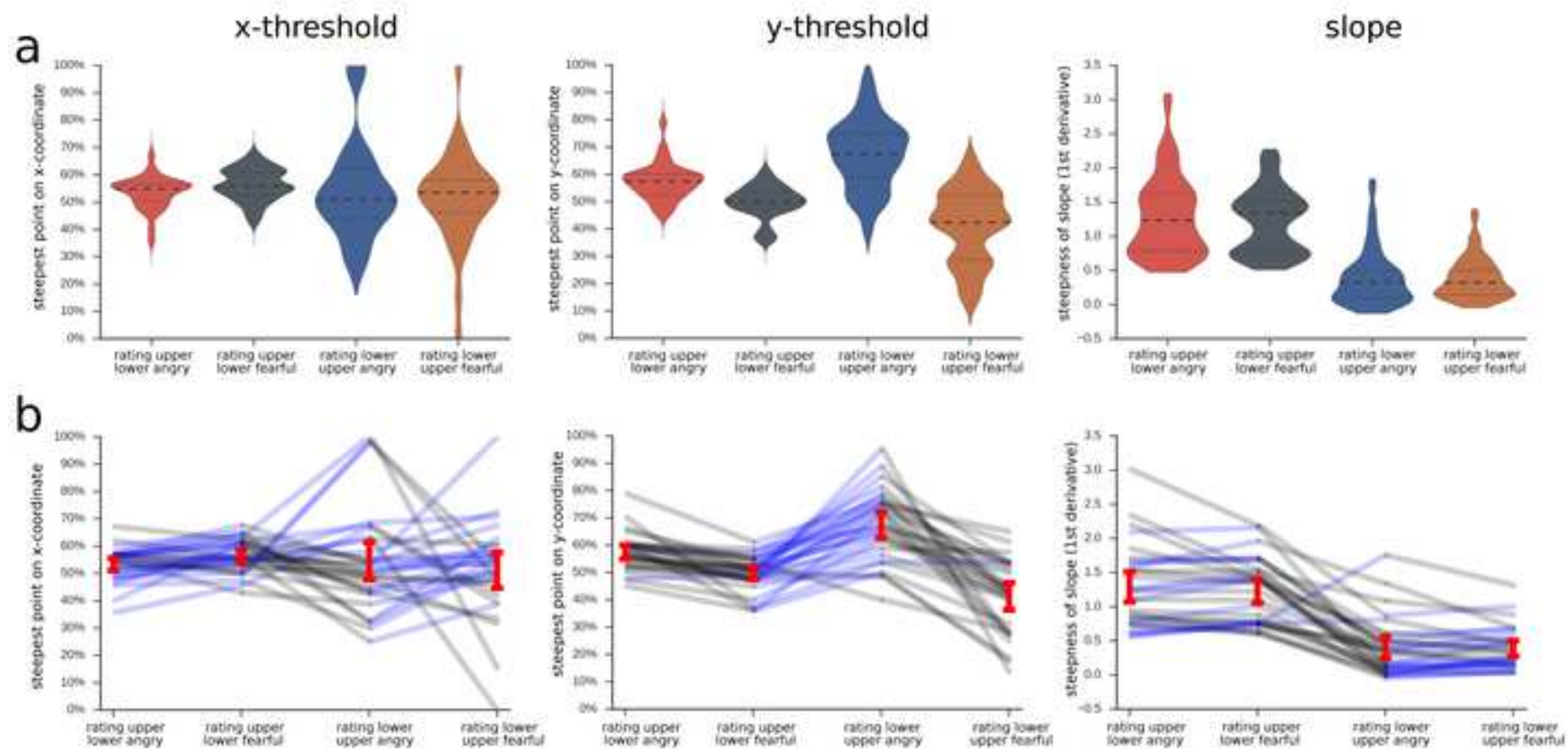
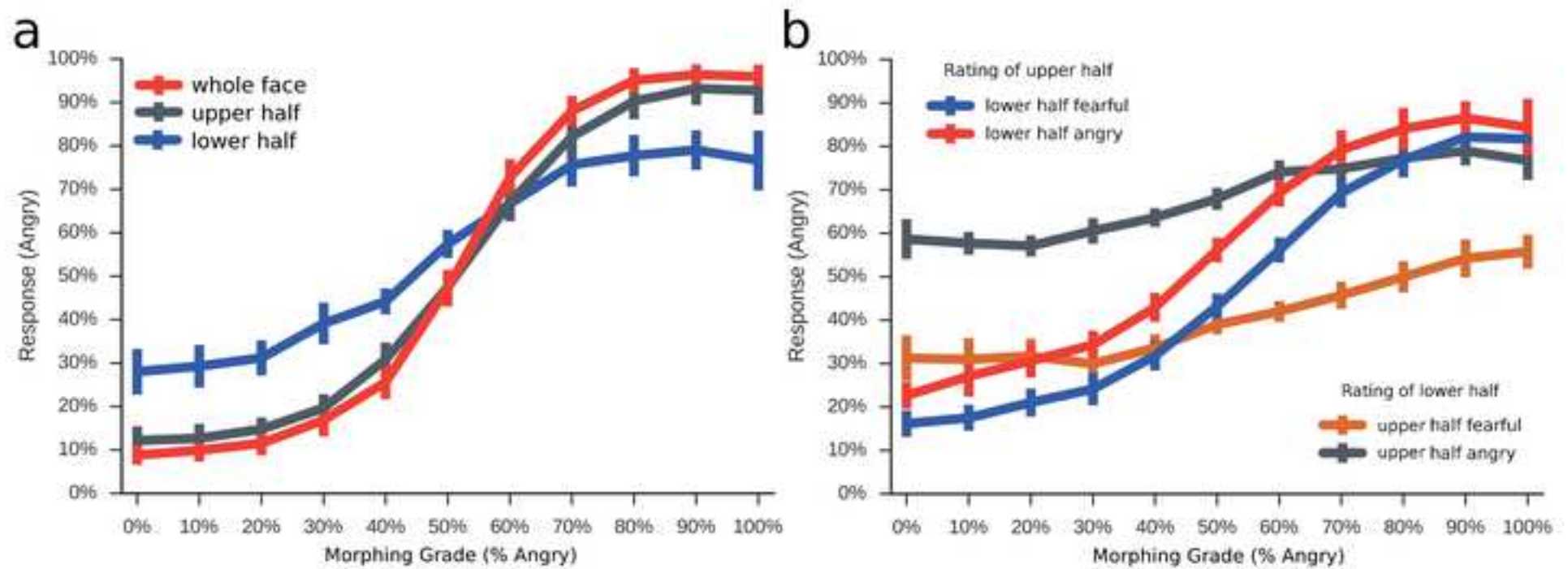




Fig9

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S1 Code

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# **Categorical Perception of Fear and Anger Expressions in Whole, Masked and Composite Faces.**

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# ABSTRACT

Human observers are remarkably proficient at recognizing expressions of emotions and at readily grouping them into distinct categories. When morphing one facial expression into another, the linear changes in low-level features are insufficient to describe the changes in perception, which instead follow an s-shaped function.

