1 There's a Time and a Face: The Time Course of Composite Face Processing

2 Carmen Lynch, Xue Jun Cheng, Daniel R. Little

3 The University of Melbourne

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7 Correspondence concerning this article should be addressed to Daniel R. Little, School of
8 Psychological Sciences, University of Melbourne, Melbourne, Victoria 3010, Australia.
9 E-mail: daniel.little@unimelb.edu.au. Preregistration available here:
10 <https://osf.io/hjm3z>. Experimental and modelling code is available here:
11 <https://github.com/knownlabUnimelb/FACESTOP SIGNAL>.

Abstract

Faces are considered a special class of holistically-processed object. The composite face task is a widely-used tool to infer holistic processing. In this task, recognition of one half of a composite face is shown to be hampered by interference from the other half of the face. Although this effect has been documented numerous times, when used in different paradigms, composite faces do not always exhibit effects consistent with holistic processing. The present study explored the cause of these discrepant findings by combining a composite face task with a signal-to-respond paradigm. The amount of time to make a face recognition decision was manipulated by introducing a response signal, and the resulting changes in accuracy were mapped over the time course of processing, which was then used to fit a speed-accuracy trade-off model. We found that holistic processing emerges late in the time course after approximately 400 ms processing time for easy to discriminate faces and after approximately 1000 ms for difficult to discriminate faces.

Keywords: Face recognition, holistic processing, composite faces, response signal

Public Significance Statement: This study shows that interference from the bottom half of the face emerges slowly over time when making decisions about whether the top half of a face is the same or different than one just seen. Further, interference was stronger when the top half was very different from the just seen face.

Some face processing tasks, such as the composite face task, consistently provide evidence that faces are processed holistically (see the meta-analysis in Richler & Gauthier, 2014). This naturally leads to a hypothesis that other tasks, which also measure how features are processed, using composite faces should demonstrate results consistent with holism. This hypothesis is often rejected when composite faces fail to evoke holistic processing in other tasks (Amishav & Kimchi, 2010; Cheng, McCarthy, Wang, Palmeri, & Little, 2018; Fitousi, 2015; Richler, Palmeri, & Gauthier, 2015). The purpose of this paper is to test two explanations for these task differences: difficulty and time.

The first explanation is that if discriminations between faces (e.g., in a same-different judgment) are too difficult, then attention might need to be selectively deployed to specific features, breaking any Gestalt or configural processing (Blaha, 2017; Perry, Blaha, & Townsend, 2008). Tasks which fail to show holistic processing may be using discriminations which do not allow for attention to the entire configuration or face template. For instance, composite faces often fail to show interference in categorization paradigms, such as the Garner tasks (Amishav & Kimchi, 2010; Fitousi, 2015; Richler et al., 2015) and related tasks (Cheng et al., 2018).

The second explanation is that holistic processing might take time to emerge. Processing might start as analytic or independent but through a gradual widening of attention, might become holistic (Fitousi, 2019). On the other hand, processing might start out as holistic and, over time, become more independent (cf., White, Ratcliff, & Starns, 2011). There is ample evidence that attention changes dynamically over the course of a trial (see e.g., Sewell & Smith, 2012; Smith & Ratcliff, 2009). Tasks which fail to find holistic processing may not be assessing the same temporal location of processing as is assessed by the composite face task.

A third, alternative explanation is that different tasks operationalise holism in different ways (Richler, Palmeri, & Gauthier, 2012). Although we do not test this

explanation in this paper, we feel that it is worth including to provide context for our investigation. As explained below, in a composite face task, composite faces, made up of top and bottom halves from different faces, are presented one at a time with a brief delay in between, and participants must respond as to whether the target half of the face, for example, the top half, is the same in both presentations while ignoring the distractor half (e.g., the bottom). Holism is inferred as the interference that occurs when a top half is paired with a bottom half of a different face and the halves are aligned along the vertical meridian. When the face halves are misaligned, there is less interference. Thus, the composite face task operationalises holism as a congruency $\times$ alignment interaction, with congruency referencing whether the top and bottom are both the same, both different, or whether only one is the same and the other is different. This has proven to be a reliable hallmark of holistic processing with faces but not other objects (Meinhardt, Meinhardt-Injac, & Persike, 2014; Richler & Gauthier, 2013, 2014).

One alternative task, the Garner paradigm (Garner, 1974), operationalises holism as integrality; that is, a non-invariance in the mean response time across several stimulus conditions designed to invoke facilitation and interference. Composite faces do not demonstrate integrality in the Garner task (Fitousi, 2015; Richler et al., 2015). Hence, different tasks might not be measuring the same latent construct.

Nevertheless, the question remains as to why, and some definitions of holism are theoretically stronger than others. For instance, measures of holistic processing based on the ordering of means across conditions are weaker than measures derived from strong inference methods (Platt, 1964; Smith & Little, 2018). In systems factorial technology (SFT, Little, Altieri, Fifić, & Yang, 2017; Townsend & Nozawa, 1995), a set of methods and theoretically-based analyses are used to characterise different aspects of information processing. As defined by SFT, coactive processing, in which the top and bottom face halves are assumed to be pooled into a single object representation, most closely aligns with the idea of holism (Fifić, Nosofsky, & Townsend, 2008; Wenger & Townsend, 2001).

Coactivity can be contrasted with the independent processing of the top and the bottom face halves, either in serial (i.e., sequentially) or in parallel (i.e., simultaneously). These forms of processing generate nonparametric predictions which are based on mathematical proofs and methods, allowing for qualitative contrasts of each theory. For instance, Cheng et al. (2018) used systems factorial technology (Little et al., 2017; Townsend & Nozawa, 1995) to examine the processing of composite faces in a categorization task and found that composite faces are processed independently, with the top and bottom halves often processed serially. As it seems important to pursue a theory of holism which generalises performance predictions across tasks, we pursue a reconciliation of the robust composite face task results with the independent processing found using SFT to analyse composite faces.¹ To understand why different tasks might not measure holistic processing in the same way, we focus on examining how difficulty and time affect the emergence of holism in the composite face task.

In this paper, we will use a composite face task combined with a signal-to-respond in which participants respond to a test face after one of six possible time lags. The response signal lags are varied from so short that performance should be close to chance levels (50 ms) to long enough that performance should reach asymptotic accuracy (1800 ms). The corresponding changes in accuracy are mapped by virtue of the speed-accuracy trade-off (SAT) function. The resulting picture of processing is complemented with the fitting of a shifted exponential function, otherwise known as the SAT model (McElree & Doshier, 1989, 1993; Ratcliff, 1978; Reed, 1973). The SAT model captures the asymptotic or peak level of detection accuracy (measured in d'), as well as the dynamics of processing (McElree & Doshier, 1993) comprising the onset and the rate of processing. These three features are compared between composite types that differ in discriminability between the aligned and

¹ Other tasks have also found independence using composite faces, which argues against holism. For example, Fitousi (2015) assessed the workload capacity of composite faces using a redundant target task. Fitousi observed a composite face effect, but only observed supercapacity for aligned composites in three out of eight participants. For misaligned composites and all other participants, capacity was instead limited, consistent with some forms of independent processing.

misaligned conditions, to decompose any differences in processing. Several recent papers have also investigated the time course of composite face processing. However, these investigations have relied on distributional measures (Fitousi, 2019) or have varied encoding time but not decision time (Richler, Mack, Gauthier, & Palmeri, 2009; Richler, Mack, Palmeri, & Gauthier, 2011), thus preventing direct comparison between tasks (e.g., the composite face task and SFT, Cheng et al., 2018).

Composite Face Task

The composite face task (Young, Hellawell, & Hay, 1987) relies on the phenomenon that when two face halves (e.g., the top and bottom) from two different individuals are aligned, there is an illusory percept of a unique face. Top and bottom halves of composite faces used in composite face tasks are often taken from separate individuals and presented in an unmodified form (see many of the studies cited in e.g., Richler & Gauthier, 2014) though the top and bottom halves of schematic or modified faces are also used (Chua, Richler, & Gauthier, 2014, 2015; Richler et al., 2015). Participants are much slower and less accurate at making recognition decisions about one half of the face due to interference from the other face half; this is termed the *composite face effect*. However, when the face halves are horizontally offset (i.e., misaligned), the illusion is broken and recognition performance for each half is greater than in the aligned condition. In this task, holistic processing is often defined as a “failure of selective attention”, where we have difficulty disengaging attention from the whole face due to our extensive experience in processing upright, aligned faces (Richler et al., 2012).

