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Redundancy effects in the processing of emotional faces

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How does the visual system represent the ensemble statistics of visual objects? This question has received intense interest in vision research, yet most studies have focused on the extraction of mean statistics rather than its dispersion. This study focuses on another aspect of ensemble statistics: the redundancy of the sample. In two experiments, participants were faster judging the facial expression and gender of multiple faces than a single face. The redundancy gain was equivalent for multiple identical faces and for multiple faces of different identities. To test whether the redundancy gain was due to increased strength in perceptual representation, we measured the magnitude of facial expression aftereffects. The aftereffects were equivalent when induced by a single face and by four identical faces, ruling out increased perceptual strength as an explanation for the redundancy gain. We conclude that redundant faces facilitate perception by enhancing the robustness of representation of each face.

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1. Introduction

Rapid processing of emotional stimuli that connote fear, anger, or happiness is an important skill in social interactions. One type of emotional stimuli that humans frequently encounter is facial expression. For example, fearful faces often reflect a potential threat. Their emotional content can be perceived without awareness and with minimal attention (Morris, Öhman, & Dolan, 1999; Vuilleumier et al., 2001). Although much research has focused on the perception of facial expression, most of this work has been restricted to the perception of an isolated face. Every day, however, we often encounter more than one person at a time. How does the simultaneous presence of multiple faces influence the perception of facial expression and identity?

Several studies suggested that perceptual averaging occurs when different facial expressions are shown simultaneously. When shown multiple morphed faces depicting different levels of an expression (e.g., sad), participants were able to rapidly extract the mean intensity of the expression (Haberman & Whitney, 2007, 2009). In addition, a valence-neutral face is judged more positively when accompanied by a happy face than an angry face (Sweeny et al., 2009; see also Tamietto et al., 2006). The concept of perceptual averaging is important in vision research because perceptual averaging simplifies the coding of multiple objects. Rapid extraction of the mean of visual stimuli has been demonstrated for size (Chong & Treisman, 2003, 2005) and orientation perception (Parkes et al., 2001), as well as for the perception of facial expression (Haberman & Whitney, 2007, 2009), gender (Haberman & Whitney, 2007) and identity (de Fockert & Wolfenstein, 2009).

The studies reviewed above have shown that the mean, or "central tendency," of a sample of visual stimuli affects perception. Other studies have shown that the dispersion of the sample also matters. The efficiency of mean size extraction is higher when the sample stimuli have normal, uniform, or homogeneous distribution than when the distribution is skewed (Chong & Treisman, 2003). In addition, outliers in a sample are discounted when people estimate mean facial expression (Haberman & Whitney, 2010). Finally, redundant information in a sample of visual stimuli affects perception and memory. For example, Miller (1982) found that people were faster detecting a target when two copies, rather than one, were shown. The redundancy gain is also found with complex stimuli. People remembered a neutral face better when it was shown along with three identical copies than when it was shown in isolation (Jiang et al., 2010). However, the underlying mechanism for the redundancy gain remains controversial (Corballis, 1998; Fischer & Miller, 2008; Mordkoff & Yantis, 1991).

The purpose of the present study is to examine the impact of visual redundancy on the perception of emotional faces. We compare the perception of a single emotional face with that of multiple emotional faces depicting the same expression. Theoretically, any of three patterns is possible: no difference, a redundancy cost, or a redundancy gain.

First, it is possible that when multiple emotional faces are shown, their mean facial expression is automatically encoded (*the averaging model*). Perceptual averaging occurs rapidly and automatically (Chong & Treisman, 2003; Haberman & Whitney, 2009). A simple averaging model states that the signal from a

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sample equals the mean of the sample. It does not include improvements to the reliability of the sample estimate. In turn, no difference should be observed between the multiple-face and single-face conditions.

Alternatively, a redundancy cost may be expected if multiple faces compete for neural representation, suppressing the encoding of any single one. It is known that multiple stimuli compete for neural representation in the visual cortex (Desimone & Duncan, 1995; Kastner et al., 2001). The competition leads to sensory suppression of individual stimuli. Several areas of the visual cortex, including areas V2, V4, MT, MST, and the inferior temporal cortex, demonstrate neural suppression when multiple objects are presented (Desimone & Duncan, 1995). Such suppression may result in less efficient coding of faces in the multiple-face condition compared with the single-face condition (*competition and suppression account*).

Finally, a redundancy gain is expected on a *summation account*. If signals from different faces are summed up, this may convey an advantage compared with the single-face condition. The summation account is consistent with the idea of ensemble coding, which goes beyond simple perceptual averaging by pooling signals across multiple samples (Alvarez, 2011; Parkes et al., 2001).