Important questions are, whether there are single diagnostic regions in the face that drive categorical perception for certain pairings of emotion expressions, and how information in those regions interacts when presented together.

We report results from two experiments with morphed fear-anger expressions, where (a) half of the face was masked or (b) composite faces made up of different expressions were presented.

When isolated upper and lower halves of faces were shown, the eyes were found to be almost as diagnostic as the whole face, with ~~the response function showing a steep category boundary preserved categorical perception~~. In contrast, the mouth allowed for a substantially lesser amount of accuracy and ~~responses followed a much flatter psychometric function nearly absent categorical perception~~.

When a composite face consisting of mismatched upper and lower halves was used and observers were instructed to exclusively judge either the expression of mouth or eyes, the to-be-ignored part always influenced perception of the target region. In line with experiment 1, the eye region exerted a much stronger influence on mouth judgements than vice versa. Again, categorical perception was significantly more pronounced for upper halves of faces.

The present study shows that identification of fear and anger in morphed faces relies heavily on information from the upper half of the face, ~~most likely particularly~~ the eye region. Categorical perception is possible when only the upper face half is present, but

compromised when only the lower part is shown. Moreover, observers tend to integrate all available features of a face, even when trying to focus on only one part.

# 1. INTRODUCTION

Facial expressions are a powerful means of conveying information about the emotional state of an individual. Recognizing and correctly interpreting these non-verbal signs is of vital importance for successful social interaction [1].

Faces are not only complex stimuli, but their expressions can often be subtle and ambiguous. Despite this, human observers can readily recognize expressions of emotions and assign them distinct labels. A large body of research suggests that there are a number of basic emotions which are correctly recognized by most observers [2], although their exact number is under debate [3]. Even when the expressions' intensity varies continuously, as in manipulated faces where one expression is gradually morphed into another, human observers readily group them into distinct categories with a high level of confidence [4].

Such categorical perception is demonstrated by identification tasks where linear changes in low-level features (e.g. basic visual properties like colour or shape) lead to non-linear changes in perception, which are best described by a sigmoid function with a steep category boundary. In general, categorical perception refers to the phenomenon that objects from the same category will be perceived as more similar than objects from different categories [5], despite being equally far apart from each other on a given physical dimension. One example is human colour perception, where two different wavelengths will only be perceived as two different colours when a category boundary is crossed [6]. For facial expressions, categorical perception has been demonstrated in a number of seminal studies [7–9].

Faces are inherently multidimensional stimuli, and in face processing categorical perception can relate to different dimensions (identity, age, attractiveness, gender, emotion), which in turn may depend on different facial features. Regarding emotion, each

expression of a basic emotion can be described in terms of a number of muscle groups that are active when a person shows that particular emotion [10]. For example, fear will most frequently be expressed in the face by the brows raised and drawn together, the upper eyelids raised, the lower eyelids tensed, the lips stretched back and, in some cases, the mouth opened [11,12]. Furthermore, masking studies have demonstrated that each basic emotion is recognized through different diagnostic areas of the face [13]. For example, fear can be best recognized when the eyes are visible, while happiness is best inferred from the mouth region. On the other hand, eye tracking studies have shown that for all six basic expressions, including ones of low intensity, people focus primarily on the eyes [14]. While eye tracking studies shed light on how observers usually inspect faces under free viewing conditions, masking studies help to understand what information is indispensable in order to make a correct decision. Therefore a masking approach helps to make causal inferences about the diagnostic value of each facial feature.

To understand categorical perception of facial expressions, it is essential to know which information in the face is used to make a categorical decision and how facial features are integrated into a perceptive whole, so that successful categorization can occur.

The term 'holistic processing' refers to the fact that faces are preferentially processed as a whole [15–17]. Findings from the composite face illusion, where complementary upper and lower face halves are combined into a whole face, serve to illustrate this mechanism: It is considerably more difficult to make a decision about the properties of either half in such composites than it is to judge each part in isolation [18]. For example, it may be more difficult to recognize a person's identity from a lower face half when it has been combined with the upper face half of another person, while the same task is easy when each half is presented in isolation [18]. Using happy and angry faces, interference from composites with mis-matching expressions have been found reflected in slower reaction times [19,20].



So far, both masking studies [13] and composite face paradigms [19] used full-blown facial expressions instead of gradually morphed faces. Chen and Chen [21] have used morphed happy-sad expressions in a composite face, but always asked to judge the whole face and not its parts, therefore making it difficult to draw inferences on how the perception of one facial feature is influenced by another one.

Masking or composite face studies with morphed faces however allow to better describe human behaviour in psychophysical terms, as the subjective perception dissociates from the changes in low-level features. They also allow to better understand how we process subtle and ambiguous expressions, which are arguably most relevant in daily life.

Therefore, it is useful to investigate the relationship of categorical perception and featural (i.e. focusing on single parts) or configural (i.e. integrating parts into a whole) face processing with masked and composite faces. Main questions are, whether there are diagnostic regions in the face that are sufficient to allow for categorical perception, and whether multiple features need to be integrated when making categorical judgements.

Therefore, to better understand mechanisms of categorical perception of facial expressions, a promising approach is to break down the face into its features and understand how each contributes to identifying a certain expression. In a second step, the features can be re-assembled into a whole and one can investigate how they are integrated to infer an expression from a whole face.