Partial vs. complete design. In the partial design (Hole, 1994; Rossion & Boremanse, 2008; Young et al., 1987), the target face half (e.g., top) can be either the same as or different from the respective part of the study face, but the distractor half (e.g., bottom) is always different (see the dotted panels in Figure 1). Holistic processing is inferred from improved recognition performance on the *same*-trials in the misaligned

condition compared to the aligned condition. However, in the aligned condition, performance is reduced because the changing bottom half interferes with recognising that the top half has not changed.

In the complete design (Gauthier & Bukach, 2007), by allowing the distractor half to be different between the study and test, two states of *congruency* are introduced: the tested target half can also be different from the study target half (i.e., *congruent*) or the tested target half can be the same as the studied target half (i.e., *incongruent*; see Figure 1). In a congruent composite, the distractor half can provide additional evidence in favour of a decision about the target half (i.e, both halves are the same or both halves are different), therefore improving decision accuracy and speed; whereas in an incongruent composite, the distractor half can provide conflicting evidence against a decision about the target half (i.e., one half is the same while the other is different), therefore hampering decision accuracy and speed. If the faces are processed holistically, then recognition performance should be improved on congruent trials compared to incongruent trials. Furthermore, if misaligning the face halves breaks holistic processing such that each half is processed as a distinct part, then congruency should have little to no effect. Consequently, a congruency $\times$ alignment interaction provides a standard for inferring holistic processing in the complete design (Richler & Gauthier, 2014). In addition, the complete design allows for the computation of a bias-free measure of decision accuracy via signal detection theory (Green & Swets, 1966; Macmillan & Creelman, 2005).

In a meta-analysis of the composite face task, Richler and Gauthier (2014) found a mean weighted effect size of $\eta_p^2 = .32$, 95% CI = [.26, .38] from 48 independent data sets that used the congruency $\times$ alignment interaction as an index. Moreover, the meta-analysis effect size for the complete design was more than double that of the partial design, $\eta_p^2 = .14$, 95% CI = [.07, .22]. Subsequent studies have likewise observed interactions of similar magnitude (Richler et al., 2015). Notably, Cheng et al. (2018) observed a similarly-sized interaction effect using the same type of face morph composite

Figure 1. Partial and complete design of the composite face task. The partial design (indicated by the dotted lines) only makes use of the trials in which there is a change to the distractor face half (here that is the bottom half). The complete design makes use of all variants of congruent and incongruent trials (all four panels of the figure).

stimuli that we employ in the present study (introduced below). Ultimately, it is quite clear that the congruency $\times$ alignment interaction is a reliable and robust index of holistic processing. A remaining question, and the target for this paper, is why composite faces do not always produce results consistent with holistic processing in other tasks.

Discrimination difficulty and holistic processing. Perry et al. (2008) used a set of face morphs to examine whether processing exhibited supercapacity processing - a hallmark of coactivity, which, as we have argued above, should be considered a theoretically strong operationalisation of holism since inference of supercapacity is based on nonparametric and qualitative contrasts allowing for strong inference (Platt, 1964; Smith & Little, 2018). Their faces included features morphed to be of low discriminability (constituting 66% morphing between features) or high discriminability (constituting 33% morphing), but neither set elicited supercapacity. In her theoretical review, Blaha (2017)

argued that faces requiring fine-grained discriminations may result in focused attention and prevent holistic processing.

The present study examines the effect of discriminability by varying the ease with which a change can be detected in each half of the composite. We use a similar face morphing technique to Cheng et al. (2018) to obtain face halves of low and high discriminability. A key question is whether the congruency $\times$ alignment interaction will appear at both levels of discriminability. It is possible that difficult discriminations, requiring attention to be directed to specific face parts, eliminate holistic processing (Blaha, 2017). On the other hand, discriminations which are too easy might be processed before any interference arises from the distractor face half. Hence, we focus on both discriminability and the time course of processing composite faces.

The Time Course of Composite Face Processing

Using a partial design, Hole (1994) found evidence for holistic processing only at a short (80 ms) presentation time but not at a long (2000 ms) presentation time. This suggests that holistic processing gives way to analytic processing over time, but Hole's study is limited by the use of simultaneous presentation of the comparison faces, which allows for participants to shift attention between faces and may enable a feature-matching strategy at the longer presentation time that is not possible at the shorter presentation time. To be clear, different processing strategies may have been used at the short and long processing times. More recent studies using a complete composite design have found congruency effects as soon as performance was above chance levels (at 50 ms; Richler, Mack, et al., 2009). This latter study manipulated the presentation time of the study face and test face in two separate experiments with eight different presentation times (ranging from 17 to 800 ms). This study, however, only examined a congruency effect. Congruency effects have also been seen in novices with non-face objects due to strategic reasons (Richler, Bukach, & Gauthier, 2009; Wong & Gauthier, 2010); consequently, we focus on

Figure 2. Composite types used in the present study. Each half could be the same as the study face (S), differ by a low discriminability change (L) or differ by a high discriminability change (H), resulting in nine composite types: one where both halves are the same (congruent-same; S/S), two where only the bottom half changes (incongruent-same; S/L and S/H), two where only the top half changes (incongruent-different; L/S and H/S), and four where both top and bottom halves change (congruent-different; L/L, L/H, H/L, and H/H). Congruent composites are indicated by the dotted line panels and incongruent composites by the solid line panels.

the congruency $\times$ alignment interaction as a more diagnostic measure of holism (Richler & Gauthier, 2014).

Richler et al. (2011) assessed the time course of processing upright and inverted composite faces by presenting the test face at one of three encoding times. They found that the hallmark interaction was present at the later times of 183 and 800 ms but not 50 ms. Additionally, Fitousi (2019) used three different measures of RT distributions: delta plots, cumulative distribution functions, and conditional accuracy functions, and found that composite face effects emerged at later RTs. Fitousi concluded that feature-based processing is initially dominant and that it takes time for the face to be processed as a whole, perhaps requiring time for attention to spread to the distractor face half. Although

Fitousi's results are compelling, they are based on the comparison of RT distributions from conditions in which processing time was not manipulated. The present study follows both studies from Richler and colleagues by limiting the amount of time available for encoding the test face. Unlike Richler and colleagues, however, we also introduce a response signal at different time points to prompt the participant to respond (Ratcliff, 2006; Reed, 1973). In the previous studies, it is unclear whether processing continued after the test face was removed. Further, manipulations of encoding time may result in different processes being employed at short and long presentation times. In our task, by forcing responding at each response signal we ensure that processing terminates at each measured time point.

Mapping out the time course of composite face processing is important for theories of holistic face processing because it allows us to determine when in processing interference occurs. The classic view of holism (see e.g., Jacques & Rossion, 2009) is that holism emerges early in processing. Evidence for this view comes from event related potential studies showing early activation to the presence of a face in a scene (Rossion & Jacques, 2012) and the early detection of difference in the target half of composite faces (Jacques & Rossion, 2009). Yet integration of the top and bottom halves could occur either early in processing (i.e., faces are encoded holistically from the outset) or later in processing (i.e., holistic processing emerges from individually encoded top and bottom halves) in the composite task. For example, as pointed out by Meinhardt et al. (2014), diagnostic differences only modulate later ERP components, and recent investigations using RT distributions (Fitousi, 2019) have implicated the emergence of holism only later in processing. The SAT function also decomposes processing into different latent parameters. If interference slows down encoding, then we might expect to see differences in the rate of processing. Alternatively, differences could arise in the peak asymptotic level of processing interference once the entire composite has been encoded.

The Present Experiment

We make several predictions regarding performance in our task. For the incongruent-different composites (see Figure 1), we predict that d' will increase as the strength of evidence for a change in the target half increases (going from L to H). This prediction should hold in both the aligned and misaligned conditions. This is a manipulation check to ensure that discrimination of the target half is affected by the strength of the change.

We predict that as the strength of evidence for a change in the distractor half (i.e., the bottom) increases (going from Same to Low to High) the false alarm rate will also increase. In the misaligned condition, the false alarm rate should not differ between composite types as the target half does not change and the distractor half should be easier to ignore. This is also a manipulation check to ensure that the effect of congruency $\times$ alignment interaction is sensitive to the strength of the interference.

