A Shape-Based Account for Holistic Face Processing

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Abstract

Faces are processed holistically, so selective attention to one face part without any influence of the others often fails. Here three experiments investigated what type of facial information (shape or surface) underlies holistic face processing and whether generalization of holistic processing to non-experienced faces requires extensive discrimination experience. Results show that facial shape information alone is sufficient to elicit the composite face effect (CFE), the most convincing demonstration of holistic processing, whereas facial surface information is unnecessary (Experiment 1). The CFE is eliminated when faces differ only in surface but not shape information, suggesting that variation of facial shape information is necessary to observe holistic face processing (Experiment 2). Removing three-dimensional (3D) facial shape information also eliminates the CFE, indicating the necessity of 3D shape information for holistic face processing (Experiment 3). Moreover, participants show similar holistic processing for faces with and without extensive discrimination experience (i.e., own- and other-race faces), suggesting that generalization of holistic processing to non-experienced faces requires facial shape information, but does not necessarily require further individuation experience. These results provide compelling evidence that facial shape information underlies holistic face processing. This shape-based account not only offers a consistent explanation for previous studies of holistic face processing, but also suggests a new ground—in addition to expertise—for the generalization of holistic processing to different types of faces and to non-face objects.

Keywords: face perception, holistic processing, composite face effect, shape information, surface information

A Shape-Based Account for Holistic Face Processing

One well-established finding in face perception research is that faces are processed holistically (Farah, Wilson, Drain, & Tanaka, 1998; Hole, 1994; Tanaka & Farah, 1993; Yin, 1969; Young, Hellawell, & Hay, 1987; for reviews, see Maurer, Le Grand, & Mondloch, 2002; Richler & Gauthier, 2014; Rossion, 2013). That is, faces are perceived as indecomposable whole piece rather than a collection of independent face features. Although holistic face processing has been defined differently between studies, and has been inferred from various research paradigms (Maurer et al., 2002; Richler, Palmeri, & Gauthier, 2012; Rossion, 2013), its most convincing demonstration is the *composite face effect* (CFE, Hole, 1994; Young et al., 1987; see also Cheung, Richler, Palmeri, & Gauthier, 2008; Richler, Tanaka, Brown, & Gauthier, 2008). When the top and bottom parts of different persons' face are fused together (i.e., composite face), people often fail to selectively process one part without influences from the other in the whole face. Such failure of selective attention is reduced or eliminated when the fusion of two face parts is disrupted (e.g., by laterally misaligning both halves).

Two lines of research have investigated what underlies holistic face processing: one concentrates on perceiver-based factors and another on face-based information. The *perceiver-based approach* emphasizes that holistic processing come from perceivers' substantial experience in individuating faces or other objects (i.e., *expertise hypothesis*, Diamond & Carey, 1986; Gauthier & Tarr, 1997; Wong, Palmeri, & Gauthier, 2009). Specifically, extensive face individuation experience leads to an attentional strategy that obligatorily encodes all face parts as a whole. This strategy becomes automatic with increasing experience and cannot be intentionally ‘turned off’, causing the CFE (Richler & Gauthier, 2014; Richler, Wong, & Gauthier, 2011). Thus, “holistic processing is the outcome of an attentional strategy that has become automatized with experience” (Richler & Gauthier, 2014, p1282). According to this expertise hypothesis, people can develop holistic processing for any non-face objects through the same mechanism (i.e., expertise). This prediction gains support from studies demonstrating holistic processing for objects of expertise (Gauthier, Curran, Curby, & Collins, 2003; Gauthier & Tarr, 1997; Wong et al., 2009), but has difficulty explaining why holistic processing sometime fails to emerge following extensive experience (e.g., Robbins & McKone, 2007).

The face-based approach, in contrast, highlights the importance of face-based information for holistic processing (e.g., de Heering, Wallis, & Maurer, 2012; Goffaux & Rossion, 2006; Jiang, Blanz, & Rossion, 2011; Meinhardt-Injac, Persike, & Meinhardt, 2013; Richler, Palmeri, & Gauthier, 2015). The rationale behind this line of studies is that if holistic processing is supported by certain type of visual facial information, then removing such information should eliminate holistic processing. To characterize which information might support holistic processing, some studies compared the contributions of high and low spatial-frequency facial information (Goffaux, 2009; Goffaux & Rossion, 2006; but see Cheung, Richler, Palmeri, & Gauthier, 2008); others differentiated roles of facial shape and texture information (Jiang et al., 2011; Meinhardt-Injac et al., 2013); and still others tested whether holistic processing relies on facial configuration information (i.e., spatial relations between face features; de Heering et al., 2012; Richler et al., 2015; see also Farah, Tanaka, & Drain, 1995). Since each subset of studies emphasizes only one aspect of facial information, a coherent account of what underlies holistic face processing, therefore is required to generalize holistic processing to non-experience faces, remains to be established.

The face-based approach differs from the *domain-specificity hypothesis* for holistic processing, (McKone, Kanwisher, & Duchaine, 2007; Robbins & McKone, 2007), although both primarily attribute holistic face processing to face itself. According to the domain-specificity hypothesis, holistic processing is unique to faces, and such uniqueness may be caused by an *innate face template* that is used to code the basic structure of a face (e.g., the T-shape arrangement of eyes, nose, and mouth), or by unique experience in practicing individual-level discrimination for faces during the sensitive period (McKone et al., 2007; see also Tsao & Livingstone, 2008). In contrast, the face-based approach addresses what information within faces specifically supports holistic processing, and thus, if present in other stimuli (other types of faces or non-face objects), might activate holistic processing too. Furthermore, the domain-specificity hypothesis implies that faces (upright faces in particular) are sufficient for activating holistic processing, whereas the face-based approach does not, because holistic face processing could be eliminated when the relevant underlying information is removed.

In the present study, we combined both the perceiver- and face-based approaches to investigate what kind of facial information supports holistic processing, and when such information is present, whether holistic processing can generalize to any other faces without extensive experience in discriminating them. To unravel what in a face gives rise to holistic processing, we investigated the sufficiency and necessity of two types facial information—3D shape (e.g., 3D geometric structure) and surface reflectance (e.g., color and texture)—for holistic face processing. We tested facial shape and surface information because both are crucial for face recognition (Jiang, Blanz, & O'Toole, 2006; O'Toole, Vetter, & Blanz, 1999; Russell, Biederman, Nederhouser, & Sinha, 2007), and face recognition ability is closely linked to holistic processing (DeGutis, Wilmer, Mercado, & Cohan, 2013; Richler, Cheung, & Gauthier, 2011).

To logically establish the sufficiency and necessity of facial shape and surface information for holistic processing, one must selectively eliminate one type of information while preserving the other and vice versa. Note, however, that to differentiate the roles of facial shape and surface information, prior studies often keep one type of information fixed (e.g., by averaging) while varying the other (Jiang et al., 2006, 2011; O'Toole et al., 1999; Russell et al., 2007). This manipulation can address the role of shape or surface *variation* in holistic face processing or face discrimination, but cannot address whether shape or surface information *alone* is sufficient for holistic processing or face identification, because both shape and surface information are still available (albeit one of them remains constant).

We tested what type of facial information, surface or shape, is required for holistic face processing by selectively removing one type of facial information while leaving the other unchanged. In Experiment 1, we eliminated facial surface information while sparing 3D facial shape information (i.e., statue-like, *shape-only faces*), and then measured holistic face processing (i.e., the CFE) using two composite tasks: one for shape-only faces and the other for normal *complete* faces (i.e., shape plus surface information). This design allowed us to test both the necessity of surface information and the sufficiency of shape information for observing holistic face processing. If facial surface information is necessary for holistic processing, the CFE should be observed in complete but not shape-only faces, which contain no surface information. If facial shape information is sufficient for holistic processing, both shape-only and complete faces should exhibit CFE. If, however, both shape and surface information contribute to holistic processing, we should observe CFE for both types of faces, with larger CFE for complete than shape-only faces.

In Experiments 2 and 3, we selectively manipulated facial shape information. Experiment 2 investigated whether facial surface information, together with fixed facial shape information, is sufficient to elicit holistic processing. We measured CFE for complete faces and for *same-shape faces*, in which all faces shared identical 3D facial shape information while maintaining individual surface information. This design also tested whether *variation* of facial shape information is necessary for observing holistic processing. Experiment 3 further investigated whether 3D facial shape information is necessary for activating holistic face processing. We removed 3D facial shape information (as well as surface information) while maintaining 2D facial shape information such as the lines and contours of face features (i.e., *line-drawing faces*), and then measured holistic processing for these line-drawing faces and complete faces. If 3D facial shape information is necessary for observing holistic face processing, then the CFE observed in complete faces should be eliminated in line-drawing faces.

To address whether generalization of holistic processing to initially non-experienced faces requires extensive individuation experience, we measured holistic processing for both own- and other-race faces. In comparison with life-long practices in discriminating own-race faces, most people have little or no experience in individuating other-race faces. Some studies suggest that this dramatic difference leads to stronger holistic processing for own- than other-race faces (Michel, Caldara, & Rossion, 2006; Michel, Rossion, Han, Chung, & Caldara, 2006; Tanaka, Kiefer, & Bukach, 2004), whereas others do not (Mondloch et al., 2010; Zhao, Cheung, et al., 2014; Zhao & Hayward, 2010; for a review, see Hayward, Crookes, & Rhodes, 2013). Recent studies only found an overall higher discrimination performance for own- than other-race faces, but no cross-race difference in terms of holistic processing (Harrison, Gauthier, Hayward, & Richler, 2014; Zhao, Hayward, & Bülthoff, 2014; see also Bukach, Cottle, Ubiwa, & Miller, 2012). These studies suggest that holistic processing may apply to other types of faces without further experience in discriminating them. Nonetheless, what type of facial information may support such generalization remains unknown.

