Holistic processing as measured in the composite task does not always go with right hemisphere processing in face perception

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# **Abstract**

The hemispheric asymmetry literature traditionally posits that holistic processing is a property of right hemisphere processing. Nevertheless, a counterexample was recently found: studies showed that Chinese character recognition expertise is associated with reduced holistic processing (as measured in the composite task) and increased right hemisphere lateralization (as indicated by a left-side bias effect in character perception), revealing that these two effects may be separate processes. With a computational model of face recognition, in which we implement a theory of hemispheric asymmetry in perception that posits a low spatial frequency bias in the right hemisphere and a high spatial frequency bias in the left hemisphere (i.e., the Double Filtering by Frequency Theory, Ivry and Robertson, 1998), we show that when the face recognition task relies purely on featural information, there is a negative correlation between holistic processing and right hemisphere lateralization. In contrast, when the face recognition task relies purely on configural information, there is a strong positive correlation between holistic processing and right hemisphere lateralization. In another simulation, we used real face images, which naturally embed both featural and configural changes, and observed no correlation between holistic processing and right hemisphere lateralization. We then replicated this simulation result behaviorally with East-Asian participants doing the holistic processing (composite) task and a left-side bias (chimeric face judgment) task with East-Asian faces. Together, these results suggest that holistic processing as measured in the composite task and right hemisphere lateralization are separate processes that can be influenced differentially by task requirements.

Keywords: Hemispheric lateralization; Holistic processing; Face processing; Computational cognitive neuroscience

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1. **Introduction**

In the literature on face recognition, a mechanism thought to be central to face recognition is holistic processing. Holistic processing of faces commonly refers to the phenomenon of experiencing viewed faces as a whole instead of independent facial parts (e.g., Tanaka & Farah, 1993). In contrast, complex objects are thought to be represented through the assembling of primitive parts (Marr & Nishihara, 1978; Biederman, 1987). In a review on holistic face perception, Behrmann, Richler, Avidan, and Kimchi (in press) described three main accounts of holistic processing: the “all of a piece” holistic representational account, the interactive account, and the automatized attentional account (see (Richler, Palmeri & Gauthier, 2012) for a list of additional accounts of holistic processing and their corresponding measurementss). The “all of a piece” account assumes that perceived faces undergo no or minimal part decomposition and are represented as an undifferentiated whole (Farah, Wilson, Drain, & Tanaka, 1998). The interactive account stipulates that features of faces (i.e., the facial parts) are automatically processed conjointly with second-order configural information (i.e., the distance between facial features). This integration of featural and configural information is rooted in our experience of perceiving dynamic or expressive faces, in which facial parts and second-order configuration simultaneously interact (Behrmann et al., in press). The automatized attentional account originates from studies using composite faces (Hole, 1994; Young, Hellawell, & Hay, 1987). In these studies, participants commonly have to selectively attend to and match the top halves of two faces and to ignore the bottom halves. Participants demonstrate lower accuracy in matching two identical tops when the two bottoms are different compared with when they are the same. This suggests that participants fail to selectively engage attention to the tops, and integrate automatically the top and bottom halves (Gauthier & Bukach, 2007). This automaticity of failure of selective attention is limited to faces and other objects for which we have expertise (Richler, Wong, & Gauthier, 2011).

These three accounts of holistic processing are assessed with different tasks because they conceptualize holistic processing and operate its measurement differently. To have three different tasks to measure holistic processing may seem problematic. Richler, Palmeri and Gauthier (2012) raised indeed the problem in the field of holistic processing research of multiple definitions and measurements of holistic processing which constitutes an obstacle tohinders the unifintegration ofying research resultsadvances in the . For the holistic representational account, the part-whole paradigm is used (Tanaka & Farah, 1993). After learning a face (“This is Bob.”), participants perform two-alternative forced choice recognition memory tests. In the isolated part condition, participants see for example two noses and identify which one is Bob’s. In the full-face condition, participants see two faces that differ only in the part (e.g., the nose) tested in the isolated face condition and identify which face is Bob’s. In Tanaka & Farah (1993), participants showed better recognition in the full-face condition than in the isolated part condition, suggesting that a face representation is better retrieved from the whole face than from any of its parts. For the interactive account of holistic processing, Amishav and Kimchi (2010) used Garner’s speeded classification task (Garner, 1974) to test whether facial features are processed independently from their configuration, and vice versa. In a featural judgment task, participants discriminate faces using featural information while ignoring configural information kept either constant (baseline condition) or varied (filtering condition). In the configural judgment task, the manipulation between featural and configural information is reversed. Amishav and Kimchi found a “Garner interference”: participants performed worse in the filtering condition than the baseline condition in both the featural and configural judgment tasks, indicating that features and configuration are processed conjointly. For the automatized attentional account of holistic processing, the common task for measuring holistic processing is the complete composite paradigm (Gauthier & Bukach, 2007), inspired by the seminal composite tasks of Hole (1994) and Young et al. (1987). In a simultaneous complete composite paradigm, participants are presented with two composite faces: each face is made of top and bottom halves of one face or two different faces. Participants are asked to attend only to the two top halves and judge whether they are identical or not. If face processing is holistic, participants will automatically attend to and process the bottom halves in addition to the top halves. In congruent trials, the irrelevant bottom halves lead to the same response as the top halves. In incongruent trials, the irrelevant bottom halves lead to a response conflicting with the response from the top halves. HP is characterized by the interference from the bottom halves while matching the top halves. It is measured by the performance difference between congruent trials and incongruent trials. A positive difference is indicative of holistic processing. Because the complete composite task taps into automatic attentional processes, the amount of holistic processing yielded by the complete composite task can be interestingly modulated by a prior task priming local or global attention by using for example Navon stimuli (Gao, Flevaris, Robertson, & Bentin, 2011). Using hierarchical letter stimuli, Gao et al. (2011) found that global priming augments holistic processing, and that local priming did not affect holistic processing as compared with a non-priming baseline. Hence, holistic processing as measured by complete composite seems closely related to global processing. Similarly, part-based processing may be associated with local attention. Hereafter we adopt the automatized attentional account of holistic processing, and measure holistic processing with the complete composite paradigm.