To address these questions, two experiments with faces morphed from fear to anger were performed. Beginning with the seminal work by Etcoff and Magee [9], fear-anger pairings have been frequently used for investigating categorical perception (e.g. [7,8] ; cf. [5]).

Previous masking studies with full-blown fear and anger expressions have shown that both expressions are mainly recognized from the eye region [13] and studies with neurological patients also point to a special role of the eyes for recognizing fear [22]. Therefore, one can hypothesize that categorical perception of fear and anger will rely mostly on the features in

the upper half of the face. In line with research on the composite face illusion [19,20], the more informative half of the face should also dominate the perception of a full face.

In the present study, the first experiment was carried out to investigate how observers make categorical decisions from morphed faces when only a limited amount of features is present. In this experiment, an upper face half, a lower face half, or an intact face ~~were~~~~was~~ shown and observers were asked to categorize each morph as being either angry or fearful. The second experiment investigated how this relates to performance in a composite face task, when participants have to ignore one half of the face to make an optimal decision. In this experiment, a face assembled of an upper and lower half was presented. The observers had to judge only one half at a time, while the distractor half was showing either full-blown anger or fear. Together, these experiments aim to elucidate the psychophysics of recognizing facial expressions.

## **2. EXPERIMENT 1**

### **2.1 Participants**

30 participants took part in the experiment (22 female). Mean age of participants was 25 years (range: 18-32). Participants received course credit or 5 EUR for participation.

Participants reported no history of neurological or psychiatric illness and had normal or corrected-to-normal vision. The study was approved by the ethics board of Bielefeld University (Ethic Statement Nr. 2014-010). All participants gave oral informed consent before taking part in the experiments.

Two participants showed performance close to guessing for all conditions combined with exceptionally fast reaction times, indicative of non-compliance. Their data were excluded, leaving 28 participants for further analysis.

### **2.2 Material**

Anger and fear pictures of 20 identities (10 male, 10 female) were selected from the KDEF [23] and NimStim [24] databases. The pictures were used to generate morphs in 9 steps with Gimp 2.6 ([www.gimp.org](http://www.gimp.org)) and the GAP toolbox, resulting in 11 morphing grades including the original images. Faces were divided into an upper and lower half, with the border defined as being above the nostrils at the bridge of the nose of the middle morph. This border was defined for each face identity and subsequently applied to all of its morphs.

In Experiment 1 there were three visibility conditions (whole face, upper half, lower half). The half of no interest was blurred with a very broad Gaussian filter, preserving only a rough outline of the face, thereby conveying a feeling of wholeness, while rendering the masked features invisible (cf. Fig 1).

**[Figure 1. Design of Experiment 1.** Illustration of a face morphed from the original fearful (outer left) to the original angry expression (outer right) in 9 intermediary steps, resulting in a total of 11 face morphs; a, whole face; b, upper half intact ('eyes' condition); c, lower half intact ('mouth' condition); due to copyright restrictions, the depicted example is an in-house generated face which was not used in the present experiment.]

### **2.3 Design**

A two-alternatives forced choice identification task was used, in which participants had to decide for each face whether its expression was 'angry' or 'fearful'. Each of the 20 identities was presented in 11 morphing grades. The experiment consisted of two runs with a total of 40 trials per cell, resulting in a resolution of 2.5% for identification performance. The first run was repeated after a short break, to allow for analyses of intra-subject stability. This resulted in a total of 440 trials per masking condition (11 morphs x 20 identities x 2 runs). Pictures were shown with no time limit until a response was given, after which the next stimulus was shown directly, to allow for smooth work-flow. Participants were able to monitor their progress on a status bar presented at the bottom of the screen. Order of stimuli was randomized, the only constraint being that two subsequent trials never contained the same face identity.

Participants had to press the left or right mouse button to indicate whether the target face part showed an angry or fearful expression (button assignment counterbalanced between participants). Experiments were performed using Presentation software (Version 17.1, [www.neurobs.com](http://www.neurobs.com)). All experiment files, including raw data, can be found in supplementary files S7 Code and S8 Dataset.

### **2.4 Analysis**

To characterise the participants' performance, a logistic function was fitted to their data.

The logistic function ( $F_{\text{logistic}}(x; \alpha, \beta) = 1 / [1 + \exp(-\beta(x - \alpha))]$ ) is well-suited to describe

observers' performance in psychometric terms [25, p. 82]. ~~It also provides slope~~

~~information ( $\beta$  parameter) to quantify the steepness of the curve at the point of guessing.~~

An s-shaped logistic function with a steep slope is indicative of high precision in

distinguishing between two categories and little uncertainty [25, p. 20]. If categorical

perception occurs, the steepest point in the psychometric curve corresponds to the category

boundary, as this is the point where two stimuli will be discriminated best [5]. ~~However, it~~

should be noted that the logistic function might occur for any linear system limited by

~~Gaussian noise [26], including decisions based on simple image features such as contrast~~

~~[27]. However, while the mere presence of a nonlinear or s-shaped curve in an~~

~~identification task is not sufficient to claim the occurrence of categorical perception, its~~

~~absence argues strongly against it. Therefore, a linear function ( $F_{\text{linear}}(x; \alpha, \beta) = \beta * x + \alpha$ ), as an~~

~~approximation to a logistic function with uniform slope was fitted to the data. If the logistic~~

~~and linear function provide a similar fit for a certain condition, this would indicate that~~

~~observers are unable or at least very poor at distinguishing between two distinct categories.~~

To derive the point of steepest increase, the limits of the logistic function were always

defined by the lowest and highest value of the raw data, so that it provided an optimal fit

even in cases when responses never crossed 50% guessing (cf. Experiment 2). Functions

were fitted using an iterative optimization strategy, employing a non-linear least-squares

procedure to derive the ~~parameters for threshold intercept and slope which describe the~~

~~best-fitting function for the raw data. These parameters, together with the sum of squared~~

~~errors (ss<sup>2</sup>) of the best-fitting linear or logistic function~~ The steepest point of each curve

was defined by computing the first derivative of the function. The position of this point on

the x- and y-axis (threshold) as well as its value (slope) were then compared between

conditions.