Current theories of holistic processing differ in their predictions about the present study. According to the domain-specificity hypothesis, holistic processing should persist for all types of faces tested here, because our face stimuli are sufficiently "face-like" to match the upright face template and to activate holistic processing (e.g., McKone et al., 2007). According to the expertise hypothesis (e.g., Bukach, Phillips, & Gauthier, 2010; Wong et al., 2009), holistic processing should be more pronounced in own- than other-race faces, and more pronounced in complete faces than in shape-only or line-drawing faces, because people have much less individual-level discrimination experience with the latter. The face-based approach has revealed seemingly mixed results, with some emphasizing facial shape information whereas others emphasizing facial surface information in eliciting holistic face processing (Jiang et al., 2011; Meinhardt-Injac et al., 2013). Nonetheless, it expects similar level of holistic processing for own- and other-race faces, provided that they present same type of facial information. Therefore, by manipulating facial shape or surface information and perceivers' experience (i.e., own- or other-race faces), the present study may reveal a broader picture about what underlies holistic face processing, and importantly, what is required to generalize holistic processing to other type of faces or even non-face objects.

Experiment 1: Removing Facial Surface Information

Experiment 1 investigates whether facial shape information alone is sufficient to elicit holistic processing, and whether holistic processing generalizes to other-race faces without extensive individuation experience with those faces. Participants performed four composite tasks, one for each face type (complete vs. shape-only faces) and each race (own- vs. other-race faces). Comparing the pattern of responses between face types would reveal whether shape-only faces show similar holistic processing as normal faces, whereas comparing results of own- and other-race faces will tell whether holistic processing applies to non-experienced faces with and without surface information.

Methods

Participants

Eighteen people participated in the study (10 females, mean age = 27, SD = 5 years). All were Caucasians. For this and all subsequent experiments, the procedures were approved by local Ethics Review Board in accordance with the Declaration of Helsinki; written informed consent was obtained from each participant before the experiment.

Composite Task

We used a complete design of the composite task to measure holistic processing (**Figure 1**, for rationale and potential advantage of this design, see Richler et al., 2011; Richler & Gauthier, 2014; but see Rossion, 2013). Participants performed a sequential matching task about the top halves of two composite faces. Following Richler et al. (2011), the first composite face was always aligned. The second face was either aligned (*aligned condition*) or misaligned (*misaligned condition*). In both alignment conditions, the top halves of the two faces were either identical (*same condition*) or different (*different condition*). The irrelevant bottom halves were also manipulated. In the *congruent condition*, the bottom halves were identical in the same condition and were different in different condition. In the *incongruent condition*, they were different in the same condition and were the same in the different condition.

---------- (*Figure 1 about here*) ----------

Holistic processing is operationally defined as a significant congruency effect that is modulated by alignment: Discrimination performance should be better on congruent than incongruent trials (i.e., congruency effect), and the significant congruency effect observed in aligned condition should be reduced or eliminated in misaligned condition (i.e., interaction between congruency and alignment). These two indexes defines holistic processing as the inability to selectively attend to one face part in aligned faces, but less so in misaligned faces (Farah et al., 1998; Richler et al., 2011).

Stimuli

Complete faces. Forty complete faces (**Figure 2A**) were created based on the laser-scanned faces (http://faces.kyb.tuebingen.mpg.de, Blanz & Vetter, 1999), including twenty Asian faces (10 female) and twenty Caucasian faces (10 female). Each face had separate texture and 3D shape information. We rendered face images by applying the texture information onto the corresponding shape for each face. All face images were converted to grayscale, centered on a gray background (270 × 270 pixels, average size of individual faces, 156 × 226 pixels, about 4° × 6° in visual angle). Faces were masked with an oval shape, hiding the neck below the chin and the ears. We split each face into top and bottom halves (270 by 135 pixels each), and then combined these face halves to create composite faces as illustrated in Figure 1. Both face halves in a composite face shared the same race and gender. For the misaligned condition, we shifted the top half to the right and the bottom half to the left for 33 pixels. Top and the bottom halves of all composite faces were separated by a 1-pixel black line.

---------- (*Figure 2 about here*) ----------

Shape-only faces. Sculpture-like, shape-only faces were created by rendering the above 40 faces without mapping their texture (**Figure 2B**). We edited these shape-only faces using the same method as for complete faces to form composite faces. Importantly, the identities of face halves for each composite face matched exactly those of the corresponding composite faces made of complete faces, ensuring that complete and shape-only face trials shared the same identity information and differed only in surface information. Therefore, performance differences between different types of faces cannot be attributed to variation of face identities.

Procedure

Participants were instructed to judge whether the top halves of the two sequential presented faces were the same, and to ignore the irrelevant bottom halves. In each trial, after a fixation cross (250 ms) and a blank screen (250 ms), participants first saw one composite face (300 ms), then a masking image consisted of scrambled face parts (500ms), followed by another composite face (300 ms), and finally a response screen displayed until a response was made (**Figure 2**). To avoid potential floor effect in shape-only trials, we used a longer presentation time (300 ms) than in Richler's (2011) design (200 ms), for both complete and shape-only face trials. The inter-trial interval was 1 second.

Participants performed 4 blocks of composite task (2 face-types × 2 races). Block order was counterbalanced across participants (i.e., half of them judged own-race faces first and the other half other-race first; similarly, half of participants judged complete faces first whereas the other half shape-only faces first). Each block had 160 trials (2 alignment conditions × 2 congruency conditions × 2 same/different conditions × 20 exemplars) that were presented in random order. Participants had 8 practice trials for each face type, and were instructed to respond as accurately as possible without sacrificing response speed.

Results

Participants' performance was measured as response sensitivity (d'). In this and subsequent experiments, we report all significant statistics (α =.05) along with effect size (i.e., partial eta squared, η_p^2, in ANOVA or Cohen's *d* in *t*-test). Mean d' scores are reported with standard errors (i.e., $M \pm SE$).

<u>*Caucasian faces: Both complete and shape-only faces show CFE*</u>

Response sensitivity for Caucasian faces is plotted in **Figure 3A**. A 2 (face type) × 2 (alignment) × 2 (congruency) repeated measures ANOVA revealed a significant congruency effect (congruent trials: 2.42 ± .13; incongruent trials: 1. 78 ± .16), $F(1,17) = 54.10$, $p < .001$, $\eta_p^2 = .76$. The interaction between congruency and alignment was significant, $F(1,17) = 30.65$, $p < .001$, $\eta_p^2 = .64$, indicating holistic face processing. The interaction between face type, congruency, and alignment was not significant, $F(1,17) = .81$, $p = .381$, $\eta_p^2 = .05$, suggesting that holistic face processing was similar for complete and shape-only faces. There were also significant main effect of alignment, $F(1,17) = 5.36$, $p = .033$, $\eta_p^2 = .24$, and face type, $F(1,17) = 65.78$, $p < .001$, $\eta_p^2 = .79$. Higher performance for complete than shape-only faces (2.60 ± .15 vs. 1.60 ± .15) reveals that removing surface information impairs overall face discrimination.

Separate 2 (alignment) × 2 (congruency) ANOVAs confirmed that both complete and shape-only faces were processed holistically. Both types of faces showed significant congruency effect (both $F(1,17) > 25.14$, $p < .001$, $\eta_p^2 \geq .60$), and significant interaction between congruency and alignment (both $F(1,17) > 12.48$, $p < .003$, $\eta_p^2 > .42$). The congruency effect was significant for aligned trials (both $t(17) > 4.65$, $p < .001$, Cohen's $d \geq 1.10$), but not for misaligned trials (both

$t(17) \leq 1.26$, $p \geq .225$, Cohen's $d < .30$, **Figure 3A**), suggesting that the inability to selectively attend to the top half was eliminated when it was misaligned with the bottom half.

---------- (*Figure 3 about here*) ----------

Asian faces: Both complete and shape-only faces show CFE

Performance for Asian faces mirrored those for Caucasian faces (**Figure 3B**). A 2 × 2 × 2 ANOVA revealed a significant congruency effect (congruent trials: 2.28 ± .12; incongruent trials: 1.79 ± .14), $F(1,17) = 40.19$, $p < .001$, $\eta_p^2 = .70$, and a significant interaction between congruency and alignment, $F(1,17) = 19.27$, $p < .001$, $\eta_p^2 = .53$. The three-way interaction was not significant, $F(1,17) = 1.62$, $p = .220$, $\eta_p^2 = .09$, suggesting that complete and shape-only faces involve similar levels of holistic processing. Removing surface information also impaired discrimination of Asian faces, with better performance for complete than for shape-only faces (2.18 ± .14 vs. 1.90 ± .13), $F(1,17) = 7.91$, $p = .012$, $\eta_p^2 = .32$.

Separate ANOVAs for complete and shape-only faces revealed significant congruency effect (both $F(1,17) \geq 19.27$, $p < .001$, $\eta_p^2 > .53$), and significant congruency by alignment interaction (both $F(1,17) > 10.66$, $p < .005$, $\eta_p^2 \geq .39$), indicating that both types of faces are processed holistically. The congruency effect was significant for aligned trials (both $t(17) > 4.74$, $p < .001$, Cohen's $d \geq 1.12$), but not for misaligned trials (both $t(17) < 1.47$, $p \geq .161$, Cohen's $d < .35$). Thus, the obligatory processing of irrelevant face parts disappeared when top and bottom face halves were misaligned.