For the congruent-different composites, we predict that d' will increase as the strength of evidence for a change increases in both the target and distractor halves. The expected ordering from lowest to highest is L/L, L/H, H/L, H/H. Crucially, if no interference from the distractor half is present it is expected that d' should be equivalent for the L target half composites (L/L and L/H) and for the H target half composites (H/L and H/H), which is also what we predict for the misaligned condition. This prediction reflects that the strength of the interference should affect the aligned condition but not the misaligned condition. For the misaligned condition, only the strength of the difference in the top half should matter.

Finally, we will assess the hallmark congruency $\times$ alignment interaction across the time course. If the composite face effect emerges, then d' should differ for L/L, L/H, H/L, and H/H between aligned and misaligned conditions; however, we make no predictions about when in the time course this will occur. If the difference is present early in the time

course, this would support the early emergence of holistic processing, perhaps indicating that aligned faces are encoded holistically and are processed at a different rate to misaligned faces. By contrast, a later difference would support the late emergence of holistic processing, implicating interference arising over time. A strength of our method is that we can easily differentiate these two accounts.

Method

Participants

The first and second authors and a female student volunteer from the University of Melbourne completed 29 one-hour sessions. The volunteer was reimbursed \$15 per hour. The average age was 23.7 ($SD = 2.08$), years and all participants reported as right-handed and having normal or corrected-to-normal vision. We chose to collect many trials from a small number of participants as this provides a high level of precision at the level of the individual participant, individual stimulus, and individual response signal lag, appropriate for modelling of the SAT (Smith & Little, 2018). All participants completed two conditions: the aligned condition followed by the misaligned condition. The second author completed the experiment with no prior experience with the stimuli or method but was familiar with the hypotheses being tested. The volunteer was completely naïve to the purpose of the study. All testing was approved by the University of Melbourne Human Research Ethics Committee, approval ID number 1034866.16.

Stimuli and Apparatus

Stimuli were presented on a 1280×1024 resolution Dell 22" monitor in a darkened room. The experiment was coded and presented using MATLAB (Mathworks Inc.) and PsychToolbox (Brainard, 1997). Responses were recorded with a calibrated RT box (Li, Liang, Kleiner, & Lu, 2010) on an Ubuntu 14.04 operating system.

Stimuli were composite faces consisting of a top half extending from the forehead to the upper part of the nose, and a bottom half extending from the lower part of the nose to the neckline (see Figure 4). To create the halves, a set of 54 *base faces* were selected from Kayser (1997; see also Steyvers, 1999). Twenty *morph sets* were then created by selecting four base faces (A, B, C, and D) at random, with replacement across sets, and morphing them together using a field morphing technique (see Steyvers, 1999), such that each morph set was a 3×3 matrix with variation between A and B forming one dimension and between C and D forming the other dimension (see Figure 3). Only the faces on the diagonals were used. On each trial, a top face half and a bottom face half were randomly drawn from the corner items of two morph sets to create a study composite face. Hence, from the 20 morph sets, there were 80 possible top face halves and 80 possible bottom face halves, yielding 6400 unique faces.

The presentation of a study face was always followed by a test face. Each half of the test face was drawn from the same morph set as the respective half of the study face. A test face half could be the same as the study face (S), differ by a low-discriminability change (L), or differ by a high discriminability change (H). In terms of the morph set in Figure 3, an L change is one step on both dimensions of the morph space (e.g., the top-left vs the centre) and an H change is two steps on both dimensions (e.g., the top-left vs the bottom-right).

The only difference between the aligned and misaligned stimuli was that for the latter the face halves were horizontally offset by 85 pixels such that the edge of the bottom half lined up with the nose of the top half (see the bottom row of Figure 4).

Participants sat at a viewing distance of 60 cm. Each aligned composite was 400×340 pixels, subtending a visual angle of $6.68^\circ \times 5.67^\circ$. Each misaligned composite was 400×425 pixels, subtending a visual angle of $6.68^\circ \times 7.09^\circ$. A gap of 10 pixels provided a smoother transition between the morphed halves and subtended a visual angle of 0.17° . A

Figure 3. An example of a morph space. Twenty 3×3 morph sets were created by field morphing four base faces together: A, B, C, and D. Dimension X represents the morphing between C and D. Dimension Y represents the morphing between A and B. For example, the top left-hand corner face is comprised of 50% A and 50% C, while the middle face is comprised of 25% of each base face. Each study face half was drawn from the corner item of a morph set, therefore each test face half could have been the same (from the same corner item), of a low discriminability change (an item from one step on each dimension of the morph space; i.e., the middle face of the matrix), or of a high discriminability change (two steps on each dimension; i.e., the diagonally opposite corner item)

309 Gaussian blur was also applied to the edges of each face.

310 Design and Procedure

311 Participants completed one training session and 28 experimental sessions (14 for each
 312 alignment condition) over several weeks. The training session consisted of six blocks of 78
 313 trials with blank face templates, where the goal was to practice responding within 100 to
 314 300 ms of the response signal, followed by four blocks of 78 trials making easy face

discriminations (i.e., using only S/S and H/H composites).

Each experimental session consisted of ten blocks of 78 trials, equating to 780 trials. Trials were divided into 130 trials for each of the three composites, where the top half remained the same (i.e., S/S, S/L, S/H), and 65 trials for each of the six composites where the top half was different (i.e., L/S, L/L, L/H, H/S, H/L, H/H). This equated the number of same and different response trials. The order of trials was randomised within each session. Participants were told to prioritise responding on time over responding accurately as trials outside of the 100 - 300 ms window would be discarded.

Each trial commenced with a fixation cross presented for 500 ms. A study face was then presented for 500 ms, followed by a blank screen for 500 ms, and then a test face presented until the response signal (Figure 4). Once the response signal was presented, participants indicated whether the top half of the face was the same or different with the left and right buttons on the RT box, respectively. The response signal, a set of XXXs appearing above and below the test face, appeared at one of six randomised lags: 50, 100, 200, 400, 800, and 1800 ms. Accuracy feedback (e.g., “CORRECT” or “WRONG”) was provided for 250 ms followed by a blank screen for 400 ms. Latency feedback was then provided for 500 ms followed by a blank screen for 300 ms. A message was flashed on-screen if a response was within 100 ms after the response signal (i.e., “TOO FAST”), if it was 300 ms or longer after the response signal (i.e., “TOO SLOW”), if it was before the response signal (i.e., “PLEASE WAIT FOR THE RESPONSE SIGNAL”), or if it was an ideal response (i.e., “ON TIME”). Participants took short self-timed breaks in between blocks.

Data Analysis

Changes in discriminability or d' were modelled as a function of the total time to process a given stimulus using the SAT model (Doshier, 1976; McElree & Doshier, 1993). This model has been used extensively to describe recognition memory processes in response

Figure 4. An example of a trial. A fixation cross was presented for 500 ms, then a study face for 500 ms, followed by a blank screen for 500 ms, and then a test face was presented until a response signal was shown. The response signal (XXXs) appeared at one of six time lags: 50, 100, 200, 400, 800, or 1800 ms. The top row depicts an incongruent change in the aligned condition; the top half has stayed the same and the bottom half has changed. The bottom row depicts a congruent change in the misaligned condition; both halves have changed.

signal paradigms (Doshier, 1976; McElree & Doshier, 1993; Ratcliff, 2006; Reed, 1973).

Although it is not a model of processing, it generally provides descriptive adequacy, closely mimics the fit of the expression for growth of accuracy derived from the diffusion model (2000 observations per experimental condition are needed to discriminate the two at a probability level of .95; Ratcliff, 1978, 2006; Wagenmakers, Ratcliff, Gomez, & Iverson, 2004), and has parameters with psychologically meaningful interpretations. The SAT function models d' at each time point as:

$$d'(t) = \hat{d}' \left[1 - \exp \left(-\frac{1}{\tau} (t - T_0) \right) \right], \quad T_0 > 0 \quad (1)$$

where the asymptote, $\hat{d}'$, describes the peak level of accuracy for a stimulus (or composite)

type; the time intercept, T_0 , describes the onset of accuracy beginning to grow above chance levels; and the rate, τ , describes the growth of accuracy or processing rate towards asymptotic levels. Composite faces which differ in overall discriminability should have different values of $\hat{d}'$. Composite faces which are encoded or processed at different rates should have different values of τ . If one composite exceeds chance performance at an earlier point in time than another, then this should lead to differences in T_0 . The parameters of this model and the resulting discriminability (d') and response bias (c) values at each response signal lag were estimated using Bayesian hierarchical modelling implemented in JAGS (Plummer, 2003). These estimated values were compared between composite types and alignment conditions to determine differences in processing.