Furthermore, for cross-validation, data from one half of the experiment were used to predict the other half of the data. Since each participant performed every trial twice, data from the first half of the experiment were used to predict the data from the second half (and vice versa). For each condition, one half of the participants' data was compared to all conditions of the other half using sums of squared errors ( $ss^2$ ) ~~used to fit a logistic or linear function~~. This allowed assessing whether results were stable across experiment repetitions. The more similar two conditions are, the smaller the  $ss^2$  should be. Using sums of squared errors has the advantages of being an intuitive measure of similarity and being virtually assumption-free [28, p. 106].

~~used to fit a logistic or linear function. Subsequently, the  $ss^2$  between these data and the left-out half were computed. For example, a logistic function was fit to the first half of the whole face condition and this fitted function was then compared to the raw data of the second half of the experiment, using  $ss^2$ .~~

~~This allowed assessing whether it is possible to predict what condition a participant was in, given the responses made in a previous run and the function fitted to that data.~~

We also investigated whether left-out data can be better predicted by using raw data or by a logistic function fitted to these data. If a logistic function provides a superior fit to left-out raw data (smaller  $ss^2$ ), this should indicate that the simplifying assumption made by the psychometric function are sensible and add to our understanding of the underlying perceptual mechanisms.

Data analysis was performed with Python 2.7.9 ([www.python.org](http://www.python.org)) using NumPy, SciPy, Pandas, Matplotlib, and the IPython Notebook, all as provided with Anaconda 2.2.0 (Continuum Analytics; [docs.continuum.io/anaconda](http://docs.continuum.io/anaconda)). Full code and output for all analyses can be found in the online supplement. Refer to S1 Code and S2 Code for data import and restructuring; S3 Code for main data analysis; S4 Code for fitting psychometric functions;

~~S5~~ Code for ~~and~~ cross-validation; and to ~~S65~~ Code for analyses of single face identities.

Analyses of Variance (ANOVA) for repeated measure designs were additionally carried out using IBM SPSS 22.

## 2.5 Results

### 2.5.1 Comparison of response curves for different masking types

Identification performance was compared across all 11 morphing grades for the three masking conditions (full face, upper face half, lower face half). Participants' performance is illustrated in Fig 2. A 3x11 repeated-measures ANOVA showed a significant main effect of morphing grade, reflecting that anger responses increase as the faces are morphed towards this expression ( $F_{(10,270)}=620.7, p<0.001, \eta_p^2=0.96$ ). There was no main effect of masking condition ( $F_{(2,54)}=2.3, p=0.112, \eta_p^2=0.08$ ), indicating that there is no bias that would shift the responses between conditions. A significant condition-by-morphing grade interaction ( $F_{(20,540)}=63.5, p<0.001, \eta_p^2=0.70$ ) indicated that the shape of the response curve differs between conditions. Paired t-tests for repeated measures and the Wilcoxon signed rank test as its non-parametric equivalent were carried out to test differences between conditions for all morphing grades. Results were only considered significant if the p-value for both metrics fell below  $\alpha=0.05$ .

Identification performance was best (i.e. significantly farthest from guessing) for the whole face, compared both to the upper (all  $ps<0.05$ , except 50% angry morphs) and lower half (all  $ps<0.05$ , except 60% angry morphs). Furthermore, performance was significantly better for the upper than for the lower half (all  $ps<.05$  except for 50% and 60% angry morphs). This indicates that observers were able to make the most accurate decisions when presented with a whole face, followed by face halves containing only the eye region.

Performance was worst when only the mouth region was visible.

Judgements of the eye region closely resembled the whole face responses, as indicated by a significantly smaller difference between upper and whole face decisions compared to lower and whole face decisions (all  $ps<0.05$  for pairwise comparisons of differences, except for 50% and 60% morphs).



[ **Figure 2. Main Results Experiment 1.** Percent angry responses (y-axis) across the 11 morphing grades morphed from fear to anger (x-axis) for the three different visibility conditions (coloured lines); ~~smaller right hand figures depict responses on single-participant level for each condition;~~ 'whole face', whole face is visible (no masking); 'lower half', lower face half is visible (upper half is masked); 'upper half', upper face half is visible (lower half is masked).]

### 2.5.2 Cross-validation of conditions

If differences between conditions are genuine and stable, each condition should be able to predict itself best, e.g. the whole face condition of the first half of the experiment should be most similar to the whole face condition of the second half.

This was confirmed by split-half cross-validation with each half of the experiment used once as test and as training set, within each participant. Each condition was significantly closest to its analogue from the other half of the experiment, as expressed in significantly smallest  $ss^2$  for these pairings (all  $p < 0.01$  for pairwise comparisons).

Furthermore, the upper and whole face conditions were significantly more similar to each other than to the lower half condition ( $p < 0.01$ ). This stronger similarity of the eye region to the whole face ratings further corroborates that the upper half carries more information about fear and anger expressions than does the mouth region.

### ~~2.5.3 Comparison of the superiority of a logistic fit to the data~~

~~A linear and logistic function were both fitted to the data of each participant and  $ss^2$  were computed for all three masking conditions (Fig 3a), with a better fit indicated by smaller  $ss^2$ . The superiority of the logistic over the linear function was significantly greatest for the~~

~~whole face, followed by the upper face half, and lower face half, respectively ( $F_{(2,54)}=34.1$ ,  $p<0.001$ ,  $\eta_p^2=0.56$ ; all  $ps<0.001$  for pairwise comparisons).~~

### 2.5.3 Comparison of **thresholds and slopes of the logistic function between conditions**

When fitting a logistic function to each participant's data for each condition, the steepness of the slopes can be compared as measure for the presence of a category boundary, with a steep slope indicating stronger categorical perception (Fig 3).

Results show that the ~~slopes were steepest for the whole face condition, followed by the upper and lower half ( $F_{(2,54)}=128.2$ ,  $p<0.001$ ,  $\eta_p^2=0.83$ ; all  $ps<0.001$  for pairwise comparisons)~~ logistic functions for all conditions had their thresholds close to 50% guessing, with no significant differences between conditions (Table 1, Fig 4). There was a clear effect for the slope, which was steepest for the whole face condition, followed by the upper and lower half (Table 1, Fig 4; all  $ps<0.001$  for pairwise comparisons), indicating a more abrupt shift from fear to anger responses when the whole face is visible and ~~a more~~ smooth shifts in responses when viewing the lower face half.