In addition to the holistic processing effect, face processing has been shown to involve right hemisphere lateralization, as indicated by the left side bias effect: a chimeric face made from two left half faces from the viewer's perspective is usually judged more similar to the original face than one made from two right half faces (Gilbert & Bakan, 1973; Brady, Campbell, & Flaherty, 2005). The left side bias effect is for psychologists a commonwidely adopted behavioral indicator of right hemisphere lateralization (Gilbert, & Bakan, 1973). Face stimuli can be replaced with other stimuli to test for these stimuli lateralization.

A seminal functional Magnetic Resonance Imaging (fMRI) study identified an area inside the fusiform gyrus (the *fusiform face area, FFA*) responding preferentially to faces, with larger activation in the right hemisphere than the left hemisphere (Kanwisher, McDermott, & Chun, 1997). Follow-up fMRI studies confirmed the dominance of the right hemisphere during face processing, and a more complex network of face-preferential areas has emerged (Ishai, Schmidt, & Boesiger, 2005; Rossion, Hanseeuw, & Dricot, 2012). ERP data also show that faces elicit larger N170 than other types of objects, especially in the right hemisphere (Rossion, Joyce, Cottrell, & Tarr, 2003). These fMRI/ERP studies did not used chimeric faces as stimuli. They, but they provided evidence for a right hemisphere lateralization of face processing in agreement with the behavioral data based on chimeric faces.

The holistic processing effect has been linked in fMRI studies to right hemisphere lateralization in face selective areas (Harris & Aguirre, 2008; Schiltz, Dricot, Goebel, & Rossion, 2010). For example, Schiltz et al. (2010) showed that when participants match two top identical halves of aligned composite faces presented sequentially, there is a release of adaptation of BOLD signal in the right FFA (rFFA) when the two task-irrelevant bottoms are different compared with when they are the same. This release of adaptation is absent for misaligned faces. This result indicates that populations of neurons in the rFFA involved in selective attention to a face part are influenced by changes in other face parts only when the face is aligned, i.e., presented as a whole.

Gauthier and Tarr (2002) trained participants to become experts in the recognition of a novel object type (Greebles). By the end of the training, participants demonstrated an increase in holistic processing of Greebles. The holistic processing measured for Greebles behaviorally for five participants was positively correlated with the activity of the fMRI signal in the right middle fusiform area captured in a previous study from the same participants performing a Greeble recognition task. Gauthier and Tarr suggested that increased holistic processing is a marker of expertise and goes with right hemisphere lateralization in the FFA. This result, although limited to Greeble recognition, is consistent with the hemispheric asymmetry literature that posits a holistic/analytic preferential dichotomy between right hemisphere and left hemisphere processing (Bradshaw & Nettleton, 1981), and suggests that holistic processing and right hemisphere lateralization effects go together. This coupling of holistic processing and right hemisphere lateralization remains to be tested behaviorally for face stimuli. We tested it in this study by using the complete composite task and the chimeric face judgment task.

Nevertheless, a counterexample was recently found: Chinese character recognition experts have reduced holistic processing and increased right hemisphere lateralization in processing Chinese characters compared with novices (Hsiao & Cottrell, 2009). Put simply, Chinese characters are made of strokes fit in a squared shape. Featural information (i.e., the strokes) is critical to Chinese character recognition, but configural information (e.g., the spacing between the strokes) is not (Ge, Wang, McCleery, & Lee, 2006; McCleery et al., 2008), in contrast to face recognition. A Chinese expert reader can recognize between 3000 and 4000 characters, a number of comparable magnitude to the number of faces adults can recognize (Mondloch, Le Grand, & Maurer, 2002). Hsiao and Cottrell (2009) adapted the complete composite task with Chinese character stimuli, and the chimeric face judgment task with chimeric mirror-symmetric Chinese characters (created in the same fashion as chimeric faces). Novices showed the congruency effect indicative of holistic processing of Chinese characters, but experts did not. Chinese experts engage in better selective attention on character parts compared with novices. In the chimeric Chinese characters judgment task, only experts showed a preference for left-chimeric characters, and novices had no preference. This result suggests that experts engage the right hemisphere more than novices in processing Chinese characters. Hsiao and Cottrell (2009) thus suggested that increased left side bias and reduced holistic processing are the markers of expertise in Chinese character recognition. Unlike face expertise, the left side bias for Chinese characters is associated with reduced holistic processing instead of increased holistic processing. This suggests that holistic processing as measured in the complete composite task and right hemisphere lateralization may be separate processes that do not always go together.

Faces and Chinese characters differ in both featural and configural dimensions. In the featural dimension, faces consist of common features (i.e., the eyes, nose, and mouth) and the features of different faces usually look similar to each other; in contrast, Chinese character recognition involves discriminating different combinations of more than two hundred basic stroke patterns (Hsiao & Shillcock, 2006), which usually look dissimilar to each other. In the configural dimension, second-order spatial relations (i.e., distances) between components have been shown to be more important in face recognition than in the recognition of other visual object classes (Farah et al., 1998), whereas this configural information is not important in Chinese character recognition, since changes in distance among character components do not change the character identity (Ge et al., 2006). The difference between face and Chinese character recognition in their reliance on configural and featural information may explain the different relationships between holistic processing and right hemisphere lateralization found between them.

Thus, here we hypothesize that right hemisphere lateralization and holistic processing as measured in the complete composite task do not always go together, and it depends on the requirements of the recognition task in either the featural or the configural dimension. Firstly, we examine this hypothesis through computational modeling by using artificial human-like faces that differ purely in configuration or purely in features in a face recognition task, and real faces from the FERET dataset (Phillips, Wechsler, Huang, & Rauss, 1998) that embed both configural and featural differences. Secondly, we collect human data for both the complete composite task and the chimeric face judgment task.