Holistic processing without extensive individuation experience

To examine whether different levels of face-individuation experience influence holistic processing for own- and other-race faces, we performed separate 2 (race) × 2 (alignment) × 2 (congruency) ANOVA, one for each face type. For complete faces (**Figure 3**, left column), the congruency effect, $F(1,17) = 40.83$, $p < .001$, $\eta_p^2 = .71$, and its interaction with alignment, $F(1,17) = 21.11$, $p < .001$, $\eta_p^2 = .55$, were both significant, signaling holistic face processing. Moreover, the interaction between face race, congruency, and alignment was not significant, $F(1,17) = .83$, $p = .374$, $\eta_p^2 = .05$. This result suggests that holistic processing generalize to other-race faces without extensive experience in discriminating those faces. In addition, own-race faces showed higher overall performance than other-race faces (2.60 ± .15 vs. 2.18 ± .14), $F(1,17) = 13.26$, $p = .002$, $\eta_p^2 = .44$. Thus, extensive face individuation experience improves face discrimination, but does not enhance holistic face processing.

Shape-only faces showed similar results to complete faces (**Figure 3**, right column). The main effect of congruency, $F(1,17) = 60.84$, $p < .001$, $\eta_p^2 = .78$, and its interaction with alignment, $F(1,17) = 40.32$, $p < .001$, $\eta_p^2 = .70$, were both significant. There was also a significant interaction between face race and congruency, $F(1,17) = 4.73$, $p = .044$, $\eta_p^2 = .22$, with larger congruency effect for own-race faces ($F(1,17) = 50.95$, $p < .001$, $\eta_p^2 = .75$) than other-race faces ($F(1,17) = 19.27$, $p < .001$, $\eta_p^2 = .53$). Nonetheless, the three-way interaction was not significant, $F = .01$, $p = .756$, $\eta_p^2 < .01$, suggesting that holistic processing can generalize to unfamiliar other-race faces based exclusively on facial shape information. Other-race shape-only faces showed unexpectedly a higher performance than own-race faces (1.90 ± .13 vs. 1.60 ± .15), $F(1,17) = 9.97$, $p = .006$, $\eta_p^2 = .37$.

Facial shape information alone is sufficient to elicit holistic processing

The magnitude of CFE in each condition is illustrated in **Figure 4**, which was calculated as the difference between congruency effect observed in aligned and misaligned trials. All these CFEs were significant (all $t(17) \geq 3.27$, $p < .005$, Cohen's $d \geq .77$). A 2 (face type) by 2 (face race) repeated measures ANOVA only revealed a marginally significant effect of face type, $F(1,17) = 3.97$, $p = .063$, $\eta_p^2 = .19$. The shape-only faces even showed numerically higher CFE (1.10 ± .17) than complete faces (.78 ± .17). Therefore, facial shape information alone is sufficient to elicit holistic processing, and is sufficient to generalize holistic processing to non-experienced other-race faces.

---------- (*Figure 4 about here*) ----------

Discussion

Experiment 1 demonstrates for the first time that shape-only faces are processed as holistically as normal, complete faces. This result clearly favors the hypothesis that facial shape information underlies holistic face processing. In contrast, although adding facial surface information improves overall performance for the composite task, facial surface information is not necessary for observing holistic face processing. Moreover, although individual-level discrimination experience with own-race faces enhances face recognition ability, it is not required to generalize holistic processing to other subtype of faces. Instead, stimuli showing merely facial shape information will suffice. Similar holistic processing for own- and other-race faces echoes results of previous studies (Harrison et al., 2014; Zhao et al., 2014), and concurs with the proposal that expertise with own-race faces may improve the overall ability to process face features and their spatial relations rather than merely enhance holistic processing (Hayward et al., 2013; Hayward, Rhodes, & Schwaninger, 2008; Rhodes, Hayward, & Winkler, 2006).

Although facial surface information is unnecessary for observing holistic processing, whether it is *sufficient* to elicit holistic face processing remains unknown. Facial surface and and shape information may contribute to holistic face processing independently, so that facial surface information alone may lead to holistic processing as well. Similarly, while Experiment 1 demonstrates the sufficiency of facial shape information for holistic processing, its *necessity* remains to be determined. To address these questions, in Experiments 2 and 3 we tested how people process faces when facial shape information is selectively manipulated while facial surface information is spared.

Experiment 2: Removing Variation of Facial Shape Information

Experiment 2 investigates whether facial surface information is sufficient for observing holistic processing when facial shape information is controlled, and whether extensive individuation experience with own-race faces is sufficient to elicit holistic processing. We tested whether the CFE persists when faces in a trial share the same 3D shape information while differing in terms of facial surface information (i.e., *same-shape faces*), for both own- and other-race faces. If facial surface information contributes to holistic processing independent of facial shape information, we should observe the CFE in both complete and same-shape faces, because both contained identical surface information. In contrast, if the CFE is caused by different facial shape information between face halves, it should be disrupted in the same-shape faces.

Methods

Participants

Eighteen people participated in the study (11 females, mean age = 27 years, SD = 5). All were Caucasians, and none of them took part in Experiment 1.

Task, Stimuli, and Procedure

Participants performed 4 blocks of composite task, one for each face type (complete and same-shape faces) and each race (own- and other-race faces), with block order counterbalanced across participants. As in Richler et al. (2011), the two composite faces were displayed for 200 ms each, which produced similar levels of performance across Experiments 1 and 2. The procedure and the stimuli for *complete faces* were identical to those in Experiment 1 (**Figure 5A**).

---------- (*Figure 5 about here*) ----------

Same-shape faces were created based on complete faces. We first created an average facial shape across all ten faces in each category (e.g., male Caucasians), and then applied the texture information from individual faces onto the averaged 3D facial shape (for details, see Blanz & Vetter, 1999). These same-shape faces are therefore different from each other in terms of surface information while sharing the same 3D facial shape information (**Figure 5B**). We then edited these same-shape faces using the same method as in Experiment 1. Again, the identities of same-shape face halves matched those in complete faces.

Results

Caucasian faces: Complete but not same-shape faces show CFE

Response sensitivity for Caucasian faces is plotted in **Figure 6A**. A 2 (face type) × 2 (alignment) × 2 (congruency) ANOVA revealed a significant congruency effect (congruent trials: 2.21 ± .14; incongruent trials: 1.81 ± .12), $F(1,17) = 23.88$, $p < .001$, $\eta_p^2 = .58$. The interaction between congruency and alignment was marginally significant, $F(1,17) = 3.86$, $p = .066$, $\eta_p^2 = .19$. Importantly, the three-way interaction was significant, $F(1,17) = 6.23$, $p = .023$, $\eta_p^2 = .27$, indicating that complete and same-shape faces are processed differently. Performance for complete faces was higher than that for same-shape faces (2.40 ± .15 vs. 1.61 ± .14), $F(1,17) = 29.46$, $p < .001$, $\eta_p^2 = .63$, suggesting that controlling variability of facial shape information reduces face discrimination ability.

Separate 2 (alignment) × 2 (congruency) ANOVAs confirmed a significant CFE for complete faces but not for shape-only faces. For complete faces, both the congruency effect, $F(1,17) = 11.38$, $p = .004$, $\eta_p^2 = .40$, and the congruency by alignment interaction, $F(1,17) = 11.56$, $p = .003$, $\eta_p^2 = .40$, were significant. The congruency effect was significant in the aligned condition ($t(17) = 4.63$, $p < .001$, Cohen's $d = 1.09$), but not in the misaligned condition ($t < 1$). These results replicated those of Experiment 1. For same-shape faces, however, there was only a significant congruency effect, $F(1,17) = 12.42$, $p = .003$, $\eta_p^2 = .42$. The interaction between congruency and alignment was not significant, $F(1,17) = .002$, $p = .967$, $\eta_p^2 < .01$. Unlike the results for complete faces, better performance for congruent than incongruent trials was observed for both aligned trials ($t(17) = 1.98$, $p = .064$, Cohen's $d = .47$) and misaligned trials ($t(17) = 2.63$, $p = .018$, Cohen's $d = .62$). Thus, the standard CFE (i.e., larger congruency effect for aligned than misaligned trials) was disrupted in same-shape faces, indicating that variation of facial shape information is a prerequisite to elicit holistic processing.

---------- (*Figure 6 about here*) ----------

<u>*Asian faces: Complete but not same-shape faces show CFE*</u>

Response sensitivity for Asian faces is shown in **Figure 6B**. We found a significant congruency effect (congruent trials: 2.15 ± .12; incongruent trials: 1.89 ± .14), $F(1,17) = 8.28$, $p = .010$, $\eta_p^2 = .33$. The congruency effect was modulated by both alignment, $F(1,17) = 31.64$, $p < .001$, $\eta_p^2 = .65$, and face type, $F(1,17) = 13.74$, $p = .002$, $\eta_p^2 = .45$. The three-way interaction was not significant, $F(1,17) = 1.15$, $p = .299$, $\eta_p^2 = .06$. Complete faces showed better performance than same-shape faces (2.17 ± .13 vs. 1.88 ± .14), $F(1,17) = 6.78$, $p = .019$, $\eta_p^2 = .29$, suggesting that facial shape information contributes to face discrimination.