[ **Figure 3. Data on single participant level.** Each line represents a participant; each row of the figure indicates a masking condition, as illustrated by the example stimulus on the left-hand side. Each column indicates a different metric describing the data: 'raw data', the original data for each participant; 'logistic function', the best-fitting logistic function for each individual participant, with point of steepest slope indicated by a dot; 'derivative of function', the slope of the fitted logistic function, with the highest value indicated by a dot.]

[**Figure 4. Parameters of logistic function for different masking conditions.**

a, violin plots with width indicating density of values, inner lines indicating median and 25% and 75% quartiles; b, red bars indicate 95% confidence intervals of the mean for each condition; line graphs in the background depict the raw data of each participant; black lines indicate that the participant's value for the left-hand condition is numerically bigger than the right-hand value; blue line indicates that the value is smaller for the left-hand compared to right-hand condition; 'whole face', whole face is visible (no masking); 'upper half', upper face half is visible (lower half is masked); 'lower half', lower face half is visible (upper half is masked).]

**Table 1. Comparison of curve parameters for experiment 1**

condition	mean (SD)			F	p	$\eta_p^2$
	whole face	upper half	lower half			
x-threshold	0.53 <sup>a</sup> (0.04)	0.53 <sup>a</sup> (0.06)	0.51 <sup>a</sup> (0.08)	1.83	0.180	0.064
y-threshold	0.53 <sup>a</sup> (0.05)	0.53 <sup>a</sup> (0.05)	0.55 <sup>a</sup> (0.11)	0.77	0.415	0.028
slope	2.17 <sup>a</sup> (0.53)	1.64 <sup>b</sup> (0.47)	0.96 <sup>c</sup> (0.38)	105.30	<0.001	0.796

Results of a repeated measures ANOVA for the different curve parameters; means in the same row sharing the same superscript letter do not differ significantly from one another at  $\alpha=0.05$ ; degrees of freedom (df) for x-threshold: 1.5,41.6 (Greenhouse-Geisser corrected); df for y-threshold : 1.3, 33.9 (Greenhouse-Geisser corrected) ; df for slope: 2,54.

## 2.5.45 Cross-validation of response curves for different masking types

Left-out data from one half of the experiment were predicted using data from the other half of the experiment with the two runs of the experiment used for cross-validation. Each condition was modelled for one half of the experiment using raw data a linear or logistic function fitted to these data. These training sets were then compared to the left-out half of the experiment to check how the models compare to each other in predicting new data.

The results of the cross-validation analysis show that in fact the logistic function fits left-out raw data significantly better than the raw data does ( $p < 0.001$  for all conditions), indicating its suitability for describing the participants' performance. (Fig 3e) show that the superiority of a logistic over a linear function for predicting left-out data is largest for the whole face condition and weakest when only the lower face half is visible ( $F_{(2,54)} = 21.0$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.44$ ;  $p$ s  $< 0.05$  for all pairwise comparisons).

## 3. EXPERIMENT 2

### 3.1 Methods

Mean age of participants was 24 years (range 19-29). Of the 30 participants, 24 were female. Participants received course credit or 7EUR for participation and gave oral informed consent before starting the experiment.

The same boundary to divide faces into lower and upper halves as in experiment 1 was used and design choices were identical to experiment 1, with the following exceptions:

This time 100% fearful or 100% angry expression halves were combined with the morphed pictures to create the composite face illusion. There were four conditions: 'lower half 100% angry' (Fig 54a), 'lower half 100% fearful' (Fig 54b), 'upper half 100% angry' (Fig 54c) and 'upper half 100% fearful' (Fig 54d). The complementary half was presented in 11 morphing steps, and was the part which the observers were asked to identify as either angry or fearful. This part was always framed by a red square (cf. Fig 54). Participants were explicitly instructed to focus only on the framed face half and to ignore the other half.

Unlike experiment 1, order of conditions was blocked, to make it easier for the participants to focus on the part of interest. Each block required either always judging the upper half or always judging the lower half, and consisted of 440 trials, with block order counterbalanced between participants. Within blocks, order of the 20 face identities, the 11 morphed face halves and whether the to-be-ignored half was fearful or angry were randomised.

[ **Figure 54. Design of Experiment 2 (Composite Face).** Illustration of a face morphed from the original fearful (outer left) to the original angry expression (outer right) in 9 intermediary steps, resulting in a total of 11 face morphs; a, eye judgements with 100% angry lower face half; b, eye judgements with 100% fearful lower half; c, mouth judgements with 100% angry upper face half; d, mouth judgements with 100% fearful

upper half; conditions a and b or conditions c and d were always presented in one block, to aid participants in focusing on one face half only; due to copyright restrictions, the depicted example is an in-house generated face which was not used in the present experiment. ]

One participant reported to have only focused on the mouth region throughout the experiment, ignoring which face half was currently framed. These data were excluded, leaving 29 data sets for analysis.

## **3.2 Results**

### **3.2.1 Comparison of response curves for different composite faces**

Depending on the viewing condition, responses for the attended face half were biased in the direction of the to-be-ignored face half (Fig 65, Fig 7).

A 2x2x11 ANOVA with the factors upper/lower face half, anger/fear distractor and morphing grade (fear to anger) revealed a main effect of morphing grade ( $F_{(10,280)}=213.7$ ,  $p<0.001$ ,  $\eta_p^2=0.88$ ), a main effect of emotion ( $F_{(1,28)}=109.6$ ,  $p<0.001$ ,  $\eta_p^2=0.80$ ) and significant interactions between all factors (all  $ps<0.001$ ). The main effect of emotion in the distractor half reflects that responses for the eye region were shifted towards anger when the lower face half was angry, and towards fear when the lower half was fearful ( $p<0.01$  for all 11 morphing grades). The same bias occurred for the judgements of the mouth region, when the upper half was either angry or fearful (Fig 65e; all  $p<0.001$ ). The interaction effect between emotion and face half ( $F_{(1,28)}=26.0$ ,  $p<0.001$ ,  $\eta_p^2=0.48$ ) reflects that the bias was significantly stronger for mouth judgements than for eye judgements, indicating that the upper face half exerts a stronger influence on the lower half than vice versa. Across all 11 morphing grades, fearful and angry distracting halves led to

bigger differences in mouth judgements, compared to the differences in eye judgements (all  $p < 0.001$ , for pairwise comparisons of differences).