Computational models can be used to simulate human behavior with embedded neurophysiologically plausible principles so that the simulation data can reasonably be compared with human data, or lead to new predictions for future behavioral studies. They are great for exploring hypotheses while controlling for confounding variables since modeling gives us an excellent control over variables (Cottrell & Hsiao, 2011). Here we use a connectionist model of face recognition, the intermediate convergence model, which is shown to be able to account for the left side bias effect in face perception (Hsiao, Shieh, & Cottrell, 2008). The model embeds in its architecture of the visual processing pathways some key principles of visual neuroscience (see details in the Modeling section). First, Gabor filtering of input faces models initial feature extraction in V1 (Figure 1a). Then, extraction of higher-level features is implemented through dimensionality reduction, simulating processes beyond V1 up to lateral occipital regions. These higher-level features then are used as the input to a two-layer neural network. The hidden layer of the network learns representations that are task-specific and is analogous to the FFA. The output layer of the network labels input faces and simulates the function of the frontal areas. Importantly, the intermediate convergence model also implements a theory of hemispheric asymmetry in perception, the Double Filtering by Frequency (DFF) theory (Ivry & Robertson, 1998). Central to the DFF theory is the claim that the two brain hemispheres are differentially tuned to the range of spatial frequencies relevant to the task at hand: the left hemisphere is preferentially tuned to high spatial frequencies, and the right hemisphere to low spatial frequencies. Hsiao et al. (2008) showed that this model is able to account for the left side bias effect in face perception, suggesting that the left side bias effect may be due to the importance of low spatial frequencies information in face recognition (e.g., Dailey & Cottrell, 1999), which leads to right hemisphere lateralization in face processing.

Following Hsiao et al. (2008), here we use the intermediate convergence model to examine the left side bias (right hemisphere lateralization) effect in face perception. Building upon previous computational modeling of the holistic processing effect using the same or a similar model (Cheung & Hsiao, 2011; Cottrell, Branson, & Calder, 2002; Richler, Mach, Gauthier, & Palmeri, 2007), we also measure the holistic processing effect using the complete composite task (Gauthier & Bukach, 2007) in the same model and examine the correlations between holistic processing and left side bias. We hypothesize that when a recognition task depends purely on featural information (similar to Chinese character recognition), holistic processing and left side bias may be negatively correlated. In contrast, when it depends purely on configural information, holistic processing and left side bias may be positively correlated. We then examine the relationship between holistic processing and left side bias in the recognition of real faces, which depends on both featural and configural information, through both computational modeling and human subject experiments. To the best of our knowledge, we are the first to report a correlation analysis between right hemisphere lateralization as measured by the chimeric face judgment task and holistic processing as measured in the complete composite task on face stimuli for both human data and modeling data. We introduce our model, simulations, and experimental protocols below.

1. **Methods**

**2.1 Computational modeling**

**2.1.1 Architecture of the intermediate convergence model**

The model (Figure 1a) is an instance of the intermediate convergence model of face recognition (Hsiao et al., 2008). This model uses Gabor responses over the input images to simulate neural responses of cells in early visual areas such as V1 (Daugman, 1985), and Principal Component Analysis (PCA) to simulate information extraction processes through dimensionality reduction beyond the early visual areas. This PCA representation is then fed as the input to a two-layer neural network performing classification. In addition, the model implements a theory of hemispheric asymmetry in perception, the Double Filtering by Frequency theory (DFF) (Ivry & Robertson, 1997). The theory posits that visual information coming into the brain goes through two frequency-filtering stages. The first stage involves attentional selection of a task-relevant frequency range. At the second stage, the left hemisphere amplifies high spatial frequencies information, while the right hemisphere amplifies low spatial frequencies information. For the second stage, we implemented two conditions. In the DFF condition, the differential frequency bias in the two hemispheres is implemented by using two sigmoid functions assigning different weights to the Gabor responses in the two hemispheres. In the baseline condition, we set all weights to the Gabor responses to 0.5 so that there is no differential frequency bias between the two hemispheres (see Figure 1c).

**2.1.2 Configural versus featural recognition tasks**

In a configural recognition task, all faces have the same eyes, nose, and mouth, but their configurations differ. In contrast, in a featural recognition task, all faces have the same configuration but the features differ in their aspects.

In order to investigate the relationship between holistic processing and left side bias/right hemisphere lateralization when the recognition tasks depend on either configural or featural information, we created both configural and featural face datasets in a controlled manner comparably to Mondloch, Le Grand, and Maurer (2002). Face images of photorealistic human characters were created with the MakeHuman software (http://www.makehuman.org). We customized an Asian face model (see face input in Figure 1a) to produce all the faces. While keeping all facial features (i.e., eyes, nose, and mouth) identical, we changed the size of the spacing between the eyes and moved up or down the eyes and the mouth to create the 27 faces of the two configural sets (Figure 2a and 2b). Figure 2a and 2b respectively show the baseline configural set and the increased spacing dataset. Namely, faces in Figure 2b were made of bigger spacing between features than those in Figure 2a. Having two datasets allowed us to increase the variability of the stimuli in the examination of the relationship between holistic processing and left side bias/right hemisphere lateralization. Similarly, by changing the aspects of the mouth, the nose, and the eyes without changing the locations of these features, we created the 27 faces of the featural sets (Figure 2c and 2d). Figure 2c shows the baseline featural set. Faces in Figure 2d were obtained through having bigger magnitudes in the changes of the aspects of the features.

For each dataset in Figure 2, we created 10 training datasets by randomly sampling without replacement 20 faces out of the total of 27 faces. The 10 corresponding testing datasets were derived by rendering each image slightly darker by multiplying a scaling factor of 0.9. We used these datasets to examine how different recognition task requirements (configural vs. featural) modulate the relationship between the HP and left side bias/right hemisphere lateralization effects. In both tasks, the model in Figure 1a was trained to recognize the stimuli in the corresponding dataset.

