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The discriminability of local cues determines the strength of holistic face processing

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ABSTRACT

Face perception is thought to result from the dynamic interplay between holistic and featural modes of processing. What determines the engagement of each mode is currently unknown. Here, we investigated whether the discriminability of local feature cues is a critical determinant of holistic/featural processing engagement. We estimated the strength of holistic processing based on observers' failure to discriminate target features independently of the context of distracter features in a congruency paradigm. Feature discriminability was manipulated by varying the dissimilarity of target features parametrically, using morphing. We observed that the size of the congruency effect decayed monotonically as a function of the dissimilarity of the target features. In other words, the more similar the target features the stronger the holistic processing. A correlation analysis confirmed that local feature discriminability reliably predicted holistic engagement at upright orientation. In contrast, when a clear local feature difference was detected, perceptual contamination by the other surrounding features was prevented. This evidence firmly suggests that the interplay between holistic/featural processing depends on the discriminability of the signal provided at the local featural level.

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1. Introduction

Following the holistic theory of face perception, faces are automatically represented as wholes with little contribution of local information (Tanaka & Farah, 1993). Holistic representations presumably arise from interactive feature processing (IFP). IFP is evidenced by the difficulty to process a given feature without being influenced by the surrounding features within the face (Sergent, 1984; Young, Hellawell, & Hay, 1987). Face inversion has been shown to disrupt IFP, making observers better at processing features independently of each other (Farah et al., 1998; Rhodes, Brake, & Atkinson, 1993). Since inversion impairs the perception of faces disproportionately more than the perception of other categories (Robbins & McKone, 2007), IFP has been viewed as uniquely engaged for faces. It is thought to enable the fast and efficient identification of faces despite their high visual similarity (Richler, Cheung, & Gauthier, 2011). Neuroimaging evidence further indicates that IFP is implemented in the Fusiform Face Area (FFA; Andrews et al., 2010; Schiltz et al., 2010; Schiltz & Rossion, 2006), a region also involved in the representation of face identity (Grill-Spector, Knouf, & Kanwisher, 2004; Mazard, Schiltz, & Rossion, 2006; but see Kriegeskorte et al., 2007; Mur et al., 2010).

In some circumstances, however, upright face perception is also known to rely on the local (i.e., independent) processing of features (e.g., Cabeza & Kato, 2000; Hayward, Rhodes, & Schwaninger, 2008; Matthews, 1978; Sergent, 1984). Accordingly, recent fMRI evidence in monkeys and humans indicated that FFA contains neurons sensitive to individual feature properties (Freiwald, Tsao, & Livingstone, 2009; Harris & Aguirre, 2008, 2010; James, Huh, & Kim, 2010; Yovel & Kanwisher, 2004).

Face perception thus results from the dynamic interplay between interactive and featural modes of processing. But it is currently unknown what determines the engagement of each mode (e.g., Farah et al., 1998, p. 484). Here, we investigated whether the discriminability of local feature cues is a critical determinant of IFP/featural processing engagement. Indeed, previous evidence hints that the strength of IFP may depend on the discriminability of local featural signals. A striking example comes from composite illusion studies. The composite illusion refers to the observation that identical features look different if they are embedded within different contexts, resulting in a dramatic performance drop (e.g., Hole, George, & Dunsmore, 1999; Young, Hellawell, & Hay, 1987). In contrast, there is no illusion when different features are embedded in identical contexts, a phenomenon often neglected or only briefly reported in composite illusion studies (e.g., Goffaux & Rossion, 2006; Mondloch & Maurer, 2008; Taubert & Alais, 2009; see also Farah et al., 1998). As a matter of fact, composite illusion studies generally rely on the use of a so-called "partial" experimental design (to refer to the terminology proposed by Gauthier & Bukach,

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2007). In "partial" designs, IFP is inferred from the interference caused by "different" face contexts upon "same" target features. In other words, IFP is confounded with response modalities (Goffaux, 2009); this has led several authors to cast doubt on the validity of "partial" design to measure IFP.