Results

Data Screening

The training session and the first block of each experimental session were considered practice and excluded from analysis. Responses made before the response signal, less than 100 ms after the response signal (i.e., anticipation errors), or more than 300 ms after the response signal were also excluded from analysis, resulting in 15.3% of the total data being removed. The percentage of trials included for each participant at each response signal lag in both conditions are shown in Table 1. It is clear that participants found it more difficult to respond within the time limit at early response signals. For P3, this was more pronounced for the aligned condition, most likely because this condition was presented first.

Table 1

Percentage of Included Trials at Each Response Signal Lag

	Aligned						Misaligned					
(msec)	50	100	200	400	800	1800	50	100	200	400	800	1800
P1	65.3	81.3	91.7	93.6	93.1	90.1	64.4	80.8	89.8	94.7	93.1	90.9
P2	57.9	74.6	90.4	87.5	86.9	85.0	54.3	72.1	81.4	83.0	78.1	78.5
P3	42.0	66.0	89.3	95.2	92.6	92.2	63.9	82.2	95.3	95.4	91.8	92.2

SAT Function Analysis

Appendix A describes the details of our computational analysis. In short, we used a hierarchical Bayesian implementation of the SAT model with group-level distribution governing the parameters of the SAT function and individual level d' and criterion distributions across each response signal lag to provide likelihoods for the observed hit rates and false alarms rates. Plots of the SAT model for each composite type were used to examine how d' varied as a function of total processing time (i.e., response signal lag plus mean RT for that lag; see Table 2 for mean RTs). Mean RT was longer at shorter response signals for all participants.

Table 2
Individual-Level and Group-Level Mean RTs at Each Response Signal Lag

	Aligned						Misaligned					
(msec)	50	100	200	400	800	1800	50	100	200	400	800	1800
P1	269	256	238	229	218	203	273	259	242	237	226	211
P2	267	253	237	236	236	227	273	260	244	246	249	241
P3	271	259	241	238	237	233	270	257	239	235	235	230
Group	269	256	239	234	230	221	272	259	242	239	236	227

For brevity, we pool the individual level posteriors and provide these as a single distribution for each condition at the average total processing time (i.e., average RT + response signal). In some cases, because each participant has a considerable amount of data in each condition, this results in a multimodal distribution reflecting individual variation. For clarity, we additionally provide numerical estimates of the posterior means and 95% Highest Density Intervals (HDI's) for each participant. We additionally estimated the Bayesian SAT model, without a hierarchical structure to each participant. Results of this analysis for each participant (plotted at each individual's total processing time) are provided in our supplementary material. Group level inferences are given by examining the group level SAT parameter posteriors where appropriate.

False Alarm Analysis

First, the two plots of Figure 5 display the 95% HDIs of the false alarm rates for when the congruent-same and incongruent-same composites were aligned (left) and misaligned (right). When faces were aligned, the HDI overlap was substantial between the S/S and S/L composite types; however, the overlap with the S/H composite type was less complete. Table 3 shows the individual participant false alarm data at each response signal for each alignment and item condition. For the aligned conditions, all participants had higher false alarms at earlier response signals. Participants 1 and 2 had higher false alarms when the bottom half was a highly discriminable change, though for participant 2 this was more evident at later response signals. Participant 3 also had a higher mean false alarm rate when the bottom half was highly discriminable, but the HDI's overlapped with the false alarm distribution for the low discriminability bottom change condition. When faces were misaligned, the HDIs for the three composite types overlapped almost perfectly and indicate a low false alarm rate across the entire time course. The implication of this result is that a highly discriminable change in the bottom half increased the false alarm rate in the aligned condition but not the misaligned condition.

Figure 5. False alarm rates for congruent-same and incongruent-same composite types. The group-level posteriors for the individual-level false alarm rates are plotted for the aligned (left) and misaligned (right) conditions.

Table 3

Average posterior false alarm rates (and 95% Highest Density Intervals) for each participant in each condition at each stop signal duration

Participant	Alignment	Item	Average Total Processing Time (msec)							
			322	359	443	641	1034	2025		
1	Aligned	Same/Same	.16 [.12-.21]	.15 [.11-.19]	.03 [.01-.04]	.01 [.01-.03]	.03 [.02-.05]	.04 [.02-.06]		
1	Aligned	Same/Low	.17 [.13-.22]	.13 [.10-.17]	.06 [.04-.09]	.05 [.03-.07]	.06 [.04-.09]	.04 [.02-.06]		
1	Aligned	Same/High	.36 [.30-.43]	.29 [.24-.34]	.24 [.20-.30]	.23 [.19-.28]	.20 [.16-.25]	.15 [.12-.20]		
2	Aligned	Same/Same	.07 [.04-.10]	.04 [.02-.06]	.04 [.02-.06]	.03 [.01-.05]	.03 [.02-.05]	.02 [.01-.04]		
2	Aligned	Same/Low	.07 [.04-.10]	.06 [.04-.09]	.04 [.02-.07]	.04 [.02-.06]	.05 [.03-.08]	.03 [.02-.05]		
2	Aligned	Same/High	.08 [.05-.12]	.13 [.09-.17]	.09 [.06-.12]	.10 [.07-.14]	.14 [.10-.18]	.10 [.07-.14]		
3	Aligned	Same/Same	.00 [.00-.01]	.02 [.01-.04]	.02 [.01-.04]	.07 [.04-.10]	.05 [.03-.08]	.04 [.02-.07]		
3	Aligned	Same/Low	.03 [.01-.05]	.04 [.02-.06]	.03 [.02-.05]	.05 [.03-.08]	.08 [.05-.12]	.06 [.03-.08]		
3	Aligned	Same/High	.02 [.00-.04]	.05 [.03-.08]	.06 [.04-.09]	.09 [.06-.12]	.13 [.09-.17]	.10 [.07-.13]		
1	Misaligned	Same/Same	.09 [.06-.14]	.07 [.05-.11]	.08 [.06-.12]	.04 [.02-.06]	.07 [.05-.11]	.06 [.04-.09]		
1	Misaligned	Same/Low	.08 [.04-.11]	.10 [.07-.14]	.05 [.03-.07]	.04 [.02-.07]	.03 [.02-.05]	.03 [.02-.06]		
1	Misaligned	Same/High	.10 [.07-.15]	.07 [.04-.10]	.07 [.05-.11]	.06 [.04-.09]	.08 [.05-.12]	.09 [.06-.12]		
2	Misaligned	Same/Same	.02 [.01-.05]	.05 [.03-.08]	.05 [.02-.07]	.03 [.01-.05]	.03 [.02-.06]	.04 [.02-.07]		
2	Misaligned	Same/Low	.07 [.03-.11]	.04 [.02-.06]	.03 [.01-.05]	.01 [.00-.03]	.02 [.01-.04]	.03 [.01-.05]		
2	Misaligned	Same/High	.07 [.04-.11]	.07 [.04-.10]	.04 [.02-.07]	.03 [.02-.06]	.04 [.02-.07]	.03 [.01-.05]		
3	Misaligned	Same/Same	.01 [.00-.03]	.03 [.02-.05]	.04 [.02-.07]	.06 [.04-.09]	.05 [.03-.08]	.07 [.04-.10]		
3	Misaligned	Same/Low	.02 [.01-.04]	.03 [.01-.05]	.07 [.04-.10]	.06 [.03-.08]	.04 [.02-.06]	.07 [.04-.10]		
3	Misaligned	Same/High	.01 [.00-.02]	.04 [.02-.07]	.05 [.03-.08]	.06 [.03-.08]	.05 [.03-.08]	.05 [.03-.08]		

Effect of Discriminability: Bottom half same

We analysed the effect of a change in the discriminability of the top half when the bottom half stayed the same (i.e., incongruent-different composite faces). The top two plots of Figure 6 display the 95% HDIs of the SAT functions and d' for when the incongruent-different composite faces were aligned (left) and misaligned (right). When faces were either aligned or misaligned and processing time exceeded 400 ms, the HDIs did not overlap for the L/S and H/S composite types. This indicates that our manipulation of face discriminability was successful as, when the bottom half was the same, high discriminability top halves were identified as different with higher sensitivity than low discriminability top halves. As shown in Table 4, d' was consistent across participant and alignment condition and consistently higher for high/same compared to low/same composites.