**2.1.3 Recognition tasks with both featural and configural changes**

We previously created artificial faces to manipulate the featural and configural dimensions independently. To complement these extreme cases, we also ran our model with real faces from the FERET database (Phillips et al., 1998), a common database used in computational face recognition. Real faces embed both configural and featural changes. Hence, the model learned to use both configural and featural information to perform the recognition task. From the FERET database, we selected a set of East-Asian faces (see an example in Figure 1b) and a set of faces from four different ethnicities to run two more independent simulations. For each ethnicity (East-Asian, Caucasian, African American, and Indian), we removed faces with glasses, closed eyes, and facial hair. The FERET database is not ethnicity-balanced and comprises more Caucasian faces than other ethnicities. We selected 100 East-Asian individuals as a basis for the East-Asian dataset. For the multi-ethnicity dataset, in addition to the 100 East-Asian individuals, we selected 80 African American faces, 527 Caucasian faces, and 42 Indian faces. For each individual, we selected two face photos with different facial expressions. One photo served as the training face, and the other as the testing face. Benefiting from a larger sampling space than the artificial face datasets, the sample size was doubled from 20 to 40 faces. Hence, from the East-Asian dataset, we created 20 training datasets by randomly sampling without replacement 40 faces out of the total of 100 faces, and 20 corresponding testing datasets with the same faces as the training datasets but with a different expression. From the original multi-ethnicity dataset, we created 20 new training datasets by randomly sampling without replacement 10 faces from each of the four ethnicities and the corresponding testing datasets. We used these real face datasets to examine how another different recognition task requirement (configural plus featural) modulates the relationship between the holistic processing and left side bias/right hemisphere lateralization effects in comparison with either pure featural or pure configural task requirements. The model in Figure 1b was trained to recognize the stimuli, separately for the East-Asian and multi-ethnicity datasets.

**2.1.4 Modeling of the composite task and measure of holistic processing**

In human studies, holistic processing is usually assessed through the composite paradigm. We implemented the *complete* variant of the composite paradigm because of its robustness (Gauthier & Bukach, 2007). In this paradigm, two stimuli are presented briefly either sequentially or simultaneously. Participants attend to either the top or bottom halves of the stimuli and judge whether they are the same or different (see Figure 3). In congruent trials, the attended and irrelevant halves lead to the same response, whereas in incongruent trials, they lead to different responses. Holistic processing is indicated by interference from the irrelevant halves in matching the attended halves; it can be assessed by the performance difference between the congruent and the incongruent trials.

In face processing, holistic processing has been accounted for by computational models (Cottrell et al.; Richler et al., 2007). To assess holistic processing in our model, we applied the method used by Hsiao and Cheung (2011b), which was inspired by Richler et al. (2007). Namely, after training the model we attenuated the Gabor responses of either the top or bottom half of the images in the test set by multiplying a factor of 0.125 to simulate directing the models' attention to the bottom or top half of the images respectively. We created 4 types of stimulus pairs corresponding to the 4 conditions in Figure 3 (see an example in Figure 4a). For each simulation, a different set of twenty pairs of images in each condition was randomly drawn to form the materials (80 pairs in total). We calculated the correlation of the hidden layer representations in each pair as the similarity measure between them. A threshold was set to be the midpoint between the mean correlation of the “same” stimulus pairs and that of the “different” stimulus pairs. We assumed that the model responded “same” when the correlation of a pair was higher than the threshold, and responded “different” when the correlation was lower than the threshold. The holistic processing effect was indicated by the discrimination performance difference between the congruent and incongruent trials measured by d' (Stanislaw & Todorov, 1999).

**2.1.5 Measuring left side bias/hemispheric lateralization effects**

The model was tested with left or right lateralized inputs created by zeroing one half of the PCA representation of face inputs. Hence, for identity recognition of these lateralized inputs, only the representation from one of the visual hemifields was available to the model (see Figure 4b). Behaviorally, the left side bias is characterized by left chimeric faces being perceived more similar to original faces than the right chimeric images. Hence, recognizing the identity of one face from the left half face should be easier than with the right half face. The model accounts for the left side bias when it generalizes better for left lateralized inputs than for right lateralized inputs. Operationally, the left side (right hemisphere) bias was assessed by the accuracy difference between recognizing a left-lateralized stimulus (carrying right hemisphere/low spatial frequencies information) as the original stimulus and recognizing a right-lateralized stimulus (carrying left hemisphere/high spatial frequencies information) as the original one. We defined left side bias/right hemisphere lateralization (right hemisphere/low spatial frequencies preference; Hsiao et al., 2008) as the left side bias measured in the biased condition (i.e., the right hemisphere and left hemisphere respectively were biased towards low spatial frequencies and high spatial frequencies) minus that measured in the baseline condition (i.e., the right hemisphere and left hemisphere processed identical spatial frequencies and thus there was no frequency bias in either hemisphere) to ascertain the size of the lateralization effect due to the differential frequency bias between the two hemispheres while controlling for effects from other variables.