Separate 2 (alignment) × 2 (congruency) ANOVAs revealed a standard CFE for complete faces but not for shape-only faces. We found a significant congruency effect for complete faces, $F(1,17) = 20.56$, $p < .001$, $\eta_p^2 = .55$, but not for same-shape faces, $F(1,17) = .06$, $p = .804$, $\eta_p^2 < .01$. The interaction between congruency and alignment was significant for both complete faces, $F(1,17) = 20.52$, $p < .001$, $\eta_p^2 = .55$, and same-shape faces, $F(1,17) = 9.66$, $p = .006$, $\eta_p^2 = .36$.

However, while complete faces showed a significant congruency effect for aligned trials ($t(17) = 6.24$, $p < .001$, Cohen's $d = 1.47$) but not for misaligned trials ($t < 1$), same-shape faces showed a reversed pattern. The interaction was driven by a significant congruency effect in misaligned trials ($t(17) = 2.30$, $p = .034$, Cohen's $d = .54$), but not in aligned trials ($t(17) = 1.98$, $p = .065$, Cohen's $d = .47$). These results indicate that holistic processing involved in complete faces is disrupted when facial shape information is controlled.

Face individuation experience is insufficient for generalization of holistic processing

To examine the influence of face individuation experience on processing of complete and same-shape faces, we performed 2 (race) × 2 (alignment) × 2 (congruency) ANOVA for each face type. For complete faces (**Figure 6**, left column), there were a significant congruency effect, $F(1,17) = 31.71$, $p < .001$, $\eta_p^2 = .65$, and a significant interaction between congruency and alignment, $F(1,17) = 31.99$, $p < .001$, $\eta_p^2 = .65$. The three-way interaction was not significant, $F(1,17) = .18$, $p = .677$, $\eta_p^2 = .01$, suggesting that face race did not affect holistic processing. Own-race faces tended to show better performance than other-race faces (2.40 ± .15 vs. 2.17 ± .13), $F(1,17) = 3.43$, $p = .081$, $\eta_p^2 = .17$. These results indicate that generalizing holistic processing to other-race faces does not require extensive face individuation experience.

For same-shape faces (**Figure 6**, right column), the main effect of congruency was significant, $F(1,17) = 6.14$, $p = .024$, $\eta_p^2 = .27$, but the interaction between congruency and alignment was not, $F(1,17) = 3.26$, $p = .089$, $\eta_p^2 = .16$. This result further indicates that facial surface information together with a fixed facial shape is insufficient to elicit the CFE. The congruency effect was modulated by face race, $F(1,17) = 7.15$, $p = .016$, $\eta_p^2 = .30$; showing significant congruency effect for own- but not other-race faces. The interaction between face race, congruency, and alignment was not significant, $F(1,17) = 3.23$, $p = .090$, $\eta_p^2 = .16$, suggesting that own- and other-race same-shape faces are processed similarly in terms of holistic processing. Other-race faces showed unexpectedly higher performance than own-race faces (1.88 ± .14 vs. 1.61 ± .14), $F(1,17) = 6.18$, $p = .024$, $\eta_p^2 = .27$. These results indicate that the CFE is not guaranteed for all kinds of faces, even own-race faces that people encounter every day.

Facial shape variation is necessary to observe a CFE

The magnitude of CFE for each condition is plotted in **Figure 7**. A 2 (face type) by 2 (race) ANOVA showed a significant main effect of face type, $F(1,17) = 10.33$, $p = .005$, $\eta_p^2 = .38$, with stronger CFE for complete faces than for same-shape faces (.87 ± .15 vs. .30 ± .17). One sample *t*-test revealed significant CFE for complete faces (both $t(17) \geq 3.40$, $p \leq .003$, Cohen's $d \geq .80$), but not for same-shape Caucasian faces ($t < 1$). The same-shape Asian faces showed a significant interaction between congruency and alignment ($t(17) = 3.11$, $p = .006$, Cohen's $d = .73$). However, this interaction differs from that observed in complete faces **(Figure 6B)**, and is probably caused by other processes not related to holistic face processing. These results indicate that variation in facial shape information is required to observe holistic processing in a composite task (see also Jiang et al., 2011).

---------- (*Figure 7 about here*) ----------

Discussion

Experiment 2 provides further support for the hypothesis that facial shape, but not surface, information underlies holistic face processing. When the variation of facial shape information between composite faces was removed, the standard CFE was gone. Unlike holistic processing for complete faces, same-shape faces showed either no significant congruency effect or no significant interaction between congruency and alignment. These results indicate that it is the *variation* of facial shape information produces the CFE, ruling out the possibility that facial shape and surface information drive holistic face processing independently. Note that the lack of CFE for the same-shape faces was unlikely due to the reduced performance, because shape-only faces showed CFE despite performance drop (Experiment 1). It is unclear why responses to Caucasian and Asian same-shape faces were slightly different. But both converge in that eliminating shape variation disrupts holistic face processing.

Experiment 2 also shows how face-based information and perceivers' face discrimination experience interact in terms of holistic processing. When natural shape variation is maintained in complete faces, holistic processing can generalize to other-race faces without extensive individuation experience. However, when shape variation is removed in shape-only faces, the CFE failed to emerge, even for faces exhibiting similar properties that people use for individuation every day (i.e., own-race, same-shape faces).

Although Experiments 1 and 2 indicate that facial shape information underlies holistic processing, it remains unknown what type of shape information plays a crucial role. We differentiated two types of facial shape information in Experiment 3: Geometric structure of whole face surface in 3D space (i.e., 3D shape information) and edges and contours of face features and their 2D spatial relations (i.e., 2D shape information). We removed 3D facial shape information (as well as facial surface information) while preserving 2D shape information in composite faces. Such "knocking-out" of 3D facial shape information provided a rigorous test for the necessity of 3D facial shape information for holistic processing.

Experiment 3: Removing 3D Facial Shape Information

Experiment 3 investigates whether 3D facial shape information is necessary for observing holistic processing, and whether extensive face individuation experience is sufficient to generalize holistic processing to faces lacking this type of information. We converted complete faces into *line-drawing faces* using edge extraction filters. These line-drawing faces preserved 2D facial shape information and face identity while removing 3D facial shape information and surface information (cf. Schwaninger & Yang, 2011). We tested CFE with both complete faces and line-drawing faces from both own- and other-race faces. If 2D facial shape information is sufficient to elicit holistic processing, both complete and line-drawing faces should show similar CFE. If, however, 3D face shape information is required for the generalization of holistic processing to other types of faces, the CFE should be observed for complete faces but not for line-drawing faces.

Methods

Participants

Twenty-four Caucasian people participated in the study (14 females, mean age = 25 years, SD = 5). All were Caucasians and none of them took part in Experiment 1 or 2.

Task, Stimuli, and Procedure

Participants performed 4 blocks of composite tasks (2 face type × 2 race), with block order counterbalanced across participants. The procedure and the stimuli for *complete faces* were identical to those in Experiment 1 (**Figure 8A**).

---------- (*Figure 8 about here*) ----------

Line-drawing faces. Complete faces were converted into line-drawing faces using GIMP software (http://www.gimp.org). We first converted complete faces into black-and-white images and extracted its edge information using the difference of Gaussians filter (radius was 1 and 10 pixels respectively). We then removed dense dark points on cheek and forehead. This procedure removed 3D facial shape information while sparing details about 2D face shape information and face identity (**Figure 8B**). This procedure also removed low spatial-frequency information and preserved some edge-related high-spatial-frequency information. Other high-spatial-frequency information irrelevant to the edges of face features was eliminated, differing from conventionally used high-spatial-frequency faces (e.g., Goffaux, 2009; Goffaux & Rossion, 2006; Cheung et al., 2008). Composite faces made of line-drawing faces were created as in Experiment 1. Identities of composite faces matched those made of complete faces, excluding potential influence of identity change on holistic processing.

Results

Caucasian faces: Complete but not line-drawing faces show CFE

Response sensitivity for Caucasian faces is plotted in **Figure 9A**. A 2 (face type) × 2 (alignment) × 2 (congruency) ANOVA revealed a significant congruency effect (congruent trials: 2.33 ± .11; incongruent trials: 2.10 ± .12), $F(1,23) = 12.25$, $p = .002$, $\eta_p^2 = .35$. This congruency effect was modulated by both alignment, $F(1,23) = 19.13$, $p < .001$, $\eta_p^2 = .50$, and face type, $F(1,23) = 6.36$, $p = .019$, $\eta_p^2 = .22$. Importantly, the three-way interaction was significant, $F(1,23) = 7.47$, $p = .012$, $\eta_p^2 = .25$, indicating that complete and line-drawing faces differ in terms of holistic processing.

Separate 2 (alignment) × 2 (congruency) ANOVAs revealed that complete but not shape-only faces were processed holistically. For complete faces, both the congruency effect, $F(1,23) = 18.83$, $p < .001$, $\eta_p^2 = .45$, and the congruency by alignment interaction, $F(1,23) = 23.53$, $p < .001$, $\eta_p^2 = .51$, were significant. The congruency effect was observed in the aligned condition ($t(23) = 5.88$, $p < .001$, Cohen's $d = 1.20$), but not in the misaligned condition ($t < 1$). These results replicated those found in Experiments 1 and 2, showing a standard pattern of CFE. For line-drawing faces, however, none of statistical results was significant, all $F \leq .63$, all $p \geq .434$, all $\eta_p^2 \leq .03$, indicating a lack of holistic processing for line-drawing faces. Therefore, it is the 3D, but not 2D, facial shape information supports holistic face processing.