The bottom six plots of Figure 6 display the group-level SAT parameter posteriors for aligned (left-to-right, first three) and misaligned (last three) conditions. For both

417 alignment conditions, the HDIs did not overlap for asymptotic d' between the L/S and
418 H/S composite conditions; however, the intercept and rate HDIs were effectively identical.
419 Hence, we found that the change in discriminability in the top half resulted in a change in
420 overall detection accuracy but not in the onset or rate of accumulation. There were no
421 differences in this result between the aligned and misaligned conditions; similar levels of
422 asymptotic d' were found in both conditions.

Figure 6. Model fits to d' for incongruent-different composite types. The top two plots depict the speed-accuracy trade-off (SAT) model fit to the group-level posteriors for the individual-level d' 's. d' is plotted at each of the six total processing times (response signal lag + mean RT for that lag) in the aligned (left) and misaligned (right) conditions. The bottom six plots depict the group-level posteriors for the three SAT parameters; asymptotic d' ($\hat{d}'$), the intercept (T_0), and the rate (τ), in the aligned (left-to-right, first three) and misaligned (last three) conditions.

Table 4

Incongruent-different composite top half discriminability: Average posterior d' -prime estimates (and 95% Highest Density Intervals) for each participant in each condition at each stop signal duration

Participant	Alignment	Item	Average Total Processing Time (msec)											
			322		359		443		641		1034		2025	
1	Aligned	Low/Same	1.26	[0.98-1.51]	1.47	[1.28-1.65]	1.75	[1.55-1.96]	1.99	[1.79-2.19]	2.08	[1.86-2.29]	2.09	[1.86-2.32]
1	Aligned	High/Same	2.72	[2.35-3.08]	2.96	[2.68-3.26]	3.30	[3.06-3.56]	3.63	[3.41-3.85]	3.75	[3.50-4.00]	3.77	[3.50-4.04]
2	Aligned	Low/Same	1.46	[1.11-1.77]	1.73	[1.51-1.97]	2.07	[1.85-2.31]	2.33	[2.14-2.53]	2.42	[2.21-2.64]	2.43	[2.22-2.67]
2	Aligned	High/Same	2.85	[2.47-3.19]	3.12	[2.86-3.40]	3.49	[3.25-3.76]	3.81	[3.59-4.05]	3.91	[3.66-4.20]	3.93	[3.67-4.22]
3	Aligned	Low/Same	1.78	[1.42-2.24]	1.91	[1.61-2.27]	2.10	[1.86-2.34]	2.31	[2.15-2.47]	2.41	[2.22-2.61]	2.43	[2.22-2.67]
3	Aligned	High/Same	3.41	[2.88-3.91]	3.56	[3.15-3.93]	3.74	[3.46-4.00]	3.88	[3.63-4.15]	3.92	[3.65-4.25]	3.93	[3.65-4.27]
1	Misaligned	Low/Same	1.41	[1.15-1.65]	1.56	[1.36-1.77]	1.80	[1.61-2.00]	2.08	[1.91-2.26]	2.24	[2.02-2.44]	2.28	[2.03-2.53]
1	Misaligned	High/Same	3.22	[2.80-3.70]	3.40	[3.06-3.77]	3.63	[3.36-3.90]	3.81	[3.55-4.07]	3.87	[3.57-4.17]	3.88	[3.57-4.19]
2	Misaligned	Low/Same	2.12	[1.76-2.47]	2.30	[2.06-2.56]	2.54	[2.34-2.75]	2.71	[2.52-2.93]	2.77	[2.54-3.01]	2.77	[2.54-3.02]
2	Misaligned	High/Same	3.42	[2.97-3.88]	3.61	[3.29-3.94]	3.82	[3.57-4.08]	3.95	[3.70-4.23]	3.98	[3.71-4.28]	3.98	[3.71-4.29]
3	Misaligned	Low/Same	1.66	[1.30-1.96]	1.85	[1.61-2.10]	2.13	[1.93-2.35]	2.42	[2.25-2.59]	2.54	[2.36-2.73]	2.56	[2.36-2.79]
3	Misaligned	High/Same	2.60	[2.15-3.01]	2.98	[2.70-3.27]	3.48	[3.19-3.78]	3.88	[3.61-4.17]	4.00	[3.71-4.33]	4.02	[3.71-4.36]

Effect of Discriminability: Bottom half different

As a final manipulation check, we also examined the effect of changing the discriminability of the top half when the bottom half also changed (i.e., congruent-different composite faces), either in a low discriminability or high discriminability fashion. We found that, in the misaligned condition, there was no observable influence of the bottom half of the face, but in the aligned condition, there was a small observable effect arising in the level of asymptotic d' .

The top two plots of Figure 7 display the 95% HDIs of the SAT functions and d' for when the congruent-different composite faces were aligned (left) and misaligned (right). When faces were aligned, the HDIs for the high discriminability target half composites (H/H and H/L) overlapped substantially across the time course, and to a lesser degree but still substantially for the low discriminability target half composites (L/H and L/L). Although, the overlap was not as complete as in the misaligned condition. Close inspection of Table 5 reveals that the although the L/H condition had a consistently higher posterior mean than the L/L condition, the HDI's always overlapped. The only consistent differences were between the top high and top low discriminability item conditions; there was no difference between alignment conditions.

440 The bottom six plots of Figure 7 display the group-level SAT parameter posteriors for
441 aligned (left-to-right, first three) and misaligned (last three) conditions. For the aligned
442 condition, the HDIs for asymptotic d' did not overlap between the high and low
443 discriminability composites, but the overlap was high within each pair of composites. The
444 HDIs for intercept and rate overlapped substantially for all four composite types. For the
445 misaligned condition, these results were likewise observed, although the overlap was again
446 more complete.

Figure 7. Model fits to d' for congruent-different composite types. The top two plots depict the speed-accuracy trade-off (SAT) model fit to the group-level posteriors for the individual-level d' s. d' is plotted at each of the six total processing times (response signal lag + mean RT for that lag) in the aligned (left) and misaligned (right) conditions. The bottom six plots depict the group-level posteriors for the three SAT parameters; asymptotic d' ($\hat{d}'$), the intercept (T_0), and the rate (τ), in the aligned (left-to-right, first three) and misaligned (last three) conditions.

Table 5

Top half discriminability when the bottom half also changed: Average posterior d-prime estimates (and 95% Highest Density Intervals) for each participant in each condition at each stop signal duration