In the present experiment, we monitored the engagement of IFP using a discrimination congruency paradigm (Anaki, Nica, & Moscovitch, 2011; Farah et al., 1998; Goffaux, 2009; Richler, Tanaka, Brown, & Gauthier, 2008). In such a paradigm, subjects are required to discriminate faces based on particular target features (e.g., eyes and brows) while ignoring the context of complementary distracter features (e.g., nose and mouth; Fig. 1a). The concept of congruency refers to the relationship between the status of the target and distracter features. In congruent conditions, the response to the target feature ("same" or "different") matches the status of the distracter features ("same" or "different"), while they call for conflicting responses in incongruent conditions (a "same" target embedded in the context of "different" distracter features, or a "different" target embedded in the context of "same" distracter features; Fig. 1a). This paradigm thus uses a fully balanced, so-called "complete", design where "same" and "different" target features can be embedded in a context of "same" or "different" distracter features. The failure to process features independently, i.e. IFP, is then estimated based on the congruency effect. We manipulated the relative discriminability of local cues by varying the dissimilarity of the target feature parametrically in a given pair of faces and evaluated how this factor modulates IFP strength in behavioural responses.

2. Material and methods

2.1. Subjects

Thirteen Psychology students (Maastricht University, mean age 20.5 ± 2, all right-handed; 3 males) took part in the experiment. They provided their written informed consent prior to participation. All reported either normal, or corrected-to-normal vision. The experimental protocol was approved by the faculty ethics committee.

2.2. Stimuli

Face stimuli were full-front digital photographs of Caucasian neutral faces without glasses, facial hair, or makeup.

Six male and 20 female faces were used for morphing. The unequal numbers of male and female faces was not on purpose but