Previous studies using simple stimuli such as rectangles have led to several accounts of the redundancy gain: *race model*, *co-activation accounts*, *or interactive race model*. The *race model* proposes that multiple targets "race" for the control of response, with the one processed fastest winning the race (Corballis, 1998; Reuter-Lorenz et al., 1995). Because the race is controlled by the fastest processing face, holding the mean constant, the more diverse the sample, the higher the redundancy gain. Specifically, when each display contains identical faces, trials with slowly-processed faces will yield long response times, trials with rapidly-processed faces will yield short response times, so the average across all trials will trend toward the mean processing speed of the various faces. But when each display contains different faces, the fastest face among the set wins the race on that trial, resulting in short response time on every trial. The average across all trials will trend toward the minimum, rather than the mean, processing speed of the various faces. The race model therefore predicts a substantial redundancy gain for multiple, different faces, and a negligible gain for multiple, identical faces, compared with a single face.

The co-activation model suggests that signals from multiple targets are summed up (Miller, 1982; Ulrich, Miller, & Schröter, 2007). Unlike the *race model*, the *co-activation model* proposes that multiple stimuli do not race against each other. Instead, the signals are pooled into a single large signal, leading to faster responses to multiple redundant stimuli. This model therefore predicts a substantial redundancy gain for multiple faces, and that the gain should be equivalent for multiple different faces and multiple identical faces.

Finally, the *interactive model* assumes that multiple targets set up a race much like that of the *race model*. At the same time, however, signal from multiple targets are pooled much like the *co-activation model* (Mordkoff & Yantis, 1991). This model thus predicts a large redundancy gain for multiple different faces, and a smaller but still significant redundancy gain for multiple identical faces.

The present study was designed to test how visual redundancy affects the perception of facial expression and face identity. We will examine whether multiple emotional faces incur a cost, a gain, or no change, compared with a single face. In addition, our study will help evaluate the different models of redundancy gain. Experiments 1 and 2 aimed to test the direction of the redundancy effects in the perception of multiple emotional faces. Experiment 3 examined whether the redundancy effect reflects changes in the strength of perceptual representation of facial expressions.

2. Experiment 1: Facial expression detection

In this experiment, we asked participants to judge whether a display of faces depicted a neutral expression or a fearful expression. We chose fearful expression due to the large number of existing studies that had examined fear rather than other emotions. Expression type – neutral or fearful – was varied in orthogonal to visual redundancy. To study redundancy effects, we tested subjects in three types of displays (Fig. 1). In the baseline *single-face* condition, the display contained a single face presented in one of four visual quadrants. In the *redundant-different-identity* condition, the display contained four different individuals depicting the same expression. In the *redundant-same-identity* condition, the four faces were identical. Our main purpose was to examine whether redundant stimuli altered expression detection. Furthermore, we included the *redundant-different-identity* and *redundant-same-identity* conditions to help assess the different models of redundancy gain.

2.1. Method

2.1.1. Participants

All participants in this study were students at the University of Minnesota. They had normal or corrected-to-normal visual acuity and were 18–35 years old. All participants provided written consent. Participants received $10/h or extra course credit for their time. In Experiment 1, 28 participants (20 females and 8 males; mean age 20.3 years) completed the task, 16 in Experiment 1A and 12 in Experiment 1B. The two versions of the experiment were similar except for the location predictability of the multiple-face conditions, as explained next.

2.1.2. Apparatus

Participants were tested individually in a room with normal interior lighting. They sat unrestrained about 40 cm away from a 19″ CRT screen (resolution 1024 × 768 pixels; refresh rate: 75 Hz). The experimental program was created in Psychtoolbox (Brainard, 1997; Pelli, 1997) implemented in MATLAB (www.mathworks.com).

2.1.3. Stimuli

We used 28 faces from the Ekman database (Ekman & Friesen, 1976), including 7 fearful male faces, 7 fearful female faces, 7 neutral male faces, and 7 neutral female faces. The images were converted into gray scale, and cropped by a uniform oval that preserved the internal features of the faces while minimizing external features. All images were front view faces subtending 8° × 8° at a viewing distance of 40 cm. The background was gray.

Faces were presented in four visual quadrants; the center of each face was 5.74° away from the fixation point (Fig. 1). In the *redundant-different-identity* condition, four faces from the same gender but different identities were presented, one in each quadrant. They all depicted the same facial expression: all neutral, or all fearful. In the *redundant-same-identity* condition, a face was duplicated four times, with one copy in each visual quadrant. In the *single* face condition, a face was presented at a selected quadrant. The position of the single face was randomly determined from trial to trial in Experiment 1A, but was fixed for an entire block of 63 trials in Experiment 1B (and counterbalanced across blocks). We ran both versions of the experiment to ensure that results were not specific to whether the position of the single face was predictable or not. The two versions of the experiment were otherwise identical.