[ **Figure 65. Main Results for Composite Faces.** Percent angry responses (y-axis) across the 11 morphing grades morphed from fear to anger (x-axis) for the four different composite face conditions (coloured lines); ~~left hand figures depict mean results with 95% confidence intervals on group level; right hand figures depict responses on single-participant level for each condition;~~ 'lower fearful', observers judge the upper half, while the lower half is always 100% fearful; 'lower angry', observers judge the upper half, while the lower half is always 100% angry; 'upper fearful', observers judge the lower half, while the upper half is always 100% fearful; 'upper angry', observers judge the lower half, while the upper half is always 100% angry. ]

[**Figure 7. Data on single participant level.** Each line represents a participant; each row of the figure indicates a composite face condition, as illustrated by the example stimulus on the left-hand side. Each column indicates a different metric describing the data: 'raw data', the original data for each participant; 'logistic function', the best-fitting logistic function for each individual participant, with point of steepest slope indicated by a dot; 'derivative of function', the slope of the fitted logistic function, with the highest value indicated by a dot.]

### 3.2.2 Cross-validation of conditions

Split-half cross-validation with each half of the experiment used once as test and as training set showed that each condition was significantly closest to its analogue from the other half of the experiment (all  $p < 0.01$  for pairwise comparisons), indicative of reliable differences between conditions.

### **3.2.3 Comparison of the superiority of a logistic fit to the data**

The superiority of a logistic function over a linear function was significantly stronger for eye judgements as compared with mouth judgements (Fig 6a; main effect of face half  $F_{(1,28)}=13.7, p<0.001, \eta_p^2=0.33$ ; all  $p<0.05$  for pairwise comparisons), indicating that when observers judge the upper face half, their response function is significantly more s-shaped than when they judge the lower face half.

### **3.2.34 Comparison of threshold and slopes of the logistic function between conditions**

As in experiment 1, the steepest point of the psychometric function was located around the intermediary morph (50% fear/50% anger). However, responses were significantly shifted on the y-axis for the different viewing conditions, indicating that there was a response bias towards fear or anger, depending on the expression of the to-be-ignored half (Table 2).

When the to-be-ignored half was more fearful, the threshold was shifted towards fear, and when that half was more angry, responses were shifted towards anger. This main effect was accompanied by a significant interaction, reflecting that this bias was much strongest when the lower face half had to be rated and the upper face was the distractor (Fig 7, Fig 8, Table 2). Also, when judging the lower face half, the psychometric functions were almost flat, while they had a steep slope when the upper half had to be judged (Fig 7, Table 2).

When fitting a logistic function to each participant's data for each of the three conditions, the steepness of the slopes was significantly higher for upper than for lower face half judgements (Fig, Table), indicative of a more abrupt change in fear/anger decisions when viewing the upper half. However, since lower half judgements were biased by the eye region to the point where for many participants performance never crossed 50% guessing, slope parameters for the mouth regions are difficult to interpret.

[Figure 8. Parameters of logistic function for different composite face conditions.



a, violin plots with width indicating density of values, inner lines indicating median and 25% and 75% quartiles; b, red bars indicate 95% confidence intervals of the mean for each condition; line graphs in the background depict the raw data of each participant; black lines indicate that the participant's value for the left-hand condition is numerically bigger than the right-hand value; blue line indicates that the value is smaller for the left-hand compared to right-hand condition. ]

Table 2. Comparison of curve parameters for experiment 2													
Condition	Mean (SD)				Contrast								
	rating of upper half		rating of lower half		face half			emotion			interaction		
	lower angry	lower fearful	upper angry	upper fearful	F <sub>(1,28)</sub>	p	$\eta_p^2$	F <sub>(1,28)</sub>	p	$\eta_p^2$	F <sub>(1,28)</sub>	p	$\eta_p^2$
x-threshold	0.53 <sup>a</sup> (0.06)	0.56 <sup>b</sup> (0.06)	0.55 <sup>a,b</sup> (0.19)	0.51 <sup>a,b</sup> (0.18)	0.77	0.389	0.03	0.01	0.939	<0.01	1.44	0.241	0.05
y-threshold	0.57 <sup>a</sup> (0.07)	0.50 <sup>b</sup> (0.06)	0.67 <sup>c</sup> (0.13)	0.41 <sup>d</sup> (0.14)	0.22	0.624	0.01	100.23	<0.001	0.78	24.67	<0.001	0.47
slope	1.29 <sup>a</sup> (0.61)	1.23 <sup>a</sup> (0.47)	0.40 <sup>b</sup> (0.43)	0.39 <sup>b</sup> (0.31)	69.31	<0.001	0.71	0.18	0.178	0.06	0.54	0.542	0.01
Results of a repeated measures ANOVA for the different curve parameters of experiment 2; means in the same row sharing the same superscript letter do not differ significantly from one another at $\alpha=0.05$ .; 'face half', main effect of face half which is rated; 'emotion', main effect of whether the to-be-ignored half is fearful or angry; 'interaction', interaction between the two factors													

### 3.2.45 Cross-validation of response curves for different masking types

Analogous to experiment 1, results of the cross-validation analysis show that the logistic function was better able to fit left-out raw data than the raw data it was based on ( $p<0.001$  for all conditions), indicating that fitting a logistic function to the present data is suitable. Again, this might indicate that the fitting of a logistic function reduces irrelevant noise in the raw data and is therefore better able to generalize to new measurements. ~~over a linear function for predicting left-out data is larger for upper half versus lower half judgements (Fig 6c), but only significant when the ignored face half was fearful ( $p<0.05$ ). The difference was only numerically superior when an anger mouth was present (significant interaction effect  $F_{(1,28)}=4.8$ ,  $p=0.038$ ,  $\eta_p^2=0.15$ ).~~

## 4. RESULTS FOR SINGLE FACE IDENTITIES

Since 20 different face identities were used as stimuli in the experiments, the present results may underestimate or blur the sigmoid shape of the response functions, due to averaging over a heterogeneous set of stimuli with shifted ~~thresholds~~~~interepts~~.

Therefore, data of both experiments were re-analysed by fitting a logistic function to the responses to each of the 20 individual face identities, averaged across participants.