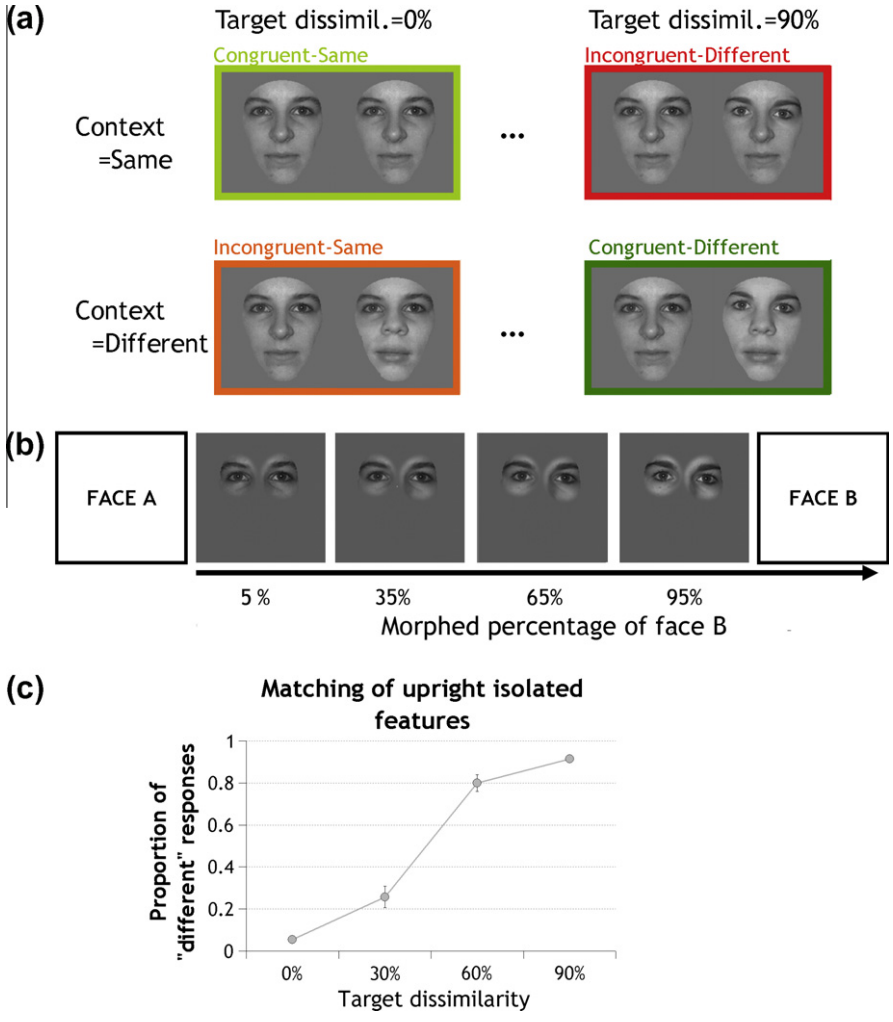

Fig. 1. Stimuli. (a) Example of face pairs with minimal (0%) and maximal (90%) dissimilarity in the simultaneous congruency task. Subjects had to discriminate a target feature (same/different matching task), i.e., the eyes and eyebrows, while ignoring the context of other features (i.e., distracters: nose and mouth). In congruent conditions, both the target and distracter features lead to an identical decision, while they call for opposite responses in incongruent conditions. (b) Example of a morphed target feature. Various morphing levels of the same continuum were selected in a pair to provide a target differing by 0%, 30%, 60%, or 90%. (c) The proportion of "different" responses elicited by upright isolated features is plotted as a function of target feature dissimilarity. Error bars represent standard error of the means.

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due to stimulus availability. Faces were paired in order to generate thirteen continua (three male continua and 10 female continua) using morphing software Morpht. For each face pair, around 100–130 control points were used. The points were placed on all salient features of the face: contour (≈45 points), mouth (≈15 points), eyes (≈11 points each), brows (5 points each), and nose (≈20 points). Faces within each pair were equated in mean luminance before they were morphed. From each continuum, we selected four morphed faces (Fig. 1b): 5% of face A (95% of face B), 35%A (65%B), 65%A (35%B) and 95%A (5%B; see Jacques & Rossion, 2006) for further details on the morphing procedure).

Using Adobe Photoshop, the region encompassing eyes and brows (i.e., target features) was cut from each of the selected morphed faces and pasted into face contexts (10 female, 7 male; face image size: 184 × 184 pixels). By combining each eye morphing continuum with several (up to 4) face contexts we generated a total of 84 eye-morphed female faces and 40 eye-morphed male faces. Face context included nose and mouth features. Faces were masked by a rounded-angle triangular grey occluder.

On a given trial, the target feature differed either by 0% (repetition of the same 5% or 35% morphed feature), 30% (by pairing 35% and 65% morphed features), 60% (by pairing 5% with 65% or 35% with 95% morphed features), or 90% (by pairing 5% and 95% morphed features). The target feature was presented either in isolation, in a congruent or in an incongruent face context. Inverted stimuli were generated by flipping all images vertically using Adobe Photoshop.

2.3. Procedure

Faces were presented in pairs and subjects had to report whether the target features (eyes and brows) were same or different across faces by pressing one of two buttons with their right index or middle fingers, irrespective of face context.

Faces appeared side-by-side on the screen (142 pixels away from screen centre). On every trial, the relative position of the two face stimuli was randomly jittered by 10 pixels in the *y* direction in order to prevent the occurrence of lateral scanning strategies. Faces remained on the screen until the subject responded, but no longer than 3000 ms. A blank interval followed (duration ranging from 700 to 1200 ms).

There were 24 different conditions: picture plane orientation (upright, inverted), target feature dissimilarity within a pair (0%, 30%, 60%, 90%) and context (isolated, congruent context, incongruent context). All conditions were randomly interleaved. To avoid response biases, the target feature was "same" in half of the trials (0% dissimilarity condition), and the remaining half of the trials was evenly distributed between the various levels of dissimilarity (20 trials per dissimilarity condition). This resulted in a total of 120 experimental trials per orientation by context condition and a total of 720 trials, divided in 40-trial blocks. During the pauses, subjects were informed about their accuracy by an on-screen written feedback.