---------- (*Figure 9 about here*) ----------

Asian faces: Complete but not line-drawing faces show CFE

Response sensitivity for Asian faces is shown in **Figure 9B**. We found a significant congruency effect (congruent trials: 2.06 ± .12; incongruent trials: 1.74 ± .11), $F(1,23) = 14.56$, $p < .001$, $\eta_p^2 = .39$, and a significant interaction between congruency and alignment, $F(1,23) = 13.13$, *p* = .001, η_p^2 = .36. The interaction between congruency and face type, and the three-way interaction between face type, congruency, and alignment were marginally significant, both *F*(1,23) = 3.38, *p* = .079, η_p^2 = .13. Therefore, holistic processing for complete faces and for line-drawing faces tended to be qualitatively different. Line-drawing faces also showed higher performance than complete faces (2.02 ± .13 vs. 1.79 ± .11), *F*(1,23) = 6.86, *p* = .015, η_p^2 = .23.

Separate 2 (alignment) × 2 (congruency) ANOVAs revealed that complete faces but not line-drawing faces showed significant CFE. For complete faces, the congruency effect, *F*(1,23) = 15.58, *p* < .001, η_p^2 = .40, and its interaction with alignment, *F*(1,23) = 14.69, *p* < .001, η_p^2 = .39, were both significant. The congruency effect was observed in the aligned condition (*t*(23) = 4.84, *p* < .001, Cohen's *d* = .99), but not in the misaligned condition (*t* < 1). In contrast, for line-drawing faces, there was only a main effect of congruency, *F*(1,23) = 4.29, *p* = .050, η_p^2 = .16. The congruency effect was observed in the aligned condition (*t*(23) = 2.50, *p* = .020, Cohen's *d* = .51), but not in the misaligned condition (*t* < 1). However, the interaction between congruency and alignment was not significant, *F*(1,23) = 2.96, *p* = .099, η_p^2 = .11. Thus, holistic processing observed in complete faces was dramatically reduced or eliminated in line-drawing faces. These results indicate that 2D facial shape information is insufficient to elicit holistic face processing similar to that observed with complete faces.

Face individuation experience is insufficient for generalization of holistic processing

To examine the influence of face individuation experience on processing complete and line-drawing faces, we conducted separate 2 (race) × 2 (alignment) × 2 (congruency) ANOVA for each face type. For complete faces (**Figure 9**, left column), both the congruency effect, *F*(1,23) =

29.58, $p < .001$, $\eta_p^2 = .56$, and the interaction between congruency and alignment, $F(1,23) = 31.95$, $p < .001$, $\eta_p^2 = .58$, were significant. As in Experiments 1 and 2, own-race faces exhibited higher performance than other-race faces (2.15 ± .12 vs. 1.79 ± .11), $F(1,23) = 25.20$, $p < .001$, $\eta_p^2 = .52$, but face race did not affect holistic processing, $F < 1$. Therefore, for normal complete faces, no further face discrimination experience is required to generalize holistic processing for other-race faces.

For line-drawing faces (**Figure 9**, right column), participants' overall discrimination performance was still higher for own- than other-race faces, $F(1,23) = 9.70$, $p = .005$, $\eta_p^2 = .30$. Nonetheless, neither the main effect of congruency, $F(1,23) = 4.13$, $p =.054$, $\eta_p^2 = .15$, nor its interaction with alignment, $F(1,23) = 3.51$, $p = .074$, $\eta_p^2 = .13$, was significant. Again, face race showed no influence on holistic processing, $F < 1$. Therefore, extensive face-discrimination experience with own-race faces is insufficient to generalize holistic processing to faces lacking of 3D shape information (i.e., own-race line-drawing faces).

3D facial shape information is necessary to elicit holistic face processing

The magnitude of CFE for each condition is plotted in **Figure 10**. The CFE was only significant for complete faces (both $t(23) > 3.83$, $p < .001$, Cohen's $d > .78$), but not for line-drawing faces (both $t(23) \leq 1.72$, $p \geq .099$, Cohen's $d \leq .35$). A 2 (face type) by 2 (face race) ANOVA confirmed that holistic processing for these two types of faces are different, $F(1,23) = 9.48$, $p = .005$, $\eta_p^2 = .29$. Mere 2D facial shape information is insufficient to elicit holistic face processing, demonstrating the necessity of 3D facial shape information for holistic face processing.

---------- (*Figure 10 about here*) ----------

Discussion

Experiment 3 shows that removal of 3D facial shape information eliminates the CFE. This finding indicates that holistic face processing relies on 3D, rather than 2D, shape information. The elimination of CFE observed with line-drawing faces suggests that 2D facial shapes are processed less holistically than either complete faces or 3D facial shapes. In addition, holistic processing can generalize to other-race faces without extensive discriminating experience, provided that 3D facial shape information is preserved and vary across faces. Conversely, when faces are devoid of such 3D shape information, holistic processing even cannot generalize to own-race faces with which people have extensive discriminating experience.

Disruption of holistic processing for line-drawing faces may be due to enhanced featural processing for these faces when 3D facial shape information is removed. While facial features (e.g., eyes, nose, mouth etc.) are integrated by smooth 3D shape information in complete faces, they are isolated in line-drawing faces and the connection between top and bottom parts is weakened. The separation of facial features in line-drawing faces should facilitate feature-based judgments. Consistent with this speculation, we observed better overall performance for line-drawing faces than for complete faces. Enhanced feature-based processing for line-drawing faces might be also due to the removal of low spatial-frequency information (Goffaux, 2009; Goffaux & Rossion, 2006; but see Cheung et al., 2008). Nevertheless, the elimination of CFE observed here is more likely caused by the removal of 3D shape than low spatial-frequency information. In Experiment 2, the CFE disappeared in same-shape faces even though low-spatial-frequency facial information was maintained.

General Discussion

While extensive research has sought for the origin of holistic processing from perceiver-based properties (e.g., expertise), the present study pinpoints visual information that supports holistic face processing. As summarized in **Table 1**, by manipulating the availability and variability of facial information, we demonstrate that facial shape information alone is sufficient to elicit holistic processing, whereas facial surface information is not required (Experiment 1). We further show that the locus of holistic processing effects lies in the variation of facial shape information. That is, when the underlying facial shape information is fixed across faces in the composite task, normal CFE disappears (Experiment 2). Finally, we demonstrate that variation in 3D facial shape information, rather than 2D shape information of face features (i.e., edges and contours), underlies holistic face processing. When 3D shape information is removed in line-drawing faces, evidence of holistic face processing disappears (Experiment 3). Therefore, 3D facial shape information is not only sufficient but also necessary to observe the CFE—the most convincing indication of holistic face processing. These results provide compelling evidence for the hypothesis that facial shape information underlies holistic face processing, and is required to generalize holistic processing to other types of faces.

---------- (*Table 1 about here*) ----------

Current theories of holistic processing not only differ in whether holistic processing for faces can generalize to non-face objects, but also imply different requirements for such generalization. The domain-specificity hypothesis suggests that stimuli must be faces or sufficiently face-like to elicit holistic processing (McKone et al., 2007; Robbins & McKone, 2007). This hypothesis could readily address the generalization of holistic processing to other-race faces and to shape-only faces. However, it needs additional assumption to explain what eliminated holistic processing for same-shape faces and line-drawing faces, as both should be sufficiently face-like to activate holistic face processing. The expertise hypothesis implies that individual-level discrimination experience is crucial for generalizing holistic processing to other faces or non-face objects (Chua, Richler, & Gauthier, 2014; Gauthier & Tarr, 1997; Richler & Gauthier, 2014; Wong et al., 2009). This hypothesis can readily address the disappearance of holistic processing for line-drawing faces. Nonetheless, additional assumption has to be invoked to explain how holistic processing could generalize to other-race faces and shape-only faces without extensive experience in discriminating those faces. Therefore, both domain-specificity hypothesis and expertise hypothesis predicted part of our results, but not all.

Toward a shape-based account for holistic face processing

The present study addresses *what* type of facial information supports holistic face processing, and is therefore required for generalization of holistic processing to various types of faces. We show that the CFE is mediated by the inability to selectively attend to one part of a smoothly unified 3D facial shape. Specifically, shape information in the top and bottom halves of an aligned composite face is perceptually grouped into a single one, based on the physical and implied (i.e., Gestalt) continuity, connectivity, and smooth transition between both halves. When facial shape information in either half is sufficiently changed, this shape-based perceptual grouping would lead to an automatic percept of a new unified shape, producing biases in judging the unchanged part of the shape (i.e., failure of selective attention). This bias is reduced or eliminated when the shape-based perceptual grouping is disrupted (e.g., misaligned faces), is reduced (e.g., line-drawing faces), or fail to form a perceptually *new* unified shape (e.g., same-shape faces). This shape-based account suggests that whether holistic face processing originates from innate face template (i.e., domain-specificity hypothesis) or automatized attention spreading to all face parts (i.e., expertise hypothesis), it is tuned to facial shape information.

This shape-based account for holistic face processing requires two assumptions. First, facial shape information can be extracted from face images. Consistent with this assumption, Schwaninger and Yang (2011) found that people can extract 3D facial shape information from normal, complete faces, but failed to do so from line-drawing faces (see also Jiang, Blanz, & O'Toole, 2009). Second, sufficiently different shape information between faces signals perception of different shape-based facial properties (e.g., identity). In line with this assumption, both behavioral and neural responses of human face discrimination can be well explained by shape-based face recognition models (Jiang et al., 2006; Yue, Biederman, Mangini, von der Malsburg, & Amir, 2012). Conversely, when physical change of facial shape information fails to elicit perception of a *new* shape-based identity, holistic processing would not be observed. Therefore, simply swapping one face half does not warrant a CFE.