Participant	Alignment	Item	Average Total Processing Time (msec)											
			322		359		443		641		1034		2025	
1	Aligned	Low/Low	1.23	[0.92-1.51]	1.49	[1.30-1.68]	1.84	[1.63-2.07]	2.17	[1.96-2.38]	2.29	[2.07-2.50]	2.31	[2.08-2.54]
1	Aligned	Low/High	1.70	[1.40-1.97]	1.94	[1.75-2.14]	2.25	[2.06-2.46]	2.52	[2.33-2.70]	2.60	[2.40-2.80]	2.61	[2.41-2.82]
1	Aligned	High/Low	2.48	[2.11-2.84]	2.89	[2.64-3.15]	3.40	[3.13-3.68]	3.77	[3.53-4.02]	3.86	[3.61-4.12]	3.87	[3.61-4.14]
1	Aligned	High/High	2.58	[2.20-2.95]	3.02	[2.76-3.30]	3.57	[3.29-3.86]	3.96	[3.71-4.22]	4.05	[3.79-4.33]	4.06	[3.79-4.34]
2	Aligned	Low/Low	1.61	[1.29-1.88]	1.82	[1.59-2.04]	2.13	[1.91-2.37]	2.45	[2.26-2.66]	2.60	[2.40-2.83]	2.64	[2.41-2.90]
2	Aligned	Low/High	2.01	[1.70-2.31]	2.22	[2.00-2.46]	2.50	[2.30-2.72]	2.73	[2.56-2.92]	2.82	[2.62-3.03]	2.83	[2.63-3.05]
2	Aligned	High/Low	2.66	[2.22-3.06]	3.12	[2.83-3.46]	3.61	[3.30-3.95]	3.93	[3.68-4.19]	4.01	[3.74-4.30]	4.02	[3.75-4.32]
2	Aligned	High/High	2.52	[2.11-2.91]	3.08	[2.79-3.42]	3.69	[3.35-4.03]	4.07	[3.80-4.34]	4.15	[3.87-4.45]	4.15	[3.87-4.46]
3	Aligned	Low/Low	1.83	[1.48-2.27]	1.97	[1.68-2.35]	2.19	[1.95-2.45]	2.44	[2.27-2.61]	2.57	[2.38-2.77]	2.60	[2.38-2.85]
3	Aligned	Low/High	2.18	[1.75-2.67]	2.33	[2.00-2.70]	2.53	[2.27-2.77]	2.71	[2.55-2.88]	2.78	[2.59-2.98]	2.79	[2.59-3.03]
3	Aligned	High/Low	3.13	[2.63-3.71]	3.36	[2.98-3.79]	3.65	[3.36-3.93]	3.90	[3.66-4.16]	3.99	[3.70-4.31]	4.00	[3.70-4.34]
3	Aligned	High/High	3.54	[2.84-4.16]	3.80	[3.39-4.21]	4.05	[3.75-4.34]	4.19	[3.91-4.52]	4.22	[3.92-4.59]	4.22	[3.92-4.60]
1	Misaligned	Low/Low	1.49	[1.22-1.73]	1.66	[1.46-1.85]	1.90	[1.72-2.09]	2.13	[1.97-2.31]	2.23	[2.03-2.43]	2.25	[2.03-2.48]
1	Misaligned	Low/High	1.66	[1.41-1.90]	1.81	[1.61-2.01]	2.03	[1.85-2.21]	2.26	[2.10-2.42]	2.36	[2.16-2.55]	2.38	[2.17-2.59]
1	Misaligned	High/Low	3.36	[2.89-3.77]	3.51	[3.19-3.82]	3.66	[3.42-3.92]	3.76	[3.50-4.03]	3.78	[3.50-4.07]	3.78	[3.50-4.08]
1	Misaligned	High/High	2.99	[2.64-3.36]	3.21	[2.92-3.53]	3.54	[3.28-3.81]	3.87	[3.62-4.14]	4.00	[3.69-4.33]	4.02	[3.70-4.38]
2	Misaligned	Low/Low	2.03	[1.67-2.37]	2.25	[2.01-2.49]	2.53	[2.32-2.74]	2.74	[2.53-2.96]	2.79	[2.56-3.04]	2.80	[2.56-3.06]
2	Misaligned	Low/High	2.19	[1.85-2.53]	2.35	[2.10-2.61]	2.56	[2.36-2.77]	2.75	[2.54-2.97]	2.81	[2.57-3.07]	2.82	[2.57-3.09]
2	Misaligned	High/Low	3.15	[2.73-3.56]	3.42	[3.12-3.73]	3.76	[3.49-4.05]	4.02	[3.74-4.35]	4.09	[3.78-4.49]	4.10	[3.78-4.51]
2	Misaligned	High/High	3.66	[3.21-4.09]	3.80	[3.45-4.12]	3.96	[3.70-4.23]	4.07	[3.79-4.38]	4.10	[3.80-4.46]	4.10	[3.80-4.47]
3	Misaligned	Low/Low	1.89	[1.57-2.23]	2.03	[1.79-2.29]	2.21	[2.02-2.39]	2.37	[2.21-2.54]	2.43	[2.24-2.62]	2.44	[2.24-2.64]
3	Misaligned	Low/High	1.70	[1.40-1.98]	1.86	[1.63-2.09]	2.10	[1.91-2.30]	2.36	[2.20-2.53]	2.48	[2.30-2.66]	2.50	[2.30-2.71]
3	Misaligned	High/Low	2.75	[2.36-3.11]	3.04	[2.78-3.32]	3.45	[3.19-3.73]	3.82	[3.57-4.10]	3.96	[3.66-4.28]	3.98	[3.66-4.33]
3	Misaligned	High/High	2.87	[2.42-3.28]	3.17	[2.88-3.48]	3.54	[3.28-3.83]	3.84	[3.59-4.11]	3.93	[3.64-4.23]	3.94	[3.64-4.25]

Congruency $\times$ alignment interaction. The hallmark of holistic processing in the composite face task is the congruency $\times$ alignment interaction in which congruency effects are diminished with misalignment. The top two plots of Figure 8 display the 95% Highest Density Intervals (HDIs) of the SAT functions and d' for *all* the congruent and incongruent composites faces at each level of discriminability when aligned (left) or misaligned (right). When faces were aligned and underwent highly discriminable changes, the HDIs for the congruent composites overlapped very little with the incongruent composites from approximately 600 ms onwards. When undergoing less discriminable changes, the overlap was more substantial across the time course though not as complete as in the misaligned condition.

The bottom six plots of Figure 8 display the group-level SAT parameter posteriors for congruent and incongruent composites faces at each level of discriminability in the aligned (left-to-right, first three) and misaligned (last three) conditions. For the aligned condition,

460 the HDIs for asymptotic d' did not overlap for the high discriminability composites but did
461 for the low discriminability composites. For the misaligned condition, the HDIs for both
462 discriminability composite pairs overlapped substantially. For both alignment conditions,
463 the intercept and rate HDIs were effectively identical.

Figure 8. Model fits to d' for all congruent and incongruent composites. The top two plots depict the speed-accuracy trade-off (SAT) model fit to the group-level posteriors for the individual-level d' 's. d' is plotted at each of the six total processing times (response signal lag + mean RT for that lag) in the aligned (left) and misaligned (right) conditions. The bottom six plots depict the group-level posteriors for the three SAT parameters; asymptotic d' ($\hat{d}'$), the intercept (T_0), and the rate (τ), in the aligned (left-to-right, first three) and misaligned (last three) conditions.

The posterior estimates for each individual participant are shown in Table B1, but for simplicity, we also calculated the interaction effect using the d' values separately for high and low discriminability conditions as:

$$(Congruent_{aligned} - Incongruent_{aligned}) - (Congruent_{misaligned} - Incongruent_{misaligned})$$

For the low discriminability composites, the HDIs for the d' interaction effect overlapped 0 until approximately 1000 ms (see Figure 9). However, for the high discriminability composites, the HDIs did not overlap 0 much earlier, at approximately 440 ms (200 ms response signal lag plus mean RT). Taken together, these results imply that the congruency $\times$ alignment interaction arises later in the time course of processing and earlier in that time course when the discriminations are easier. Table 6 shows that this result is consistent across participants with one exception though there is some variation in when the interaction emerges. The most substantial variant is that when the discriminability is high, Participant 1 shows the interaction effect from the earliest response signal.

For both the low and high discriminability composites, the group-level HDIs for the intercept and rate parameters overlapped 0 (Figure 10). For the asymptote parameter, only for high discriminability composites did the 95% HDI not overlap 0 (see Figure 10). The implication of this result is that highly discriminable changes resulted in greater congruency effects in aligned faces than misaligned faces. That is, accuracy was improved when both halves were in agreement and hampered when they were not.

Discussion

Our primary result was that for the highly discriminable composites, the interaction was found after 400 ms total processing time, and for the low discriminability targets, the

Figure 9. Congruency $\times$ alignment interactions for each d' . The 95% HDIs for the interaction are plotted at each total processing time (response signal lag + mean RT for that lag) for all low discriminability (top) and high discriminability (bottom) composites. The 95% HDIs are also reported for the 400, 800, and 1800 ms response signal lags.

interaction was found after 1000 ms total processing time. That is, when discriminations were easy and faces were aligned, the composite face effect arises earlier than when the discrimination was difficult and the faces were aligned. Recognition performance improved with congruency and was hampered with incongruency. When faces were misaligned, there was no such benefit or cost to recognition. In sum, this result suggests that holistic processing emerged late in the time course and elicited sooner for easy discriminations than for difficult discriminations. This result goes some way toward explaining why holistic processing is not found for composite faces in some types of task.