Prior to the experiment, instructions were provided on the computer monitor. Subjects were shown examples of congruent and incongruent pairs of faces and explicitly instructed that paying attention to distracter features would hamper their performance. Subjects were asked to respond as accurately as possible. Then they performed 100 practice trials with upright and inverted face pairs. During training, subjects received feedback on their accuracy (every 5 trials during the first 50 practice trials, and every 10 trials in the last practice 50 trials). During the experiment, feedback was provided every 40 trials. Stimulus presentation was operated via Eprime 1.1 on a 1024 × 768 pixels LCD screen. Viewed at 57 cm, stimuli subtended a visual angle of 6.7° × 6.7°.

2.4. Data analysis

Curve-fitting was used to characterize the relationship between "different" responses and target dissimilarity. Second, matching accuracy was submitted to a 2 by 4 by 2 ANOVA with orientation (upright, inverted), target dissimilarity (0%, 30%, 60%, 90%) and congruency (congruent, incongruent) as within-subject factors. Finally, we computed correlation coefficient between IFP strength (i.e. congruent versus incongruent accuracy difference) and the physical and the perceived target dissimilarity (i.e. target dissimilarity in percent and proportion of "different" responses in the isolated condition, respectively) at upright and inverted orientations. Conditions were compared two-by-two using Bonferroni post hoc tests.

3. Results

The discriminability of the target featural cues, i.e. the amount of target physical variation, was varied parametrically via morphing. In a given pair of faces, target features were separated by 0%, 30%, 60% or 90% on the morphing continuum. Distracter features were either completely same (0%) or completely different (100%). The strength of IFP was estimated by comparing performance in congruent and incongruent conditions.

Target features were also presented in isolation in order to determine whether the parametric manipulation of feature dissimilarity efficiently modulated the ability to detect target feature differences.

3.1. Target feature dissimilarity effect

As expected, the proportion of "different" responses increased with increasing feature dissimilarity in the upright-isolated condition. To further characterize the relationship between "different" responses and target dissimilarity, curve-fitting procedures were applied to the data. These revealed significant linear (goodness of fit: SSE = .03, adjusted $r^2 = 0.91$) and non-linear logistic components (goodness of fit: SSE = .07, adjusted $r^2 = 0.8$). But the cubic function was found to best fit the data (goodness of fit: SSE ≈ 0, $r^2 = 1$).

Our morphing procedure was thus successful in varying the discriminability of local target cues as increasing feature dissimilarity induced an increase in perceived feature difference (i.e., discriminability; Fig. 1c). The non-linear, step-like function relating behavioural responses to the continuous manipulation of feature dissimilarity further suggests that feature differences were perceived categorically (Beale & Keil, 1995).

3.2. IFP at various feature dissimilarity levels

In Fig. 2a, matching accuracy is plotted for each target dissimilarity level. Fig. 2b shows the modulation of congruency effect size as a function of feature dissimilarity at upright and inverted orientation separately. At upright orientation, the effect of congruency decreased as a function of target dissimilarity. Congruency effects were overall weaker when faces were inverted. These observations were confirmed in a 2 by 4 by 3 ANOVA.

All main effects were significant (target dissimilarity: $F(3,36) = 169.6$, $p < .0001$, partial eta squared: .93; context: $F(2,24) = 31.3$, $p < .0001$, partial eta squared: .72; orientation: $F(1,12) = 23.2$, $p < .0001$, partial eta squared: .66). All double interactions between Orientation, Congruency and Target dissimilarity factors were also significant (*ps* < .0001), as well as the triple interaction ($F(6,72) = 6$, $p < .0001$, partial eta squared: .33).