Subsequently, the ~~thresholds~~~~interepts~~ were shifted to be uniformly at the mean value of the respective condition, so that all curves share the x- and y-threshold and only differ in their (unchanged) slopes.~~50%, so that each curve is at 50% guessing (y-axis) when the face is 50% angry (x-axis).~~ The necessary shift ~~was~~ determined from the fitted logistic functions ~~was and~~ then applied to the underlying raw data, allowing to compare how the curves would be shaped, given equal ~~thresholds~~~~interepts~~ for all face identities. The results are illustrated in Fig ~~97~~ and are described in-depth in S~~65~~ Code. Visual inspection of the data suggests that a sigmoid function clearly emerges only for whole faces and upper halves in experiment 1 and for upper halves in experiment 2 when accounting for potential variability between faces, ~~thereby closely replicating the above results and demonstrating their generalizability across many stimuli.~~

[ **Figure ~~97~~.** correction for different ~~thresholds~~~~interepts~~ between face identities. Main analyses for both experiments after modelling responses to each face identity individually and shifting the ~~thresholds~~~~interepts~~ to be at the respective group mean~~-uniformly at 50%~~; a, results for experiment 1 (masking); b, results for experiment 2 (composite faces); note that a different number of data points is available for each bin on the x-axis, as functions may be partly shifted out of the displayed range, rendering estimates at the extremes less reliable; also, variability is modelled at the stimulus level, not at participant level.

~~especially in experiment 2, mouth judgements were strongly biased, with few responses at~~  
~~50% guessing~~; please refer to Supplement S~~65~~ for more details on the analysis procedure.]

## 5. DISCUSSION

The present study set out to investigate what part of the face is most diagnostic for categorical perception of fear-anger morphed expressions, and how this information is integrated when presented in a composite face.

Experiment 1 showed that the upper face half is more diagnostic than the lower half for deciding between fearful and angry expressions in an identification task. The upper half alone was sufficient for high identification performance, closely reflecting the whole face condition. Its perception could also be well-described by a logistic function with a steep category boundary, providing converging evidence for categorical perception based on the upper face half alone. When viewing the lower half, responses were significantly closer to chance, were less s-shaped and had a comparably shallower slope.

In experiment 2, it was expected that the to-be-ignored halves of the face would bias performance, and that regions that have proven most diagnostic in experiment 1 should exert a stronger biasing influence over complementary face parts than vice versa.

Accordingly, results indicated that both eye and mouth regions bias judgements on the respective other face half, with strongest influences exerted by the eyes, leading to what might be considered a breakdown of performance for mouth judgements. This effect is noteworthy, as information in the mouth region is equally present in both experiments. Nevertheless, when instructed to evaluate the mouth and ignore the eyes in a composite face, the participants' ratings reflect the expression of the eyes numerically more strongly than they reflect mouth judgements. This means that a cue that is reasonably useful for expression recognition in isolation, will be of almost no use when exposed to the influence of a strongly diagnostic cue.

The influence of the mouth on eye judgements should be considered equally striking, since it illustrates that even a very diagnostic cue that allows for recognition levels almost as

high as a whole face, can be subject to significant bias from a substantially weaker cue.

This suggests that even when analytical processing of a single feature is sufficient to allow for categorical perception, human observers seem to integrate features into a whole whenever possible.

The dominance of the eye region in the present experiments is well in line with masking studies which point towards its prominent role for both fear and anger recognition [13].

Studies with neurological patients also indicate a specific importance of the eyes in fear detection [22]. Also, when asked to evaluate expressions of emotion, observers most readily fixate the eyes [14], irrespective of the emotion in question

Regarding identity recognition, there are many studies that demonstrate the importance of the eyes. For example, when a face has to be learned in a training run and later

distinguished from distractors differing in one feature, it is easier to recognize identity changes due to differences in the eyes, compared to nose or mouth changes [29]. Masking out the eyes may even represent a legal requirement in some contexts for ensuring

anonymity. Although the scientific basis for the effectiveness of this procedure is equivocal at best [cf. 30], it illustrates the paramount importance we intuitively place on

the eye region. Regarding mental states, it is also commonly assumed that they can be

assessed best from the eye region, as reflected for example in the 'reading the mind in the eyes' test [31]. Accordingly, one must ask whether the eye advantage reported in the

present study can be generalised to other features and other expressions of emotion.

Even though the eyes may be most likely fixated when judging emotions from intact faces [14], this does not necessarily imply that most information is coded in the eye region. This

becomes obvious when considering the studies carried out with patient SM, who exhibits major difficulties at recognizing fear from faces, due to a failure to fixate the eyes [22].

Nevertheless, she is virtually unimpaired at recognizing all other basic emotions. This indicates that it must be possible to recognize those emotions utilising other diagnostic

features. Accordingly, masking studies [13] and coding systems for basic emotion expressions [10], suggest that each expression can be best recognized from a set of features specific to that emotion and that focusing on the eyes cannot be the optimal strategy in all cases.

Therefore, regarding the results of the present experiments, we would predict that the basic mechanisms outlined here will be replicated with other facial expressions, but perhaps not for the same features. For example, happy-surprised pairings should be best recognized from the mouth, as both involve mainly muscles of the lower face half [10,13,32].

Interestingly, eye-tracking studies found that increased fixating of the eye region correlates with improved emotion recognition for all expressions [14,33] and argue that fixating the eyes reflects a holistic processing strategy. One could test this assumption using happy-surprise pairings and the composite face task from experiment 2. If holistic processing is associated with fixating the eyes, then eye judgements should be easier in a composite face task, even if a strongly diagnostic distracting lower face half is present.

The present findings should not only be extended to investigate other expressions, but also further elaborated for the currently used fear-anger pairing, to shed light on the basic perceptual mechanisms at work. The employed identification task could be complemented by a discrimination task. There, it should be easier to discriminate two images when they are on opposing sides of the category boundary, compared with being both sampled from within the same category [5,6]. Thus, the sigmoid curves from the present experiments could be used to predict the discrimination performance in a follow-up experiment. As differences in slope between conditions can reflect differences in variance of the underlying noise distribution or the uncertainty of the observer [34,35], it would be important to establish that a between-category advantage [5] is indeed present at the point where the psychometric function is steepest in the identification task.