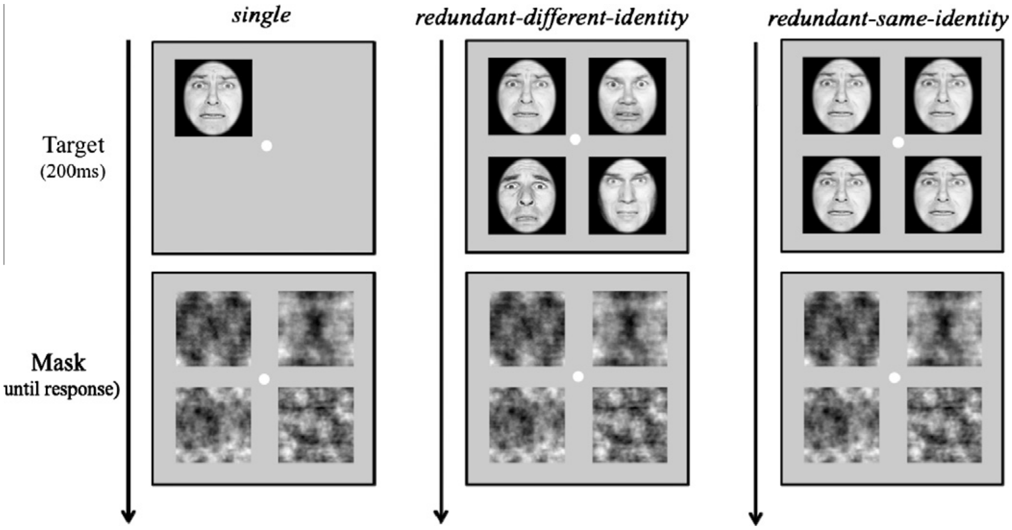

Fig. 1. Trial sequence used in Experiment 1 for three redundant conditions depicting a fearful expression. Participants classified the facial expression as neutral or fearful. All faces on a given display had the same gender and expression. The figure was not drawn to scale.

2.1.4. Procedure

Participants performed an expression detection task. On each trial, a white central fixation point was presented for 500 ms, followed by the face display. The face display was presented briefly, for 200 ms, to reduce eye movements to individual faces. Phase-scrambled masks immediately followed the face displays until participants made a response (Fig. 1). Participants pressed "N" for neutral faces and "F" for fearful faces. Feedback immediately followed each response in the form of a green fixation point for 120 ms for a correct response, or a red fixation point for 1000 ms for an incorrect response. Fig. 1 illustrates the trial sequence.

2.1.5. Design

Participants completed 504 trials, divided randomly and evenly into two facial expression conditions (fearful vs. neutral) and three redundancy conditions (*single*, *redundant-different-identity*, *redundant-same-identity*). Female and male faces were evenly distributed in these conditions. Participants were given a break every 63 trials.

2.2. Results

Results were not affected by whether the position of the single face was random (Experiment 1A) or predictable in a block of trials (Experiment 1B), as the interactions between the experimental version and other experimental variables were not significant in either d' or RT, all $ps > .10$. Therefore, we pooled data across all 28 participants. The Supplementary material includes data for Experiments 1A and 1B separately.

2.2.1. Accuracy

Because the response (fearful or neutral) was not orthogonal to stimulus type (fearful faces or neutral faces), we calculated accuracy in terms of d' (Fig. 2). Responding "fearful" when shown fearful faces was considered a hit, whereas responding "fearful" when shown neutral faces was considered a false alarm.

An ANOVA on redundancy condition revealed a significant main effect in d', $F(2,54) = 7.08$, $p = .002$. Paired-samples t-test showed that d' was significantly higher in the *redundant-different-identity* condition and the *redundant-same-identity* condition than the *single-face* condition, $t(27) = 3.83$, $p = .001$; $t(27) = 2.28$, $p = .03$, respectively. However, the two redundant conditions did not differ from each other, $t(27) = 1.38$, $p = 0.18$. Thus, accuracy in classifying facial expressions showed a significant redundancy gain for both multiple different faces and multiple identical faces. Because overall accuracy was high (over 90% in the two multiple-face conditions), it is important to also evaluate redundancy gain in RT.