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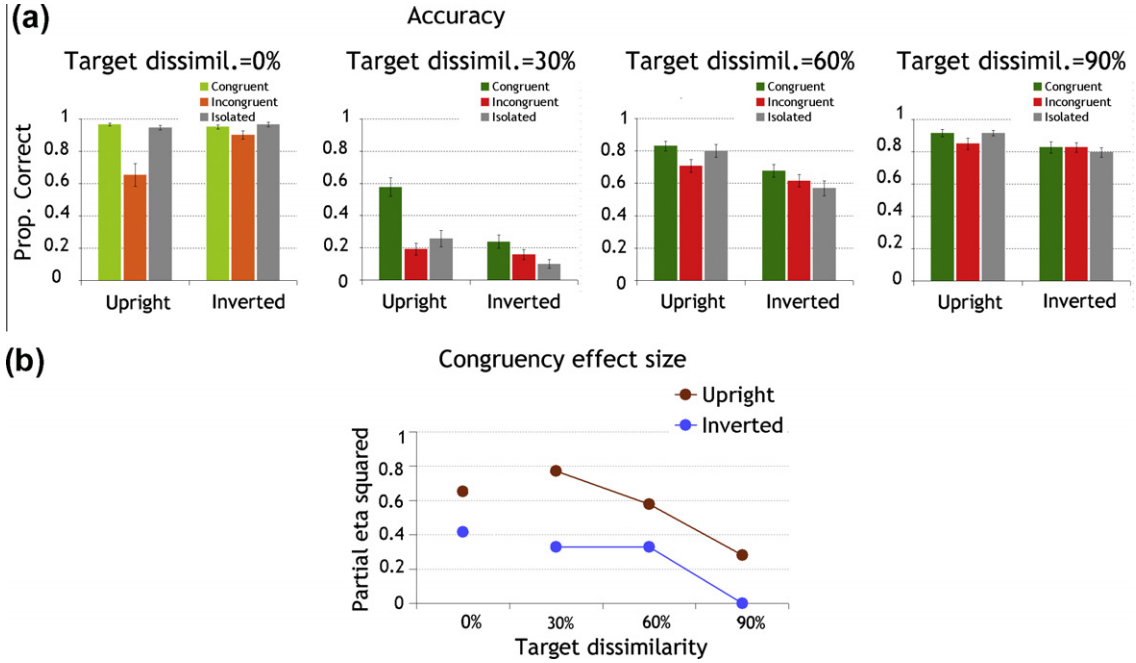

Fig. 2. Congruency and orientation effects as a function of feature dissimilarity. (a) Mean accuracy ($N = 13$) for matching target features is plotted. Error bars display the inter-subject standard error computed separately in each condition. (b) The size of the congruency effect is plotted for upright and inverted faces as a function of target feature dissimilarity.

At upright orientation, the congruency effect (difference between congruent and incongruent conditions) was significant in all dissimilarity conditions ($ps < .0001$) except the 90% dissimilarity condition ($p = .35$).

We estimated the amount of IFP engagement based on the size of the congruency effect (using partial eta squared; Fig. 2b) in each orientation by target dissimilarity condition. At upright orientation, the congruency effect size decreased as a function of target feature dissimilarity. When target features differed by 0% (identical) or 30%, the congruency effect was strong and accounted for about 65% and 80% of matching performance variance, respectively.[1] Congruency effect size then decreased monotonically as a function of target dissimilarity and fell below 30% of explained variance for 90%-dissimilar targets.

At inverted orientation, congruency effects did not reach significance in any of the dissimilarity conditions ($ps > 0.1$) but still accounted for about 40% of performance variance in 0%, 30% and 60% target dissimilarity conditions. In contrast, performance in the inverted 90%-dissimilarity condition was not influenced by the congruency of the distracter feature.

The ANOVA results show that IFP strength decreased as a function of target dissimilarity. This was confirmed by correlation analyses showing that both the local target dissimilarity (in morph percent) and the local discriminability (in proportion of "different" responses in upright-isolated condition) reliably predicted IFP strength (i.e. congruent versus incongruent accuracy difference).

For upright faces, IFP strength (i.e., the difference in performance between congruent and incongruent trials) was indeed found to be negatively correlated with both perceived and physical target differences (i.e., discriminability and dissimilarity, respectively: $r = -.52$; $p < .00001$ and $r = -.52$; $p < .0001$, respectively). In inverted faces, the correlations were not significant ($rs < .04$, $ps > .17$).