**2.1.6 Modeling details**

In the present implementation, the face input (100 x 134 pixels for artificial faces and 70 x 84 pixels for FERET faces) was filtered with a grid (6 x 6) of overlapping 2D Gabor filters in quadrature pairs at five scales and eight orientations. The five scales corresponded to 2 to 32 cycles per image. Given the widths of face images (100 and 70 pixels), the five scales correspond to the range of task-relevant frequencies. With the sixth scale, we have 2^6 = 64 cycles per image, corresponding to spatial frequencies respectively of 64/100 = 0.64 cycles per pixel and 64/70 = 0.91 cycle per pixel, which exceeds the Nyquist frequency of 0.5 cycles per pixel. The resulting 1440-dimensional Gabor representation of the face was split into left and right halves. The perceptual representation of each half was compressed using PCA into a 15-element representation for artificial faces and 38-element representation for FERET faces (see Figure 1a and Figure 1b). The number of selected principal components for both artificial and real faces account for the same amount of total variance (99%). After PCA, each principal component was z-scored to equalize the contribution of each component in the model. The PCA representation was then fed to a two-layer neural network with one hidden layer of 20 nodes for artificial faces and 45 nodes for FERET faces. The number of nodes was determined empirically to allow efficient training of the network. The output layer of the neural network had one output node for each of the 20 artificial faces or 40 FERET faces. The neural network was trained with gradient descent with adaptive learning rate back-propagation from the MATLAB® Neural Network Toolbox (Version 7.0.3). The network was trained initially on artificial faces for both 400 epochs and 150 epochs. 400 epochs was enough for all the models to reach almost perfect recognition rates on both training and testing sets (accuracy ~ 99%). However, we found a strong ceiling effect for the configural task on the baseline datasets: recognition rates for both left-lateralized stimuli and right-lateralized stimuli were very high (~ 98%) and so close that the size of right hemisphere lateralization effect was on average less than 1%. Training with only 150 epochs put an end to the ceiling effects while maintaining high recognition rates (accuracy ~ 90% for both training and testing sets). We thereafter reported results for simulations with a training of 150 epochs for artificial faces. For FERET faces, we set training duration to 200 epochs. This yielded acceptable recognition rates (82.6% for the East-Asian face set and 81.3% for the multi-ethnicity face set) and was still close to the number of training epochs for artificial faces.

For each of the featural and configural tasks, and for each of the East-Asian and multi-ethnicity real face recognition tasks, we trained the model with 20 different datasets. Hence, we collected for each task 20 data points of left side bias/right hemisphere lateralization to plot against 20 data points of holistic Δd’ (Congruent d’ – Incongruent d’). We reported whether there was significant left side bias/right hemisphere lateralization and holistic Δd’ in the two tasks. We then tested for any correlation between left side bias/right hemisphere lateralization and holistic processing. For a given dataset, we instanced the simulation of the model 40 times to simulate 40 participants.

* 1. **Behavioral experiments**

We ran two behavioral tasks: the complete composite task (section 2.2.1) to measure holistic processing, and the face chimeric face judgment task (section 2.2.2) to measure the left side bias.

**2.2.1 Holistic processing measured in the composite paradigm**

Similar to the computer simulations, we adopted the complete composite paradigm to measure holistic processing (Gauthier & Bukach, 2007). In the computer simulations, we used only aligned faces. In the behavioral experiment, we used both aligned and misaligned faces, and observed how misalignment reduced holistic processing. We used a simultaneous version of the complete composite paradigm and not the sequential version: the two composite faces are presented simultaneously on the screen.

**2.2.1.1 Materials**

The materials consisted of East-Asian male faces in grayscale from Lebrecht, Pierce, Tarr, & Tanaka (2009). We made 128 composite aligned faces and 128 composite misaligned faces (Figure 5a). Participants’ viewing distance was 50 cm, and the image for aligned faces and misaligned faces subtended respectively visual angles of 4.2° x 4.2° and 6.3° x 4.2 on the screen. The structure of the composite faces follows the four conditions of the complete composite paradigm (Figure 3).

**2.2.1.2 Participants**

We recruited 40 East-Asian participants (20 Females). They were students or staff members at the University of Hong Kong (Mean age: 24, SD: 9.6); all were right-handed according to the Edinburgh handedness inventory (Oldfield, 1971). They all had normal or corrected to normal vision. They received an honorarium or course credit for their participation.

**2.2.1.3 Design**

Congruency (congruent vs. incongruent) and alignment (aligned vs. misaligned) were the within-subject variables. The dependent variable was the discrimination performance measured by d'.

**2.2.1.4 Procedure**

Following Hsiao and Cottrell (2009), in each trial (Figure 5b), after a 1500 ms fixation cross, participants viewed for 500 ms two faces arranged vertically above and below the fixation cross at a distance of 1.1 cm, which corresponded to a visual angle of 1.3°. After 500 ms, a blank screen was presented until participants gave a response. They had to attend to the top halves of the two faces and reported whether they were identical or not by pressing two buttons on a response box (Psychology Software Tools***®***) simultaneously with either their two index or two middle fingers. After pressing the buttons, another blank screen was shown for 1000 ms, and then the next trial started. Participants ran two blocks: one block with aligned faces and the other with misaligned faces. The order of the two blocks was counterbalanced across participants. Each block was made of 64 trials, with each condition of the complete composite paradigm presented for 16 times.

**2.2.2 Left side bias measured by the chimeric face judgment task**

For a measure of left side bias equivalent to the right hemisphere lateralization of the computational simulations, we adopted a simple chimeric face judgment task with chimeric faces. A left chimeric face is a perfectly symmetric face made from two left half-faces of an original face (similarly for a right chimeric face; see Figure 6a). The left chimeric face is usually judged more similar to the original face than the right chimeric face. This left side bias effect is argued to be due to the right hemisphere advantage in face perception.

**2.2.2.1 Materials**

We used 60 grayscale East-Asian faces (Lebrecht et al., 2009) with an oval shape which removed hair and face shape information. For each face, we built the left and right chimeric faces (Figure 6a). Participants’ viewing distance was 50 cm, and the images subtended visual angles of 6.2° x 6.7° on the screen. The experiment consisted of 60 trials; mirror images of the original faces were used in half of the trials, counterbalanced across participants.

**2.2.2.2 Participants**

The same 40 participants who did the holistic processing task also performed the present chimeric face judgment task.

**2.2.2.3 Design**

The dependent variable was the left chimeric face preference measured as the percentage of selected left chimeric images over the 60 trials.