On the basis of the present data from experiment 1, we would therefore predict that discrimination performance at the category boundary should be higher for eye than mouth judgements.

In the composite face task, the peak of the discrimination function ~~might should~~ be shifted to the right and left, respectively, when judging the eyes, in accordance with the ~~interecepts~~ shifts ~~of the psychometric curve~~ due to the mouth expressions. Finally the discrimination function should be almost flat when judging the mouth in a composite face, as there is virtually no crossing of a category boundary in the present data.

To further generalise the present findings regarding fear-anger pairings, averaged faces could be used, which have the advantage that idiosyncrasies would average out while expressions prototypical for a certain emotion would be emphasized [36, p. 76]. While studies on categorical perception are often performed with a very limited number of identities ( $\leq 4$ ; [cf. 4,7,8,21]), the 20 different faces used in the present experiments should be considered a valuable step towards greater generalisability. However, the fact that the mouth provided so little diagnostic information might be partly due to the fact that 12 out of the 20 face identities expressed the emotions with a closed mouth. While this might have reduced variance in the expressiveness of the lower face half, both the pressing of the lips as well as the baring of the teeth are valid anger expressions [10,12]. Of the two, lip pressing is probably much more frequent in everyday life. Also, when making statements about the importance of either eyes or mouth for recognizing an expression, it should be kept in mind that these features were rather crudely operationalised as the upper and lower face half, respectively. While such a division is standard practice in the field [18,21,37], the muscles around the nose have likely contributed to the judgements of both face halves, and the eyebrows [38] and forehead [11] might have contributed to judgements of the upper face half. While the sclera of the eyes seems crucial for fear

detection [39], anger judgements might depend more on the surrounding muscles of the eyes and the eyebrows [13,38], especially since patient SM shows no difficulty at recognizing anger [22].

Another interesting question is to what degree the failure to concentrate on one half of a composite face can be voluntarily overridden, especially since previous work has shown that emotion recognition improvements are associated with increased fixation of the eyes [33]. This could be investigated by introducing training blocks before the experiment proper, a forced minimum exposure time to discourage spontaneous responses, biofeedback from an eye-tracking device helping to fixate on a specific face part, and rewards for correct responses.

To summarise, the present studies show that identification of fear and anger in morphed faces relies heavily on the eye region, corroborating previous research [10,13,14,19].

Expanding previous work, the study shows that observers can perform categorical perception even when viewing only a single face part. For the employed fear-anger pairings, the eye region was sufficient to allow for decisions with a high degree of certainty. This demonstrates that categorical perception can emerge based on single features only, adding to our understanding of how categorization works in complex stimuli such as faces.

Even though the eye region was almost as diagnostic as the whole face, it was not immune to biasing influences in a composite face task. When a full face with conflicting expressions was shown, the psychometric curves for eye judgements were shifted in accordance with the expression in the lower half of the face. For the first time, we can therefore show that holistic perception of a full face can be explained based on the diagnostic value of its constituent parts. In addition, given that observers were aware that a holistic processing strategy impaired their performance, this illustrates that humans



involuntarily process faces as a gestalt when trying to make categorical decisions about its expression.

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## SUPPLEMENT

**S1 Code.** Data import for experiment 1

**S2 Code.** Data import for experiment 2

**S3 Code.** Main analysis and plotting

**S4 Code.** ~~Fitting of logistic function~~~~Curve fitting and cross-validation~~

**S5 Code.** ~~Cross-validation of data~~~~Additional analyses for face identities~~

**S6 Code.** Additional analyses for face identities

**S7 Code.** Complete analysis code from S1-S6 in executable IPython Notebook format

**S8 Code.** Complete code for experiment presentation in Neurobs Presentation format

**S9 Dataset.** Complete raw data of all participants

## Reviewer #1:

**The sigmoid (or S-shaped) function is not only a necessary condition for categorical perception but also a necessary condition for any noise limited perceptual functions. Thus, its absence only suggests a lack of noise in the system regardless what kind of perception it is. Here, I challenge the authors to find any example in any aspect of perception that has no s-shape logistic function (as long as the dependent variable is probability). My recommendation here is to drop the attempt to associate s-shape function and categorical perception and focus on the empirical results. The sigmoid function is too generic to derive any useful argument from its existence. Its slope, however, can be quite informative.**

We would like to thank the reviewer for helping us to improve our manuscript. We have given this point much thought and have carefully revised our manuscript.

We have removed the linear function from our manuscript altogether, as well as direct comparisons of a linear and a logistic function. However, we would find it unfortunate to simply leave out a central point of our analysis without adequate substitute and thereby deny the readers a thorough and comprehensive picture of the data. Since the reviewer commented positively on the use of slope parameters, we have shifted the emphasis of our manuscript towards this aspect and provide more detailed descriptive statistics on this aspect.

In our revised manuscript, we not only show the raw data of each participant, but also the fitted logistic function of each participant's data. In each logistic function, the threshold value (the point where the function is steepest) is additionally visualised. The computation of the threshold value has been performed in a slightly more elaborate way, so that threshold values on the x-axis (for which morphing grade is the function steepest?) as well as on the y-axis (on which level is performance at the steepest point?) are extracted. We also visualise the steepness of the function across its whole course (i.e. the first derivative of the function), so that the slope parameter and its relationship to the data can be better understood.

These parameters are visualised both as hybrid violin/box-plots (showing the distribution of the data including median and quartiles) and as raw data (with lines indicating repeated measures of the same participant) and 95% confidence intervals. Using both types of visualisation back-to-back helps to get a quick and intuitive understanding of the data and in return has allowed to shorten the text of the manuscript. The parameters are also subjected to statistical tests, which are performed as ANOVAs (in accordance with the preferences of reviewer 2) and reported in tables, to ease readability.

Also, the readers might ask whether fitting a logistic function is appropriate for the data in the first place. We briefly demonstrate this by using cross-validation, but instead of comparing a linear and logistic function, we compare the logistic function and the original raw data in their ability to fit the left-out half of the raw data. The superiority of the logistic function in the cross-validation provides a strong and unbiased indication that it is indeed well-suited to describe the participants' behavior.

While the revised version now features more figures and two new tables, we were able to slightly shorten the text. We feel that the revised version of the manuscript is not only more