One advantage of the shape-based holistic processing account is that it functions at the level of facial shape perception irrespective of surface information, and therefore applies to other faces containing 3D facial shape information. This explains why people process other-race faces holistically without extensive discrimination experience (see also Bukach et al., 2012; Harrison et al., 2014; Zhao et al., 2014), as they also exhibit variations of 3D shapes. It also accounts for prior findings that humans even process certain non-human primate faces holistically, as long as they share very similar 3D shape information with human faces (Taubert, 2009; see also Dahl, Wallraven, Bülthoff, & Logothetis, 2009). The shape-based account may also apply to holistic processing of facial emotion (Calder, Young, Keane, & Dean, 2000), though perception of facial expression may rely on different types of shape information than perception of face identity (Calder et al., 2000; Neth & Martinez, 2010). Switch of facial expression in one face half changes whole facial shape information and vice versa, leading to a CFE for facial expression. Conversely, when two face parts show the same facial expression (even from different faces), no holistic processing would be expected because it is insufficient to elicit perception of a new expression based on facial shape information.

The shape-based account offers a parsimonious explanation for a wide range of holistic processing studies that manipulate facial information. First, it resolves discrepancies between studies investigating the roles of facial shape information in holistic processing. Since holistic face processing relies on 3D but not 2D shape information, isolated 3D facial shape information would elicit holistic face processing (Jiang et al., 2011) whereas isolated 2D line-drawing faces would not (Meinhardt-Injac et al., 2013). Second, it elucidates why manipulations of viewpoint or spatial relations among face features do not eliminate holistic face processing (de Heering et al., 2012; McKone, 2008; Richler, et al., 2014; Taubert & Alais, 2009). Holistic face processing survives such manipulations because they do not disrupt the formation of a unified 3D facial shape. Conversely, when the perceptual grouping of top and bottom facial shape information is disrupted, holistic face processing no longer persists. This may explain why holistic processing is eliminated when face halves were separated by a large gap or placed into different depth planes (Taubert & Alais, 2009), were placed into spatially and colorfully inconsistent backgorunds (Curby, Goldstein, & Blacker, 2013), or were presented with a long enough temporal gap (Cheung, Richler, Phillips, & Gauthier, 2011).

Furthermore, shape-based holistic processing may unravel why photographically negative faces showed similar level of holistic processing as positive faces (i.e., complete faces, Hole, George, & Dunsmore, 1999; Taubert & Alais, 2011). Negative faces are to some extent similar to our shape-only faces, which changes facial surface information dramatically but maintains unified 3D facial shape information, thereby eliciting holistic face processing. Finally, it may explicate why holistic processing is more prominent for low than for high spatial-frequency facial information (Goffaux, 2009; Goffaux & Rossion, 2006; Taubert & Alais, 2011; but see Cheung et al., 2008). For the ranges of spatial frequencies that have been tested, low spatial-frequency facial information often preserved coarse 3D facial shape. In contrast, high spatial-frequency filtering often disrupts this critical shape information (similar to line-drawing faces), reducing holistic face processing. Note that holistic processing for low spatial-frequency faces and for negative faces are consistent with our hypothesis that shape but not surface information underlies holistic face processing.

Interplay of face- and perceiver-based factors in holistic face processing

Highlighting the pivotal role of shape information in holistic face processing does not contradict to the hypothesis that face discrimination experience is critical for *developing* holistic processing for faces (and other objects of expertise, Gauthier & Tarr, 1997; Richler, et al., 2011; 2013; Richler & Gauthier, 2014; Wong et al., 2009). Instead, face-based information and perceiver-based attention strategy may represent two complementary sources of holistic processing: one is bottom-up and the other is top-down. Taking both into consideration may provide a more coherent account for what gives rise to holistic face processing and what is required to generalize holistic processing to other types of faces.

Our results indicate that the role of face-individuation experience for holistic face processing is contingent upon facial shape information. When 3D facial shape information and its variation are preserved, holistic processing can apply to initially non-experienced faces (e.g., other-race faces, shape-only faces) without extensive experience in discriminating those faces (see also Bukach et al., 2012; Harrison et al., 2014; Zhao et al., 2014) . Conversely, despite perceivers' extensive individuation experience for own-race faces, holistic processing fails to emerge when 3D facial shape is either fixed or removed (see also Jiang et al., 2011; Meinhardt-Injac et al., 2013). These results indicate that both the sufficiency and necessity of face-discrimination experience for holistic processing are dependent on facial shape information. Therefore, individual-level discrimination experience alone does not guarantee holistic processing for faces or non-face objects (see also Robbins & McKone, 2007).

On the other hand, face individuation experience, particularly during the sensitive period in early infancy, affects shape-based holistic face processing. Le Grand, Mondloch, Maurer, and Brent (2004) have shown that patients deprived of normal vision in early infancy fail to show the CFE , indicating that early face discrimination experience is necessary for developing holistic face processing. Moreover, holistic face processing is sensitive to face orientation, probably due to extensive experience people have with *upright* faces. Whereas holistic processing for upright faces happens at a glance, holistic processing for inverted faces takes time (Richler, Mack, Gauthier, & Palmeri, 2009; Richler, Mack, Palmeri, & Gauthier, 2011). Holistic processing for upright faces also tends to be stronger than that for inverted faces (Hole, 1994; Rossion, 2008; Young et al., 1987; Susilo, Rezlescu, & Duchaine, 2013; but see Richler, Mack, et al., 2011). While the bottom-up, shape-based holistic processing allows generalization to inverted faces (despite being processed less efficiently than upright faces), both domain-specificity and expertise hypotheses require additional assumptions to explain such generalization across face orientation.

Taken together, holistic face processing seems to originate from perceivers' early experience in discriminating faces, which either activates the innate face template or automatizes attention to all parts within a whole face. Our study indicates that once holistic face processing is developed, its generalization to other face subtypes requires 3D facial shape information. Certain distortion of facial shape information (e.g., shearing, blurring, or negation of face images) may be tolerated for such generalization; provided that it does not disrupt the unified and smoothly transitioned 3D facial shape information.

Beyond holistic face processing: Routes to holistic object processing

The interplay of individuation experience and facial shape information in holistic face processing offers a new view to an old question: Can holistic processing generalize to non-face objects? Previous studies often emphasize either that holistic processing is unique to faces (e.g., McKone et al., 2007; Robbins & McKone, 2007) or that holistic processing applies to any objects of expertise (Bukach, Gauthier, & Tarr, 2006; Diamond & Carey, 1986; Wong et al., 2009). We hypothesize that holistic processing for objects (including faces) is jointly determined by both object- and perceiver-based factors. On the one end, following extensive training, holistic processing may emerge for non-face objects, even those with different types of shape information from facial shape. On the other end, under certain circumstances, object shape information alone may suffice to elicit holistic processing without extensive training. For most of objects categories, generalization of holistic processing would require both object-based shape information and perceiver-based discrimination experience.

Prior studies have shown that holistic processing can generalize to non-face objects of expertise (e.g., Chua et al., 2014; Gauthier & Tarr, 1997, 2002; Wong et al., 2009). These studies trained participants to discriminate novel objects based on shape information, but they often overlooked such object-based information required to observe holistic objet processing. Long-term, real-world training even leads to holistic processing for objects that differ only in 2D shape information (e.g., English words or Chinese charaters; Wong et al., 2011, 2012; see also Busey & Vanderkolk, 2005), suggesting that critical shape information for holistic processing may be intrinsic to object properties (i.e., 3D shape for 3D obejcts like faces, and 2D shape for 2D objects like words). Thus, generalization of holistic processing to objects of expertise requires both discrimination experience and object-based shape information. Neither shape information (e.g., cars for yound kids; Cassia, Picozzi, Kuefner, Bricolo, & Turati, 2009) nor discrimination experience (e.g., dogs for dog experts; Robbins & McKone, 2007) guarantees holistic processing for non-face objects.

Can object shape information alone elicit holistic processing? It seems plausible under certain circumstances. For instance, Wong and colleagues (2012, p1) have found that "both experts and novices showed holistic processing [for Chinese characters], irrespective of the character structure (left-right or top-bottom) or presentation sequence (sequential or simultaneous matching)". Holistic processing of other non-face objects has also been observed (e.g., holistic processing of cars in car novices, Bukach et al., 2010; Gauthier et al., 2003). These observations suggest that, under certain circumstances, people can process non-face objects holistically without being an expert. Perceivers' experience often modulates holistic processing for non-face objects (Bukach et al., 2010; Wong et al., 2009, 2011, 2012); however, such influence does not revoke the observations that holistic processing can be achieved via other routes than expertise. It remains to be elucidated whether holistic processing for non-face objects is similar to that for faces (Richler, Wong, et al., 2011).

Conclusion

The present study demonstrates that 3D facial shape information is not only necessary but also sufficient to elicit holistic face processing. To generalize holistic processing to other types of faces, such information is required. In contrast, facial surface information is neither sufficient nor necessary. Therefore, facial shape, but not surface, information underlies holistic face processing. The shape-based holistic processing account not only addresses why holistic processing applies to faces which people have little or no discrimination experience, but also consistently explains how manipulations of facial information may affect holistic processing. Moreover, shape information may be similarly required to generalize holistic processing to non-face objects. While prior research emphasizes perceiver-based factors in establishing a unified account for holistic processing of faces and non-face objects, the present study suggests a complementary ground: the shape of faces and objects.