There were additional signs of holistic processing evident from interference effects for

Figure 10. Congruency $\times$ alignment interactions for each SAT parameter. The 95% HDIs for the interaction are plotted and reported for the asymptote ($\hat{d}'$; left), the intercept (T_0 ; middle) and the rate (τ ; right) parameters for all low and high discriminability composites.

aligned composites but not misaligned composites. Participants were less accurate at recognising that the target half had stayed the same when the distractor half had changed, but only for highly discriminable changes. As shown Table 3, this was the most striking difference between participants with one participant (P1) making considerably more false alarms to the target half than the other two. This is likely the primary driver behind the emergence of the interaction effect across the entire time course for highly discriminable composites for this participant. It is worth noting that participant 1 had the most experience with the composite stimuli. The remaining participants, who were not involved in the generation of the stimuli, had more similar results. Although the small-N design does not permit extensive generalisation, one target for future research would be to characterise whether and how familiarity with the face composites pushes the emergence of holism earlier in time.

Participants were also more accurate at recognising a change to the target half when it co-occurred with a change to the distractor half for aligned faces. There were minor differences in recognition performance between the two composites that underwent a high

Table 6

Congruence $\times$ Alignment interaction posterior mean estimates and 95% HDI's for each participant at each level of discriminability

Participant	Discriminability	Average Total Processing Time (msec)											
		322		359		443		641		1034		2025	
1	Low	-0.08	[-0.61-0.44]	0.07	[-0.33-0.46]	0.31	[-0.09-0.71]	0.58	[0.20-0.96]	0.73	[0.30-1.15]	0.76	[0.28-1.24]
2	Low	-0.08	[-0.77-0.62]	0.19	[-0.28-0.66]	0.42	[-0.05-0.88]	0.53	[0.11-0.96]	0.58	[0.12-1.04]	0.59	[0.11-1.09]
3	Low	0.03	[-0.65-0.75]	0.03	[-0.50-0.58]	0.09	[-0.35-0.53]	0.27	[-0.08-0.62]	0.42	[0.03-0.81]	0.47	[0.03-0.90]
Group	Low	-0.04	[-0.68-0.64]	0.09	[-0.40-0.59]	0.27	[-0.25-0.78]	0.46	[-0.00-0.92]	0.58	[0.10-1.07]	0.61	[0.10-1.14]
1	High	0.86	[0.07-1.63]	1.12	[0.50-1.73]	1.34	[0.82-1.87]	1.32	[0.82-1.82]	1.19	[0.58-1.80]	1.15	[0.48-1.80]
2	High	-0.71	[-1.55-0.10]	-0.06	[-0.66-0.57]	0.56	[-0.01-1.13]	0.84	[0.30-1.37]	0.87	[0.26-1.46]	0.87	[0.25-1.47]
3	High	0.45	[-0.57-1.43]	0.55	[-0.12-1.23]	0.66	[0.10-1.21]	0.73	[0.15-1.33]	0.76	[0.07-1.45]	0.77	[0.04-1.47]
Group	High	0.20	[-1.33-1.48]	0.54	[-0.51-1.56]	0.85	[0.08-1.72]	0.96	[0.26-1.69]	0.94	[0.21-1.67]	0.93	[0.19-1.66]

discriminability change to the target half, likely due to the strong evidence provided by high target change. There were larger differences evidence in asymptotic d' between composites that underwent a low discriminability change to the target half, likely due to the influence of additional evidence from the distractor half.

Implications

Early or late in the time course? Participants' recognition accuracy was considerably above chance levels from the earliest response signal (50 ms). This suggests that participants were able to adequately encode *and* respond to the target face half very quickly. The current study shows that holistic processing emerges late in the time course, after approximately 400 ms when the discrimination is easy and after 1000 ms when the discrimination is hard. This is inconsistent with Hole (1994), who found holistic processing at a short presentation time (80 ms) but not at a longer presentation time (2000 ms). This is perhaps unsurprising as Hole presented the to-be-compared faces simultaneously, which may have enabled a feature matching strategy to be employed at the longer but not the short presentation interval. Hole also used a partial composite design; because in the partial design the bottom half is always different, participants may have different biases for responding to aligned faces compared to misaligned faces and these biases may vary across different conditions, including different presentation times (Cheung, Richler, Palmeri, & Gauthier, 2008; Gauthier & Bukach, 2007; Meinhardt et al., 2014; Richler, Tanaka, Brown,

& Gauthier, 2008).

Richler, Mack, et al. (2009), who used a complete composite design, found that congruency effects for composite faces were present as soon as performance was above chance levels. That is, regardless of whether the encoding time of the study or test face was manipulated, participants were more accurate on congruent trials relative to incongruent trials from 50 ms onwards. In contrast, we found that clear congruency effects were only present after approximately 400 ms total processing time at the earliest.

Our findings are more consistent with Richler et al. (2011), who found the congruency $\times$ alignment interaction at later encoding times of the test face (183 and 800 ms). Although Richler et al. (2011) found this interaction earlier in the time course than we find here, our findings are not incompatible. The delay in our task may be explained by the additional processing required for the response signal and the use of morphed faces (that are potentially harder to discriminate even in the easiest discriminability used here). Critically, both sets of results are in agreement of a later emergence of holistic processing.

Our results also support Fitousi (2019), who found with various RT distribution measures: delta plots, cumulative distribution functions, and conditional accuracy functions, that the congruency $\times$ alignment interaction emerges at later RTs rather than earlier RTs. All things considered, the current body of research on the time course of composite face processing favours the late emergence of holistic processing.

Theories of holistic processing. Numerous mechanisms have been proposed to give rise to holistic processing (Richler et al., 2012). The two most commonly supported are the template encoding, or Gestalt, hypothesis (Galton, 1883), and the attentional strategy hypothesis (Richler et al., 2012). Although it would be unwarranted to draw direct conclusions about any one mechanism based on the findings of a single behavioural experiment, we discuss which of these two theories our results align with the most.

The findings of the current study are consistent with the idea that holistic processing

reflects an overlearned attentional strategy where, due to our extensive experience with processing whole upright faces, we struggle to disengage attention and selectively attend to an instructed face part (Richler & Gauthier, 2014; see also Gao, Flevaris, Robertson, & Bentin, 2011; Weston & Perfect, 2005). Many classic theories of attention can explain the late emergence of holistic processing (Lavie, 1995; Luck & Vogel, 1997; Pashler, 1994). For example, due to the limits of our attentional system, it can take time for attention to spread from independently processing the target face half to erroneously processing the distractor half as well.

Implications for other paradigms. Blaha (2017) argued that difficult discriminations draw more attention away from processing the whole face than do easy discriminations. In other words, a low discriminability change demands local attention to the target face part, encouraging feature-based processing. By contrast, a high discriminability change allows for global attention to the whole face, encouraging holistic processing. This supports Blaha's conjecture that the discrimination difficulty can lead to limited capacity in face processing (Ingvalson & Wenger, 2005; Perry et al., 2008; Wenger & Townsend, 2001). Likewise, it is possible that the lack of coactivity in Cheng et al. (2018), which notably used the same face morphs in a categorization task, was due to fine distinctions between faces. Future applications of composite faces should give due consideration to the discriminability of the composite face stimuli.

In summary, the findings of the current study suggest that holistic processing, as measured by the composite face task, emerges late. Moreover, difficult to discriminate changes to a face hinder the emergence of holistic processing. We propose that previous divergent findings concerning composite faces were due to task-specific differences, including face discriminability and the timing of responses. For instance, in 2AFC categorisation studies, the response time is typically less than 1 sec (see e.g., Cheng et al., 2018), and consequently, holistic processing may not have had time to emerge. Future studies should seek to address these differences when investigating other

581 operationalisations of holistic processing.

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Appendix A

Fitting the Speed-Accuracy Tradeoff (SAT) Function

The SAT model was fitted to individual and group level data for each composite type and alignment condition within a hierarchical Bayesian framework. Each participant, i 's, SAT parameters were sampled from Gaussian group-level distributions with mean, μ , and precision, λ , hyperparameters (see Figure A1). The priors for the means and precisions of the SAT parameters were uniform with a liberal yet plausible range. The SAT parameters for each participant were used to generate functions which in turn generated discriminability and response bias estimates, d'_{ti} and c_{ti} (cf., Lee & Wagenmakers, 2014), at each of the six response signal lags, t . Response bias parameters at each lag were generated independently and in turn used to generate the hit and false alarm rates, θ_{ti}^S and θ_{ti}^N . These were used as the binomial probability parameters in the likelihood function for the observed number of hits and false alarms, r_{ti}^S and r_{ti}^N . The graphical model (see Figure A1) shows details of the priors and structure.