**2.2.2.4 Procedure**

Following Hsiao and Cottrell (2009; see also Brady et al., 2005), in each trial (Figure 6b), after a 600 ms central fixation cross, participants were presented with three faces: a probe on one side of the fixation cross, and the left and right chimeric images arranged vertically 2 cm (2.4***°***) above and below the fixation cross. Left chimeric images appeared on the top in half of the trials. The probe was presented on the left of the fixation cross in half of the trials. Participants were prompted by an arrow at the center of the screen to gaze first at the probe on the side. Then, they observed the two chimeric targets and judged which one looked more similar to the probe. Participants pressed on the keyboard using the middle fingers the keys E and I to select the top chimeric image, and with the index fingers the keys F and J to select the bottom chimeric image. After 7000 ms, the three images were replaced by a blank screen for 1000 ms, and then the next trial began.

1. **Results**

**3.1 Modeling results**

**3.1.1 Configural and featural face recognition tasks**

When the face recognition task relied purely on configural information, there was a significant left side bias/right hemisphere lateralization effect, *t*(19) = 6.62, *p* < .001, and a significant holistic processing effect, *t*(19) = 8.96, *p* < .001. The main result was a strong significant positive correlation between holistic processing and right hemisphere lateralization, *r* = 0.73, p < .001 (Figure 7a). In this case, holistic processing and right hemisphere lateralization went together.

When the face recognition task relied purely on featural information, similar to the configural face recognition task, there was a significant left side bias/right hemisphere lateralization effect, *t*(19) = 18.45, *p* < .001, and a significant holistic processing effect, *t*(19) = 24.6, *p* < .001. Nevertheless, in contrast to the configural face recognition task, there was a significant negative correlation between holistic processing and right hemisphere lateralization, *r* = -0.496, *p* < .05 (Figure 7b). In this case, holistic processing and right hemisphere lateralization did not go together.

Thus, when we manipulated either the featural or configural dimension of faces given to our model performing both the left side bias and the complete composite tasks, we found opposite directions of correlation between right hemisphere lateralization and holistic processing depending on the manipulated dimension. This result suggests task requirements modulate the nature of the association between right hemisphere lateralization and holistic processing in the complete composite task.

**3.1.2 Simulation results with East-Asian faces from FERET**

When a face recognition task was performed on real East-Asian faces embedding both changes in featural and configural information, there was a significant left side bias/right hemisphere lateralization effect, *t*(19) = 54.53, *p* < .001, and a significant holistic processing effect, *t*(19) = 147.2, *p* < .001. Importantly, we found no correlation between holistic processing and right hemisphere lateralization, *r* = -0.05, *p* = .83 (Figure 8a). This was in line with our hypothesis that task requirements modulate the nature of the correlation. The East-Asian faces are more ecologically valid than the artificial faces: their inter-face variabilities along the featural and configural dimensions are natural. Because the East-Asian faces embed both configural and featural changes, the model can rely upon both dimensions to build representations.

**3.1.3 Simulation results with the multi-ethnicity face set from FERET**

When the face recognition task was performed on real faces of different ethnicities embedding both changes in featural and configural information, there was a significant left side bias/right hemisphere lateralization effect, *t*(19) = 40.17, *p* < .001, and a significant holistic processing effect, *t*(19) = 174.54, *p* < .001. In addition, here we replicated the previous finding of no correlation between holistic processing and left side bias/right hemisphere lateralization with East-Asian faces, *r* = 0.026, *p* = .91 (Figure 8b). The multi-ethnicity face set may have more apparent featural and configural variability than the East-Asian face set, as there may be more different types of facial features and a broader range of distances between facial features. Our simulations with the two kinds of real faces both resulted in the absence of a significant correlation between holistic processing and right hemisphere lateralization.

**3.2 Behavioral results with East-Asian faces and participants**

In the complete composite task, the results showed a significant main effect of congruency, F(1,39) = 49.54, p < .001, and a significant interaction between congruency and alignment, F(1,39) = 38.51, p < .001. The interaction was characterized by misalignment reducing the size of the congruency (holistic processing) effect[[1]](#footnote-0) (Figure 9a). There was a significant congruency effect in aligned trials, *t*(39) = 11.11, *p* < .001, but not in misaligned trials, *t*(39) = 1.52, *p* = .22. For the chimeric face judgment task, participants showed the typical left side bias effect: they significantly selected more often the left chimeric face than the right one (59%), *t*(78) = 4.56, p < .001.

To compare with the modeling results, we examined the correlation between the congruency (holistic processing) effect in the aligned trials and the left side bias effect from the behavioral data. We found no correlation between the preference for selecting left chimeric faces (left side bias/right hemisphere lateralization) and holistic processing in the complete composite task, *r* = 0.118, *p* = .469 (Figure 9b). This result is in agreement with the computational simulations on East-Asian and multi-ethnicity face sets. As far as we know, our study is the first report of a computational examination and a behavioral replication of a correlation analysis between holistic processing in the complete composite task and left side bias/right hemisphere lateralization as measured in the chimeric face judgment task.

1. **Discussion**

Here we investigated the relationship between holistic processing as measured in the complete composite task and left side bias (left side bias)/right hemisphere lateralization as measured in the chimeric face judgment task in face recognition. We ran computational simulations on four datasets: artificial faces varying only in second-order configuration (i.e., distances among features), artificial faces varying only in features, and real faces (East-Asian and multi-ethnicity sets). We also behaviorally tested the results of our simulations on real faces with human participants. Our computational model implements a theory of hemispheric asymmetry in perception, the Double Filtering by Frequency (DFF) theory, which posits a low spatial frequency bias in the right hemisphere and a high spatial frequency bias in the left hemispheres. This model and some variants have been shown to be able to account for the left side bias/right hemisphere lateralization (Hsiao et al., 2008) and holistic processing effects in face recognition (Cottrell et al., 2002; Richler et al., 2007).