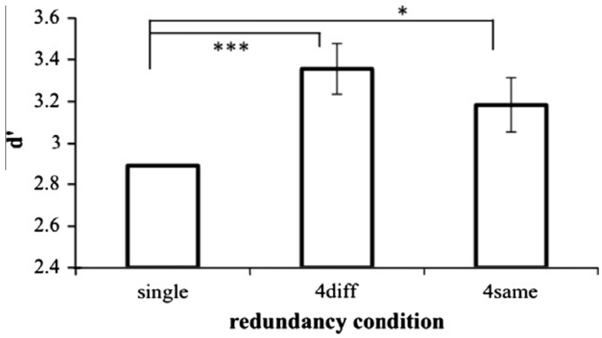

Fig. 2. Sensitivity (d') in classifying facial expression of Experiment 1. Error bars = ±1 S.E. of the difference between the single-face condition and other conditions. Single: single-face; 4diff: redundant-different-identity; 4same: redundant-same-identity condition. $^{*}p < .05$, $^{***}p < .001$.

2.2.2. RT

In the RT analysis, we did not include incorrect trials, or trials whose RT was shorter than 200 ms or longer than 4 SD of a subject's mean RT. About 0.8% of trials were removed as outliers. Fig. 3 shows RT data, separately for fearful and neutral faces.

An ANOVA on expression (neutral or fearful) and redundancy condition revealed a marginal effect of expression, as people were moderately slower in responding to fearful faces than to neutral faces, $F(1,27) = 3.37$, $p < .078$. The main effect of redundancy condition was significant, $F(2,54) = 35.11$, $p < .001$. RT was significantly faster in the two multiple-face conditions than the single face condition, all p-values < .01. RT did not differ between the two redundant conditions, $ps > .20$. The redundancy gain from multiple faces held for both fearful faces ($F(2,54) = 34.31$, $p < .001$) and neutral faces ($F(2,54) = 11.24$, $p < .001$), leading to a lack of interaction between expression and redundancy condition, $F(2,54) = 2.57$, $p = .086$.

2.3. Discussion

Experiment 1 investigated whether the categorization of facial expression was affected by the presence of multiple faces depicting

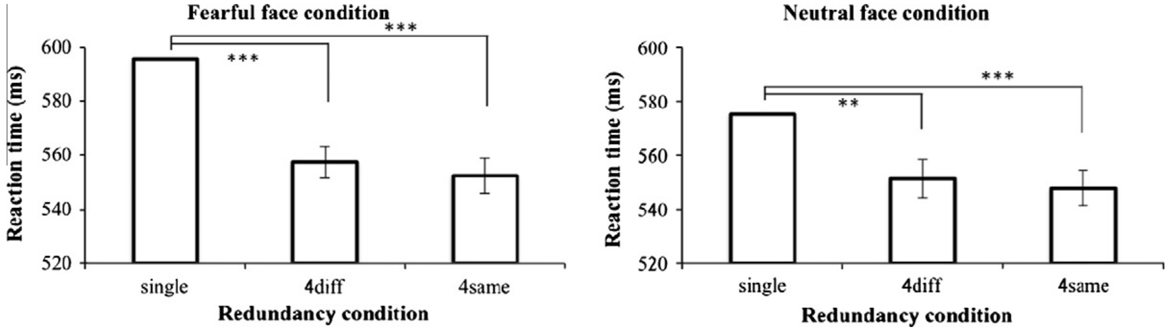

Fig. 3. RT results from Experiment 1's expression classification task. Error bars = ± 1 S.E. of the difference between the single-face condition and other conditions. Condition labels were the same as in Fig. 2. $^{**}p < .01$, $^{***}p < .001$.

the same facial expression. Our results showed a redundancy gain, as d' was higher and RT was faster when the display contained multiple faces rather than a single face. The presence of a redundancy gain suggests that a simple perceptual averaging account cannot fully explain how multiple faces are represented. In addition, the data do not support the competition and suppression account, according to which multiple different faces compete for neural representation and hence suppress the processing of individual faces.

Our study also sheds light on the mechanisms underlying the redundancy gain. Three theories had been proposed to account for redundancy gain in detecting multiple targets: race model, co-activation theory, and interactive model. The race model emphasizes the winner, or the face leading to a fastest response. The more diverse the sample (holding the mean constant), the more likely that an extremely fast race would be observed. Consequently, the race model predicts a large redundancy gain when multiple faces differed in identity, but a negligible gain when multiple faces were identical. The co-activation model, on the other hand, emphasizes the summation of signals from multiple faces. This model therefore predicts equivalent gain for multiple identical faces and multiple different faces. In Experiment 1, the redundancy gains in both d' and RT were substantial and comparable between the multiple-identical and multiple-different faces. These data therefore provide support for the co-activation theory. An element of the co-activation theory is the summation of signals from multiple faces (Alvarez, 2011; Parkes et al., 2001). Such summation can occur if the different exemplars are encoded by partially separate pools of neurons, an assumption supported by recent behavioral and neuroimaging studies on the perception of neutral stimuli (Afraz & Cavanagh, 2008).