The model was evaluated in JAGS (Plummer, 2003) by drawing 5000 posterior samples after a burn-in period of 5000 samples using Markov chain Monte Carlo (MCMC) methods (Kruschke, 2014). The posteriors showed adequate convergence from the three chains used and the $\hat{R}$ deviance value was less than 1.01 for all parameters (Gelman, Rubin, et al., 1992)².

² We also fit a four parameter function based on Reed (1973) but the SAT function was less complex, easier to interpret, and had a preferred model selection index in most cases.

Figure A1. Graphical model. Individual-level, i , speed-accuracy trade-off (SAT) model parameters; asymptotic d' ($\hat{d}'$), intercept (T_0), and rate (τ), were sampled from group-level Gaussian distributions with means (μ) and precisions (λ). The SAT parameters for each function generated the discriminability (d'_{ti}) and response bias (c_{ti}) estimates at each of the six response signal lags, t . Both signal detection theory parameters generated the hit (θ^S_{ti}) and false alarm (θ^N_{ti}) rates. Subsequently, these parameters generated the predicted number of hits (r^S_{ti}) and false alarms (r^N_{ti}), in comparison to the observed number of hits (n^S_{ti}) and false alarms (n^N_{ti})

Appendix B

Individual Participant Posterior Means for each congruency $\times$ alignment condition

Table B1

Congruency and Discriminability: Average posterior d-prime estimates (and 95% Highest Density Intervals) for each participant in each condition at each stop signal duration

Participant	Alignment	Item	Average Total Processing Time (msec)							
			322	359	443	641	1034	2025		
1	Aligned	Congruent Low	1.23 [0.93-1.50]	1.49 [1.30-1.68]	1.84 [1.63-2.06]	2.17 [1.95-2.38]	2.29 [2.07-2.50]	2.31 [2.08-2.54]		
1	Aligned	Congruent High	2.58 [2.20-2.96]	3.02 [2.76-3.30]	3.56 [3.29-3.86]	3.96 [3.71-4.21]	4.05 [3.78-4.32]	4.06 [3.78-4.34]		
1	Aligned	Incongruent Low	1.24 [1.01-1.48]	1.37 [1.19-1.57]	1.55 [1.38-1.72]	1.71 [1.54-1.89]	1.78 [1.57-2.00]	1.80 [1.57-2.04]		
1	Aligned	Incongruent High	1.96 [1.66-2.35]	2.08 [1.82-2.40]	2.28 [2.06-2.50]	2.52 [2.32-2.72]	2.65 [2.35-2.95]	2.68 [2.35-3.06]		
2	Aligned	Congruent Low	1.61 [1.29-1.89]	1.82 [1.60-2.05]	2.13 [1.91-2.37]	2.45 [2.26-2.66]	2.60 [2.39-2.83]	2.63 [2.40-2.90]		
2	Aligned	Congruent High	2.51 [2.10-2.91]	3.08 [2.79-3.42]	3.70 [3.36-4.04]	4.07 [3.80-4.35]	4.14 [3.86-4.45]	4.15 [3.86-4.46]		
2	Aligned	Incongruent Low	1.40 [1.07-1.70]	1.63 [1.42-1.86]	1.92 [1.72-2.14]	2.16 [1.98-2.35]	2.24 [2.05-2.44]	2.25 [2.05-2.47]		
2	Aligned	Incongruent High	2.54 [2.23-2.88]	2.71 [2.47-2.97]	2.94 [2.74-3.15]	3.13 [2.90-3.37]	3.20 [2.92-3.49]	3.20 [2.92-3.52]		
3	Aligned	Congruent Low	1.83 [1.49-2.28]	1.97 [1.68-2.35]	2.19 [1.94-2.46]	2.44 [2.27-2.61]	2.57 [2.37-2.76]	2.60 [2.38-2.84]		
3	Aligned	Congruent High	3.54 [2.83-4.16]	3.80 [3.39-4.21]	4.05 [3.75-4.35]	4.19 [3.90-4.53]	4.22 [3.91-4.61]	4.22 [3.91-4.62]		
3	Aligned	Incongruent Low	1.43 [1.01-1.78]	1.65 [1.38-1.91]	1.94 [1.73-2.17]	2.21 [2.04-2.40]	2.32 [2.13-2.52]	2.34 [2.14-2.57]		
3	Aligned	Incongruent High	2.86 [2.40-3.32]	3.04 [2.71-3.37]	3.27 [3.01-3.54]	3.47 [3.16-3.81]	3.53 [3.17-3.98]	3.54 [3.17-4.03]		
1	Misaligned	Congruent Low	1.49 [1.22-1.73]	1.66 [1.46-1.86]	1.90 [1.71-2.09]	2.13 [1.97-2.31]	2.23 [2.03-2.43]	2.25 [2.04-2.47]		
1	Misaligned	Congruent High	3.00 [2.64-3.36]	3.22 [2.93-3.52]	3.54 [3.28-3.82]	3.87 [3.62-4.14]	4.00 [3.70-4.33]	4.02 [3.70-4.38]		
1	Misaligned	Incongruent Low	1.42 [1.13-1.67]	1.61 [1.40-1.82]	1.91 [1.71-2.13]	2.26 [2.07-2.47]	2.45 [2.23-2.67]	2.50 [2.24-2.76]		
1	Misaligned	Incongruent High	3.24 [2.80-3.70]	3.40 [3.06-3.75]	3.60 [3.33-3.86]	3.74 [3.46-4.02]	3.78 [3.47-4.11]	3.79 [3.47-4.13]		
2	Misaligned	Congruent Low	2.03 [1.66-2.37]	2.25 [2.01-2.50]	2.53 [2.33-2.74]	2.74 [2.53-2.96]	2.80 [2.57-3.04]	2.80 [2.57-3.06]		
2	Misaligned	Congruent High	3.66 [3.21-4.08]	3.80 [3.45-4.12]	3.96 [3.71-4.22]	4.07 [3.80-4.38]	4.10 [3.81-4.46]	4.10 [3.81-4.47]		
2	Misaligned	Incongruent Low	1.75 [1.34-2.17]	2.25 [2.00-2.52]	2.74 [2.48-2.99]	2.97 [2.74-3.22]	3.01 [2.77-3.27]	3.01 [2.77-3.28]		
2	Misaligned	Incongruent High	2.98 [2.52-3.43]	3.37 [3.06-3.71]	3.75 [3.45-4.08]	3.97 [3.70-4.28]	4.02 [3.74-4.34]	4.03 [3.74-4.35]		
3	Misaligned	Congruent Low	1.89 [1.57-2.23]	2.03 [1.78-2.29]	2.21 [2.02-2.39]	2.38 [2.22-2.54]	2.43 [2.25-2.62]	2.44 [2.25-2.64]		
3	Misaligned	Congruent High	2.87 [2.41-3.29]	3.17 [2.88-3.48]	3.55 [3.28-3.83]	3.84 [3.59-4.10]	3.93 [3.64-4.22]	3.94 [3.64-4.25]		
3	Misaligned	Incongruent Low	1.52 [1.20-1.80]	1.73 [1.50-1.96]	2.05 [1.85-2.27]	2.42 [2.23-2.60]	2.61 [2.42-2.80]	2.65 [2.43-2.89]		
3	Misaligned	Incongruent High	2.63 [2.20-3.02]	2.96 [2.69-3.25]	3.43 [3.16-3.72]	3.85 [3.59-4.15]	4.00 [3.71-4.34]	4.03 [3.72-4.40]		

Appendix C

Criterion estimates

737 The criterion estimates are shown in the supplementary material for completeness and are
738 only briefly described here. Across all participants, there was a higher bias toward
739 responding different in the high conditions compared to the low conditions. Participants 1
740 and 2 had only a negligible change in that bias across the time course and between
741 alignment conditions; however, participant 3 had a higher bias towards responding “same”
742 at the shortest response signal lag (50 ms) in across all items conditions and in both
743 alignment conditions.