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Table (1 table)

Table 1. Summary of results for own-race (and other-race) faces in Experiments 1-3.

Face Type	3D Shape	Facial Surface	Congruency Effect (Aligned)	Congruency Effect (Misaligned)	Congruency × Alignment	Holistic Processing
Complete	+	+	√ (√)	X (X)	√ (√)	Yes (Yes)
Shape-only	+	-	√ (√)	X (X)	√ (√)	Yes (Yes)
Same-shape	Fixed	+	X (X)	√ (√)	X (√)	No (No)
Line-drawing	-	-	X (√)	X (X)	X (X)	No (No)

Notes. +, available and varying; -, unavailable; Fixed, available and constant; √, statistically significant results; X, non-significant results; Congruency × Alignment, interaction between congruency and alignment; Holistic processing refers to both a significant congruency effect and a significant interaction between congruency and alignment (i.e., larger congruency effect in aligned than in misaligned conditions). Results for other-race faces are shown in parentheses.

Figures (10 figures)

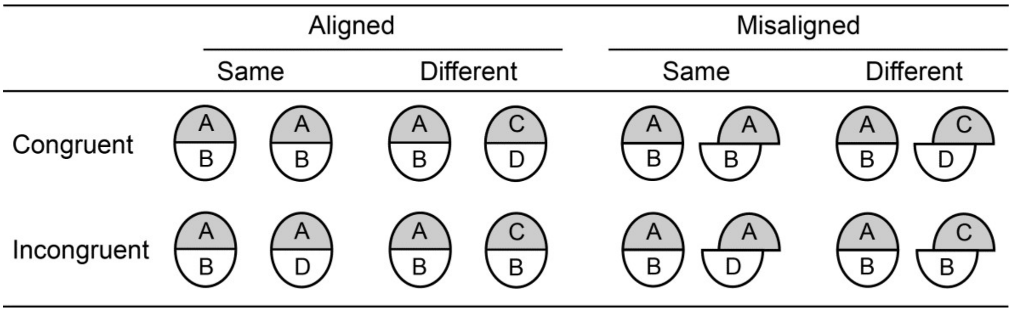

Figure 1. A complete design of composite task used in Experiments 1-3. Two schematic faces in each cell represent the first and the second faces in each trial. Letters stand for identities of face halves. The top half of the two faces may be the same as or different from each other (same vs. different), may be aligned with the bottom half or not (aligned vs. misaligned), while the bottom halves of two faces may have the same identity variation as the top halves or not (congruent vs. incongruent).

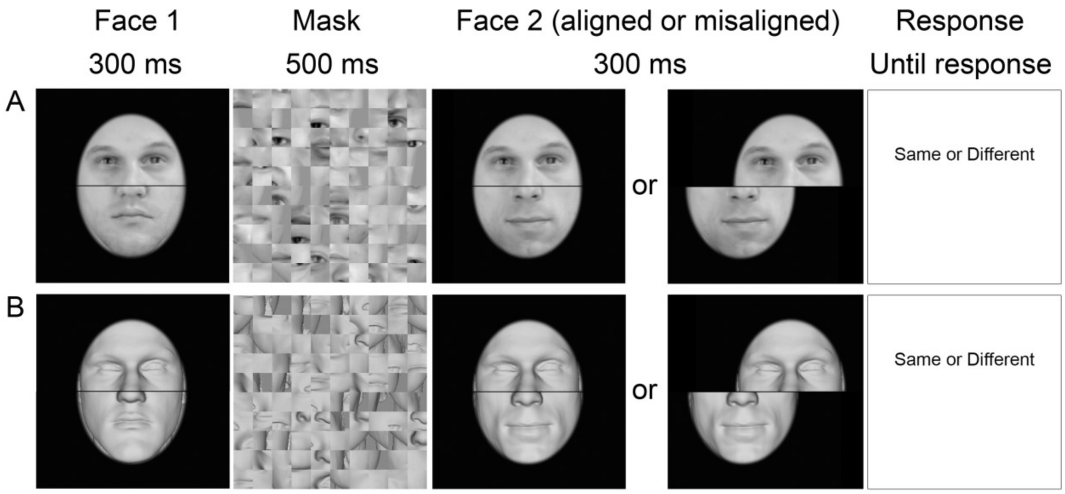

Figure 2. Exemplar stimuli and trial of the composite face task using (A) complete faces and (B) shape-only faces. Only incongruent trials for the same condition are shown here. Complete and shape-only faces show the same set of face identities.

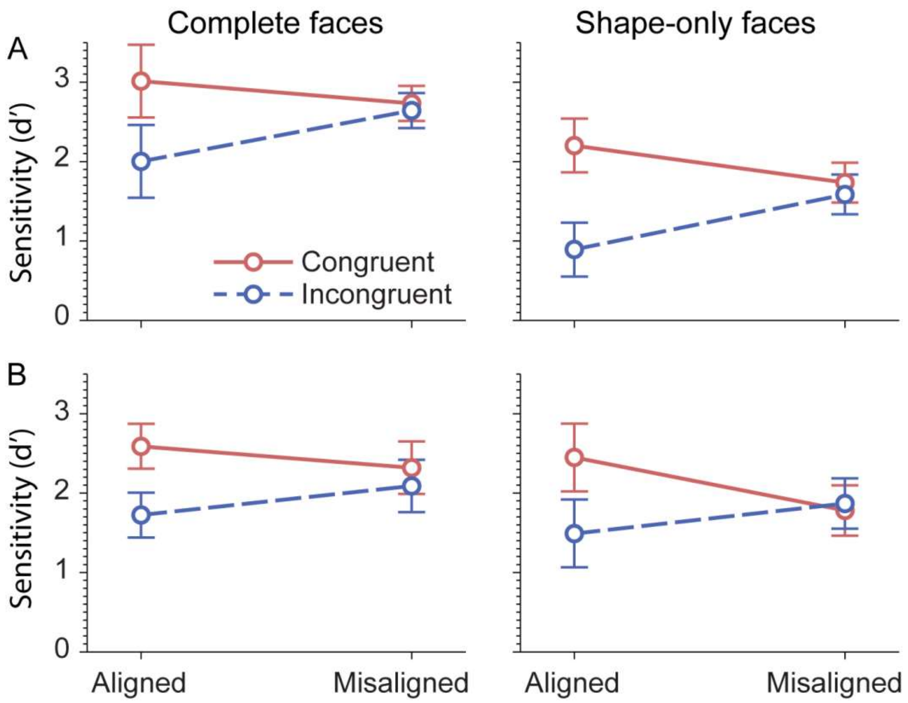

Figure 3. Response sensitivity as function of congruency, alignment, and face type for (A) Caucasian faces and (B) Asian faces in Experiment 1. Error bars represent 95% confidence intervals (CI).

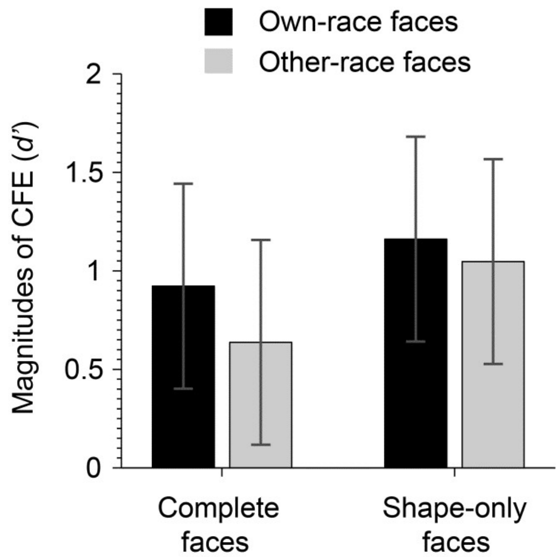

Figure 4. Magnitudes of the CFE for own- and other-race complete faces and shape-only faces in Experiment 1. The CFE was computed by subtracting congruency effect observed in misaligned condition from that observed in aligned condition (i.e., the congruency by alignment interaction). Error bars represent 95% CI.

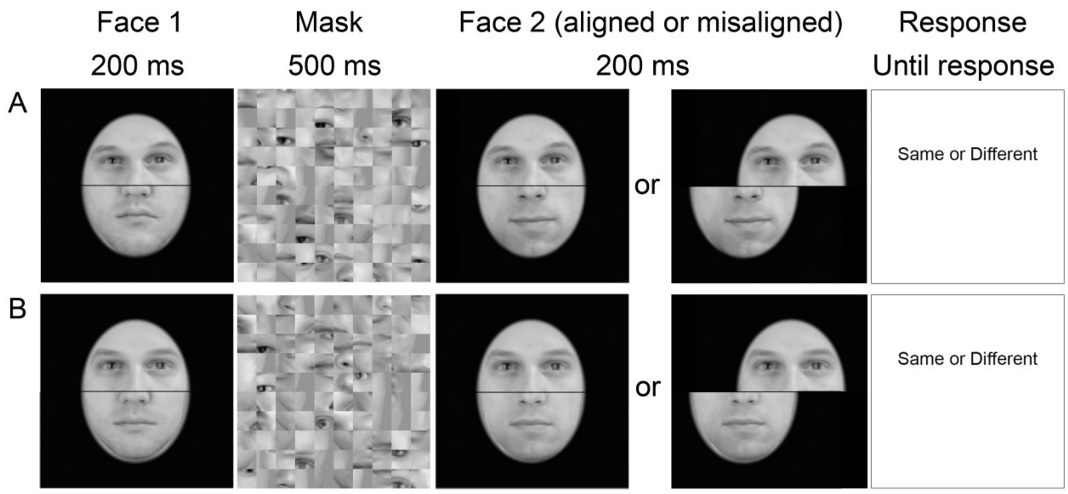

Figure 5. Exemplar stimuli and trial of the composite face task using (A) complete faces and (B) same-shape faces. Only incongruent trials for the same condition are shown here. Complete and same-shape faces show the same facial surface information but different shape information.