Redundant coding of the same face by separate pools of neurons may seem incongruent with the efficient coding hypothesis (Barlow, 1961), according to which neuronal coding of information attempts to be most efficient (e.g., the number of spikes needed to transmit a signal is minimized). However, redundant neural coding is computationally advantageous, as it provides location information about the stimuli. In addition, degradation in a subset of these neurons can be compensated by the function of the remaining neurons, contributing to graceful degradation in neural representation.

3. Experiment 2: Gender discrimination

The purpose of Experiment 2 is to replicate Experiment 1 in a face identification task. Given that the brain mechanisms supporting expression recognition are dissociable from those supporting face identification (Bruce & Young, 1986; Haxby, Hoffman, & Gobbini, 2002; Winston et al., 2004), a replication of Experiment 1 would provide converging evidence for the redundancy gain of face processing.

3.1. Method

3.1.1. Participants

Sixteen new participants (12 females and 4 males; mean age 20.1 years) completed Experiment 2.

3.1.2. Apparatus, stimuli, procedure, and design

This experiment was the same as Experiment 1A except that participants were asked to perform a gender classification task. They pressed "M" for a display of male faces and "F" for a display of female faces. Half of the displays were males and the other half were females. Within each gender, half of the displays involved neutral expressions and the other half were fearful. A display may contain one face, four identical faces, or four different faces of the same gender and expression.

3.2. Results and discussion

3.2.1. Accuracy

We calculated d' in gender classification (Fig. 4). Responding "female" when shown female faces was considered a hit, whereas responding "female" when shown male faces was considered a false alarm. To be parallel to Experiment 1, d' was calculated for neutral and fearful faces separately. We conducted an ANOVA using expression type (neutral or fearful) and redundancy condition as factors. Gender discrimination was more accurate when the faces were neutral rather than emotional, $F(1,15) = 8.08$, $p < .02$ (see Supplementary materials). In addition, d' was influenced by redundancy conditions, $F(2,30) = 7.07$, $p < .005$. Planned contrasts showed that d' was lower in the *single-face* condition than the two multiple-face conditions (single vs. 4diff: $t(15) = 3.06$, $p < .01$; single vs. 4same: $t(15) = 2.93$, $p = .01$.), which did not differ from each other, $t(15) < 1$ (see Fig. 5).

3.2.2. RT

RT was equivalent between fearful face and neutral face conditions, $F(1,15) = 1.59$, $p > .20$. It was faster when the display had multiple faces than a single face, $F(2,30) = 56.29$, $p < .001$. This pattern held for both fearful faces and neutral faces, resulting in a lack of interaction between redundancy and expression, $F < 1$. Planned contrast showed that RT was slower in the *single-face* condition than the multiple-face conditions, smallest $t(15) = 6.31$, $p < .001$. In addition, RT was comparable between the *redundant-same-identity* condition and the *redundant-different-identity* condition, largest $t(15) = .711$, $ps > .40$.

Experiment 2 replicated Experiment 1 using a gender classification rather than an expression task. In both RT and d', we observed a significant redundancy gain for multiple faces compared with a single face. These data support the co-activation model, indicating that ensemble coding of multiple faces leads to summation of the signal (Parkes et al., 2001).

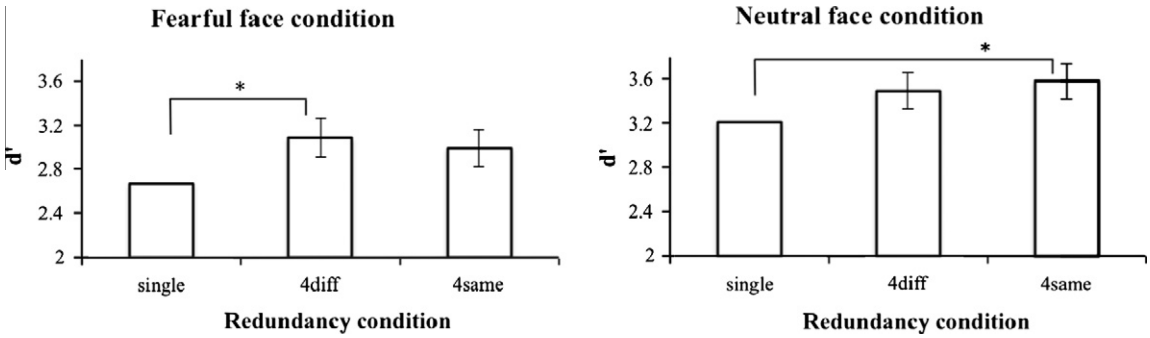

Fig. 4. Sensitivity (d') in gender classification in Experiment 2. Error bars = ±1 S.E. of the difference between the single-face condition and other conditions. Condition labels were the same as in Fig. 2. $^{*}p < .05$.