In all our simulations, the model demonstrated a left side bias/right hemisphere lateralization effect, and a holistic processing effect. Our results showed that, in the simulations of the configural face recognition task, holistic processing and left side bias/right hemisphere lateralization correlated positively. However, in the simulations of the featural face recognition task, holistic processing and left side bias/right hemisphere lateralization correlated negatively. These results are in line with a previous modeling work (Hsiao & Cheung, 2011a) using letters arranged in a triangular configuration instead of faces as stimuli. In their featural task, the model learned to recognize triangles with a fixed geometrical configuration but with different letters as vertices. Simulations showed a negative correlation between left side bias/right hemisphere lateralization and holistic processing. In their configural task, the model learned to recognize triangles with different spatial configurations but with the same letters as vertices. They found a weak positive correlation for the configural task. These results were consistent with our current findings, suggesting that holistic processing (as measured in the complete composite task) and left side bias/right hemisphere lateralization effects in visual recognition do not always go together; the relationship between them can be modulated by the reliance on configural or featural information in the recognition task.

In our configural task, faces differ in the top halves in inter-eyes distance and vertical position of the eyes. In the bottom halves, only the vertical position of the mouth changes. In this configural task, according to the positive correlation, when the model becomes more right hemisphere lateralized, the model also demonstrates more holistic processing. An increase in holistic processing simulates an increasing failure to attend selectively to the top halves: the model “gets” more and more interference from the irrelevant bottom halves while matching the two tops. right hemisphere lateralization in our model reflects a primary use of low spatial frequencies information while learning the faces. Hence, it appears that an increased reliance on the low spatial frequencies information of the configural faces goes with their internal representations being more holistic for the complete composite task: the information in the irrelevant bottoms contributes more and more to the matching task. In contrast, in the featural task, faces differ in their top halves by the appearance of the eyes and the width of the nose. In their bottom halves, they differ in the appearance of the mouth. With featural faces, according to the negative correlation, the model shows less holistic processing with more right hemisphere lateralization. Hence, for featural faces, an increase reliance on the low spatial frequencies information of the faces goes with their internal representations being less holistic in the complete composite task: the information in the irrelevant bottoms contributes and interferes less and less to the matching task. These results suggest that low spatial frequencies information may enhance integration of configural information but impair integration of featural information. Future work will verify these modeling predictions with human behavioral studies.

In our modeling, an increase in right hemisphere lateralization is associated with respectively an increase holistic processing in the complete composite task in configural face recognition tasks and a decrease in holistic processing in featural face recognition tasks. This suggests that the task requirements, either featural or configural, drive the direction of the correlation between right hemisphere lateralization and holistic processing in the complete composite task. In addition, we found no correlation between right hemisphere lateralization and holistic processing in our simulations when using two distinct datasets of real faces. Our East-Asian and multi-ethnicity face sets are characterized by natural variations in featural and configural dimensions between faces. They may impose simultaneously configural and featural task requirements on the model while it learns the faces. With the same model, the findings of no correlation or of different directions of correlation depending on the nature of the task requirements constitute converging evidence to suggest that right hemisphere lateralization and holistic processing in the complete composite task are decoupled processes. Besides, the absence of correlation between right hemisphere lateralization and holistic processing for real faces in our model suggests that the amount of holistic processing in the complete composite task for real faces is not modulated differentially by the high spatial frequencies or the low spatial frequencies of the faces. This is reminiscent of Cheung, Richler, Palmeri, and Gauthier’s (2008) finding of full-spectrum, high spatial frequencies filtered, and low spatial frequencies filtered faces being processed equally holistically in the complete composite task. More specifically, Cheung et al. (2008) reported no significant difference in the size of the congruency effect between aligned full-spectrum, high spatial frequencies filtered, and low spatial frequencies filtered faces; in addition, misalignment reduced the congruency effect across all spatial frequency conditions.

Our results of the behavioral experiments with human participants converge with the results of the simulations: we found no correlation between left side bias/right hemisphere lateralization and holistic processing with own-race faces for East-Asian participants. To the best of our knowledge, this is the first report of a correlation analysis of behavioral data for the chimeric face judgment task and the complete composite task with face stimuli. In fMRI studies, an increase in holistic processing has been previously linked to right hemisphere lateralization for a novel artificial object (Greebles; see Gauthier & Tarr, 2002) and for faces (Harris & Aguirre, 2008; Schiltz et al., 2010). It is possible that the requirements of the Greeble or face recognition tasks in these studies drove the direction of the correlation positively as in our configural face recognition task. Similarly, the finding of reduced holistic processing and increased left side bias/right hemisphere lateralization in expert Chinese character recognition (Hsiao & Cottrell, 2009; Tso, Au & Hsiao, in press) matches well with our finding of a negative correlation between holistic processing and left side bias/right hemisphere lateralization when the recognition task relies mainly on featural information, since expert Chinese character processing essentially involves featural processing and is invariant to configural changes (Ge et al., 2006; Hsiao et al., 2009; McCleerly et al., 2008).

Results from an fMRI study by Harris and Aguirre (2010) may provide important insights on possible neural mechanisms to account for the apparent separateness of holistic processing and right hemisphere lateralization. Crucially, Harris and Aguirre found that depending on the face recognition task at hand, the right hemisphere can engage either in holistic processing or analytical processing. They employed an fMRI paradigm devised by Drucker, Kerr and Aguirre (2009) to distinguish between conjoint and independent neural tuning of stimulus features. For two features, a conjoint (i.e. holistic) neural tuning is indicative of the two features being represented integrally by the same population of neurons; an independent (i.e. analytical) neural tuning implies that different populations of neurons respond to the two features separately. Harris and Aguirre (2010) used this methodology to investigate whether there is “holistic tuning” or “analytical tuning” to the eyes and mouth of a face as two different features in the left and right fusiform face areas (FFA). Harris and Aguirre observed that processing in the right FFA (rFFA) is surprisingly flexible. Depending on whether faces are aligned or misaligned or whether the eyes and mouth in faces are morphed equally or differentially, the rFFA can be either “holistically tuned” or “analytically tuned” whereas the left FFA (lFFA) remains “analytically tuned”. Interestingly, in their experiments when both lFFA and rFFA are analytically tuned to eyes and mouth, the activation is bigger for the rFFA, indicating a right hemisphere lateralization of analytical processing!