4. Discussion

How does the human brain represent faces? Answering this question will provide invaluable insight on how brain function generates complex visual experience. Face perception has been shown to be driven both by holistic and featural processing. Our study investigated the determinants of the engagement of interactive versus featural mechanisms during face perception. We hypothesized that the discriminability of face local signals (e.g., as provided by features) may moderate the engagement of IFP for faces. We tested this hypothesis by means of a congruency discrimination task where participants were asked to match target face features (e.g., eyes and brows) independently of the context of distracter features (e.g., nose and mouth). The strength of IFP was estimated by comparing target matching performance when the target feature was embedded in a congruent or incongruent context of distracter features. The discriminability of featural signals was manipulated by varying the dissimilarity of the target feature in face pairs. Target features could vary by 0% ("same"), 30%, 60% or 90% on a morphing continuum. We observed that the size of the congruency effect decayed monotonically as a function of the dissimilarity of the target features. In other words, the more similar the target features the stronger the interactive processing. A correlation analysis confirmed that local feature discriminability reliably predicted IFP engagement at upright orientation. In contrast, when a clear local feature difference was detected, perceptual contamination by the other surrounding features was prevented.

The present findings offer a new perspective on the use of "partial" versus "complete" designs to tackle IFP for faces (Richler et al., 2011). By showing that IFP selectively arises when target features

[1] The more robust congruency effect in 30% condition is likely be due to the task being overall more difficult in this condition (see Fig. 2a), resulting in stronger IFP in the 30% than in the 0% condition.

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are similar, they suggest that "partial" designs, which infer IFP based on "same" trials, are specifically tailored to capture IFP. Still, we think that "complete" designs as the one used here has more potential to advance our understanding of the contribution of IFP to face perception.

Our findings suggest that when local sensory signals conveyed by a given face are weak, the visual system tends to integrate information across visual space. A similar mechanism has been shown to operate in the primary visual cortex. Interactive processing between distant parts of the visual field is indeed known to occur in V1, a phenomenon generally called contextual modulation (Schwartz, Hsu, & Dayan, 2007). Contextual modulation strength in V1 was also shown to decay as a function of local signal contrast (Nauhaus et al., 2009; Sceniak et al., 1999), with lower contrast local inputs leading to more extensive summation over space. We do not propose that primary V1 mechanisms are responsible for face IFP dependence on feature discriminability. The disruption of IFP by inversion indeed suggests that face interactive encoding reflects elaborate observer-dependent mechanisms. However, the dependence of V1 contextual modulations upon local contrast indicates that the visual system has developed general mechanisms to dynamically adapt the extent of interactive processing to the saliency of local inputs.

Faces naturally differ both at the level of local features and their global arrangement, and both types of cues are known to be involved in the representation of faces (Sergent, 1984). Here we go further by providing direct evidence that this interactive/featural interplay depends on the discriminability of the signal provided at the local featural level. In a systematic review of the literature, McKone and Yovel (2009) showed that the size of the face inversion effect, taken as a marker of IFP engagement, decreased as a function of feature colour/brightness dissimilarity in a variety of tasks, including bizarreness ratings, distinctiveness ratings, recognition memory, familiar faces naming and matching. This suggests that IFP dependence on feature discriminability is not restricted to situations where a local feature has to be selectively discriminated as in the congruency paradigm employed here but generalizes to whole face discrimination and recognition tasks.

5. Conclusions

This study provides the first direct evidence that the strength of interactive processing is a function of local feature discriminability. We estimated the strength of interactive feature processing (IFP) based on observers' failure to discriminate target features independently of the context of distracter features in a congruency paradigm. Feature discriminability was manipulated by varying the dissimilarity of target features parametrically, using morphing.

We observed that the size of the congruency effect decayed monotonically as a function of the dissimilarity of the target features. A correlation analysis further confirmed that local feature discriminability reliably predicted IFP engagement at upright orientation. These findings have important implications for the development of face perception theories.

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