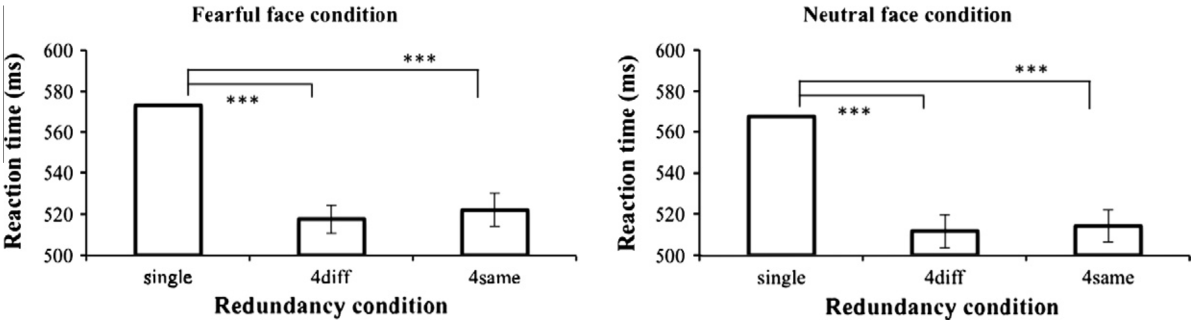

Fig. 5. RT results from Experiment 2. Error bars = ±1 S.E. of the difference between the single-face condition and other conditions. Conditions labels were the same as in Fig. 2. $^{***}p < .001$.

4. Experiment 3: Adaptation to facial expression

Experiments 1 and 2 showed that people were more accurate and faster at classifying facial expression or gender when presented with four faces of the same expression and gender rather than a single face. However, the underlying mechanism of how signals from multiple faces are pooled remains unclear. There are two main possibilities: perceptual summation may strengthen the perceptual representation of emotion from multiple faces, and statistical summation may lead to more reliable sampling of an emotion.

To test whether the presence of multiple faces increased the strength of perceptual representation, Experiment 3 examines the face expression aftereffect (Adams et al., 2010; Afraz & Cavanagh, 2008; Skinner & Benton, 2010). Because the redundancy gain from the *redundant-same-identity* condition could not be accounted for by a race model and was the main basis for the summation proposal, our investigation focused on the comparison between a single emotional face and four identical emotional faces.

The stimuli and experimental paradigm used here were taken from Skinner and Benton (2010), who showed that an average face (the "prototype") appeared emotional after prolonged viewing of an anti-expression face. For example, morphing facial expression from an average expression in linear trajectory through an average face to a point opposite fear creates an anti-fear face. After about a minute of looking at the anti-fear face, people perceive a neutral face as fearful. Fig. 6 illustrates the adaptation effect. The new feature of Experiment 3, compared with Skinner and Benton (2010), is that we evaluated the magnitude of the expression aftereffect after viewing a single face or four identical faces. Summation may strengthen the perceptual representation of the expression, in which case the aftereffect should be stronger after viewing four identical faces than a single face. Alternatively, summation may increase the accuracy of representing a specific expression without an increase in perceptual strength. If this is the case, then viewing multiple identical faces should not increase the intensity of the facial expression aftereffect.

Fig. 7 illustrates three types of adapters: a single emotional face presented in one of the four quadrants (*single*), four identical emotional faces, one in each quadrant (*redundant-same-identity*), and a single emotional face presented at fixation (*center*). In all trials, the same neutral testing stimulus was presented for people to categorize its perceived emotion. Because face aftereffect is retinotopic (Afraz & Cavanagh, 2008), we presented the testing stimulus – the prototype – at the same location as an adapting stimulus. We assessed the degree to which people perceived the testing stimulus as the anti-expression of the adapter faces.