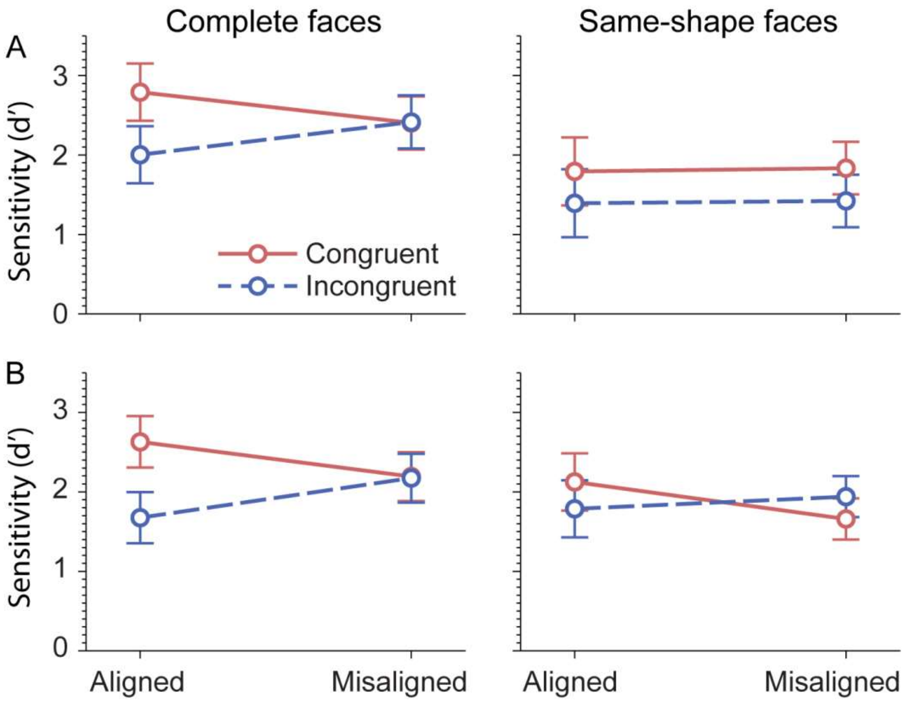

Figure 6. Response sensitivity as function of congruency, alignment, and face type for (A) Caucasian faces and (B) Asian faces in Experiment 2. Error bars represent 95% CI.

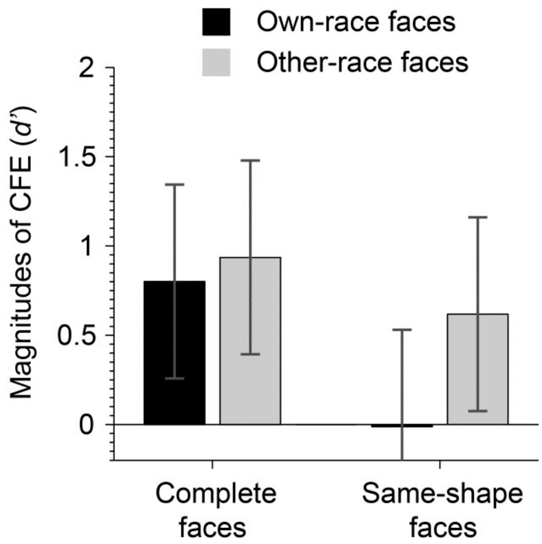

Figure 7. Magnitudes of the CFE for own- and other-race complete faces and same-shape faces in Experiment 2. The CFE was computed by subtracting congruency effect observed in misaligned condition from that observed in aligned condition (i.e., the congruency by alignment interaction). Error bars represent 95% CI.

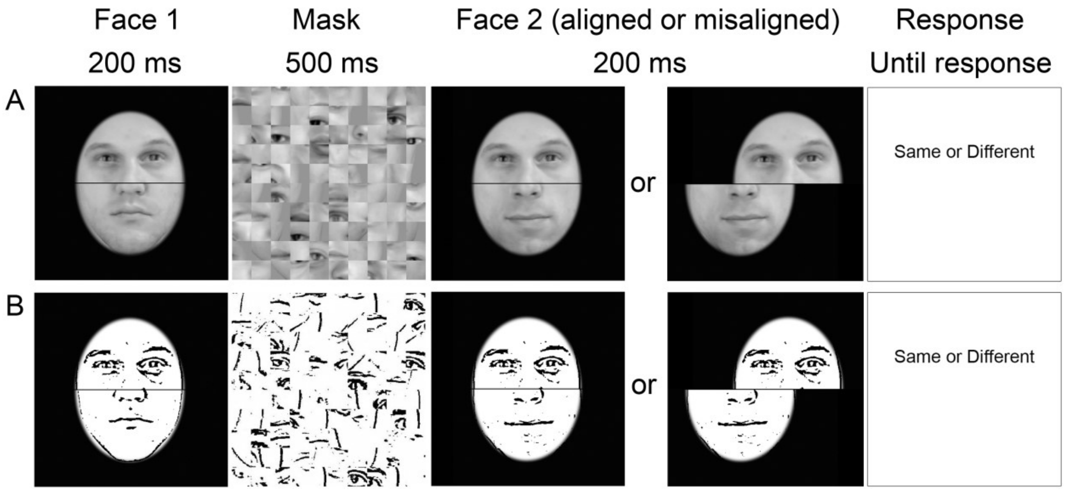

Figure 8. Exemplar stimuli and trial of the composite face task using (A) complete faces and (B) line-drawing faces. Only incongruent trials for the same condition are shown here. Complete and line-drawing faces show the same set of face identities.

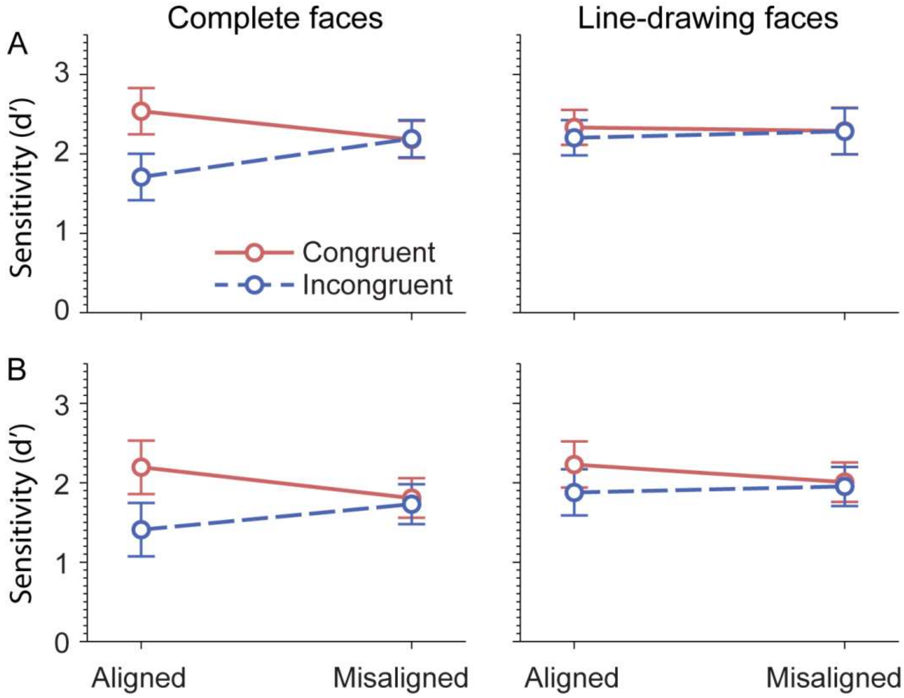

Figure 9. Response sensitivity as function of congruency, alignment, and face type for (A) Caucasian faces and (B) Asian faces in Experiment 3. Error bars represent 95% CI.

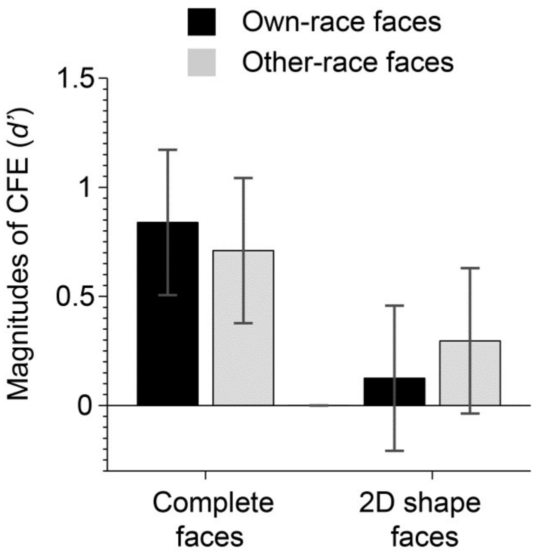

Figure 10. Magnitudes of the CFE for own- and other-race complete faces and line drawing faces in Experiment 3. The CFE was computed by subtracting congruency effect observed in misaligned condition from that observed in aligned condition (i.e., the congruency by alignment interaction). Error bars represent 95% CI.