Interestingly, convincing evidence of a decoupling of holistic processing and right hemisphere lateralization/left side bias for Chinese character processing also exists. Tso et al. (in press) studied how motor experience in writing Chinese characters modulates holistic processing and left side bias/right hemisphere lateralization of Chinese character stimuli in Chinese readers. They found that compared with novices, who do not read or write Chinese characters, holistic processing was reduced in Chinese readers who were also fluent writers (Writers), whereas in Chinese readers who had limited writing experience (Limited-writers), holistic processing was increased. In contrast, right hemisphere lateralization as measured in the chimeric face judgment task was not influenced by Chinese writing experience: both Writers and Limited-writers showed increased left side bias as compared with novices. Tso et al. (in press) proposed that holistic processing and left side bias/right hemisphere lateralization of Chinese characters may be processes of different nature: holistic processing may rely more on one’s ability to engage online global/local attentional processing, which can be modulated by sensorimotor experience, whereas the left side bias effect may depend more on the lateralization of relevant perceptual representations. A similar modulation effect of sensorimotor experience on holistic processing has also been reported in the face recognition literature: Zhou, Cheng, Zhang, and Wong (2012) found reduced holistic processing for faces with increasing face drawing experience. In a computational modeling study, Galmar and Hsiao (2013) further showed that this reduced holistic processing effect may be due to a better ability to engage local attention developed through drawing practice. It remains unclear how sensorimotor experience modulates the left side bias effect in face recognition. Future work will examine factors that may modulate holistic processing and left side bias/right hemisphere lateralization effects similarly or differently in the recognition of various stimuli to further understand the differences in the underlying mechanism between these two effects.

Note that in the current study, we focused on measuring holistic processing within an attentional framework (i.e., the holistic processing effect reflects failure of selective attention) using the complete composite task. Hence, our results concerning holistic processing are limited to the specific complete composite task. As mentioned in the introduction, other frameworks for the study of holistic processing exist, such as the holistic representational framework based on the part-whole task and the interactive framework based on Garner’s speeded classification task (see Richler, Palmeri, & Gauthier, 2012, for a review). Future studies will address the generalization of our results to these other holistic processing experimental paradigms.

In conclusion, here we investigated the relationship between holistic processing as measured in the complete composite task and right hemisphere lateralization as measured in the chimeric face judgment task when the task requirement was varied along featural and configural dimensions. Results were first derived from computational simulations and then replicated with human participants. In our simulations, when the recognition task relied only on configural information, holistic processing and left side bias/right hemisphere lateralization correlated positively; when the task depended solely on featural information, they correlated negatively. When the task relied on both configural and featural information, as in the recognition of real faces, no correlation was observed in both the computational simulations and human behavioral data. Hence, our study demonstrated how the nature of the recognition task at hand may modulate the association between right hemisphere lateralization and holistic processing. In contrast to the traditional view imparting holistic processing to the right hemisphere and analytical processing to the left hemisphere, here we show that holistic processing as assessed in the composite paradigm and right hemisphere lateralization as demonstrated in the chimeric face judgment task are separate processes that do not always go together.

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Acknowledgments

This research was supported by the Research Grant Council of Hong Kong (project code: HKU 745210H and HKU 758412H to J. H. Hsiao).

Figure 1. An intermediate convergence model of face recognition that implements a theory of hemispheric asymmetry in perception, the Double Filtering by Frequency (DFF) theory. (a) Face inputs are artificial stimuli. (b) Face inputs are real faces. Hypothesized localization of representation in the brain at each level of processing is indicated in (a). (c) Sigmoidal weighting functions: unbiased (a = 0) and biased conditions (a = 1.5).

Figure 2. (a-b) Artificial faces used in the configural recognition task. In (a), basic spacing between features; in (b), increasing spacing between features. (c-d) Artificial faces used in the featural recognition task. In (c) basic changes of features; in (d), increasing changes of features.

Figure 3. Design of the composite paradigm. Stimuli were pairs of composite (top/bottom) face images. The red rectangle signaled that top halves had to be matched while the two bottom halves had to be ignored. In congruent trials, the irrelevant bottom halves lead to the same response as the top halves. In incongruent trials, the irrelevant bottom halves lead to a response conflicting with the response from the top halves.

Figure 4. (a) Example of a stimulus pair for the simulated holistic (composite) task. It simulates selective attention to the top halves of the faces. (b) Example of a left lateralized face for the simulated left-side bias task.

Figure 5. (a) Aligned and misaligned faces for the behavioral holistic processing task. (b) Flowchart of the behavioral holistic processing task.

Figure 6. (a) Original face, left chimeric face, and right chimeric face (from left to right). (b) Flowchart of the behavioral left-side bias task.

Figure 7. Simulations results. (a) Configural face recognition task: Correlation graph between holistic processing and right hemisphere lateralization. (b) Featural face recognition task: Correlation graph between holistic processing and right hemisphere lateralization.

Figure 8. Simulation results. (a) East-Asian face recognition task: Correlation graph between holistic processing and right hemisphere lateralization. (b) Multi-ethnicity face recognition task: Correlation graph between holistic processing and right hemisphere lateralization.

Figure 9. Behavioral results. (a) holistic processing experiment: d’ as a function of congruency and alignment.

(b) Correlation graph between holistic processing and left side bias/right hemisphere lateralization, here represented by the percentage of selected left chimeric images.

1. To compare behavioral data and simulations concerning the effect of misalignment, we ran additional simulations with misaligned faces. Misalignment also reduced the size of the congruency effect for the model. [↑](#footnote-ref-0)