Our main interest is to compare aftereffects from viewing a *single* face with the aftereffects from viewing *redundant-same-identity* faces. To help interpret possible null results, we also included conditions that would result in greater perceived aftereffects; the *center* condition was one such condition. Because the receptive fields of face cells are more concentrated toward the fovea (Afraz & Cavanagh, 2008), we expect adaptation to be stronger in the *center* condition than the *single* condition (periphery). In addition, we included both extreme anti-expression faces (the "100% anti" faces), and less extreme anti-expression faces (the "50% anti" faces, created by morphing the 100% anti faces with the average). We expect the aftereffects to be stronger with 100% anti faces than 50% anti faces. If the strength of perceptual representation increased after viewing redundant faces, then the aftereffects should increase, much as they would increase when comparing *center* and *single* faces, or when comparing 100% anti faces and 50% anti faces.

4.1. Method

4.1.1. Participants

Sixteen participants completed Experiment 3 (8 females and 8 males, mean age 21.1 years). Eight participants adapted to 100% anti-expression faces and the other 8 adapted to 50% anti-expression faces. An additional sixteen participants completed a modified version of

Fig. 6. A demonstration of the facial expression aftereffect. After adapting to the left face for about 30 s, the middle ("prototype") face appears happy. After adapting to the right face for about 30 s, the middle face appears sad.

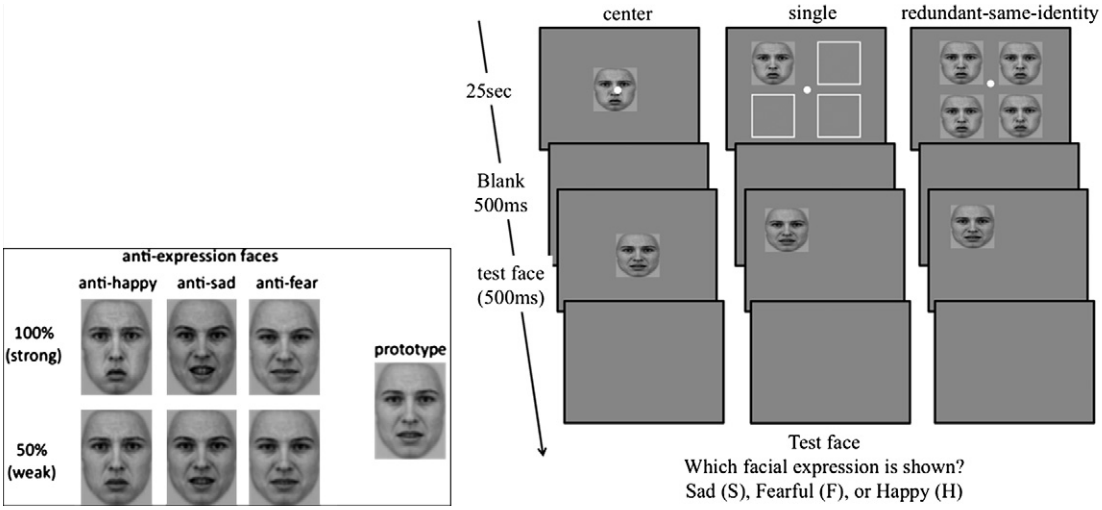

Fig. 7. Left: three types of anti-expression faces and a prototype face. The upper row shows 100% (strong) anti-expression faces and the bottom row shows 50% (weak) anti-expression faces. Right: A schematic illustration of trial sequences used in Experiment 3. The test face was presented at the same location as an adapter face. The figure was not drawn to scale.

Experiment 3 using 100% anti-expression stimuli (see Supplementary material).

4.1.2. Stimuli

We used three anti-expression faces and a prototype face from Skinner and Benton (2010). The prototype was an average from all faces (regardless of facial expressions) and appeared neutral (or ambiguous). In addition, there was one average face for each of three facial expressions: fearful, sad, and happy. Anti-expression was created by morphing an average emotional face (e.g., the fearful face) in a linear trajectory through the overall prototype face to a point opposite the original expression. For 100% anti-expression, the distance between the opposite side and the prototype was the same as that between the original expression and the prototype. For 50% anti-expression, the former distance was half of the latter. The size of a face was 8° × 8°, and the distance between the fixation and the centers of a face was approximately 7.2°.

4.1.3. Procedure

On each trial participants first viewed an adapter display for 25 s. Similar to Skinner and Benton (2010), the adapter moved around its own center point once every 5 s in a circular trajectory 1° in diameter. Participants were asked to maintain fixation. To ensure that participants had maintained fixation, the fixation flickered unpredictably (once every 5 s on average) and participants were asked to press the spacebar when they detected the flicker. The start position of the adapter was randomly selected. A blank screen followed the adapter for 500 ms, after which the neutral face was shown for 500 ms at the final location of the adapter (in the *single* and *center* conditions), or the final location of a random one of the adapters (in the *redundant-same-identity* condition). The same probe face – a neutral (prototype) face – was shown on all trials. Participants' task was to classify the facial expression of the probe by pressing one of three keys: "H" for happy, "S" for sad, and "F" for fearful. Participants had as much time as they wanted to make the response. A demo of the trials can be found at: http://jianglab.psych.umn.edu/Demos/Entries/2012/11/1_Processing_multiple_faces.html.

The experiment had 90 trials, divided into 10 blocks. The nine trials in each block were produced by crossing two factors: three adapter expressions (anti-happy, anti-sad, or anti-fearful) and three adapter redundancy conditions (*center*, *single*, or *redundant-same-identity*). In the *center* adapter condition, there was one anti-face presented at the center of the display where subjects fixated. In the *single* adapter condition, there was one anti-face at one randomly selected visual quadrant. In the *redundant-same-identity* condition, there were four anti-faces, one in each quadrant (Fig. 7). Trials were presented in a random order. Half of the participants were tested using the 100% antiface, whereas the other half were tested using the 50% antiface. The experiment took about 50 min to complete.

4.1.4. Data analysis

Although there were no right or wrong answers, we classified a response as “correct” if participants selected the facial expression that was the anti-expression of the adapter. For example, if the adapter display was an anti-sad face, and participants categorized the probe as “sad”, then the response was classified as “correct.” Chance was 33.3%.

4.2. Results and discussion

We observed a significant facial expression aftereffect, as the overall accuracy was 72.9% for people tested with 100% anti-faces, and 61.1% for people tested with 50% anti-faces. Both of these values were significantly higher than chance (33%), $ps < .001$, although adaptation was stronger following the 100% anti-faces than the 50% anti-faces, $F(1,14) = 12.80$, $p = .003$. Fig. 8 shows accuracy for the two groups of participants, separately for different prime redundancy conditions and different expression types.

Because anti-face intensity (100% or 50%) did not interact with any other factors, we pooled data across all participants. An ANOVA using adapter expression type (sad, happy, or fearful) and adapter redundancy condition (*center*, *single*, or *redundancy-same-identity*) revealed a significant main effect of adaptor redundancy, $F(2,30) = 9.60$, $p = .001$. In addition, the main effect of adapter expression type was significant, $F(2,30) = 22.03$, $p < .001$. The aftereffects were stronger for anti-happy than anti-sad, replicating previous results (Skinner & Benton, 2010). However, adapter expression type did not interact with redundancy condition, $F(4,60) = 1.23$, $p = .31$. Planned contrasts showed that aftereffects were stronger for the *center* adapter than the *single* (periphery) adapter, $F(1,15) = 13.37$, $p = .002$, and for the *center* adapter than the *redundant-same-identity* adapter, $F(1,15) = 14.83$, $p = .002$. Critically, aftereffects were equally strong for the *single* adapter and the *redundancy-same-identity* adapter, $F < 1$. The lack of an effect for *single* vs. *redundancy-same-identity* held for all expressions and both adapter strength, all $ps > .05$. Similar results were found in an additional experiment that used the 100% anti- expressions. This additional experiment controlled for the predictability of the probed face. Specifically, in the *redundant-same-identity* condition, test probe appeared at the same location on all trials (e.g., the upper left of the four adapters). Data from 16 new participants replicated Experiment 3: facial expression aftereffect was stronger in the *center* face than the *single* face and *redundant-same-identity* conditions, which did not differ from each other (Supplementary material).

Because face aftereffect is sensitive to retinotopic location (a stronger effect in a foveal than peripheral location), in a follow-up study we repeated Experiment 3 but presented the faces closer to the center of fixation. For this additional experiment ($N = 9$), the size of a face was 4° × 4°, and the distance between the fixation and the centers of a face was approximately 4.2° (rather than 7.2° in Experiment 3). Even though the faces were closer to fovea, we continued to find equivalent aftereffects in the *redundant-same-identity* condition and the *single* face condition, $F < 1$.

Might the difference in time scale account for the presence of a redundancy gain in Experiments 1 and 2, but an absent of that effect in Experiment 3? While it is logically possible that summation only occurs transiently (Experiments 1 and 2) and then fades away with increased exposure (Experiment 3), we would have been more concerned if the data were the opposite (e.g., summation with prolonged exposure, but no summation with brief presentation). Redundancy effects had been shown with longer stimulus durations and in long-term memory (Jiang et al., 2010). Therefore, it is unlikely that the lack of a redundancy gain in Experiment 3 could be accounted for by its long exposure duration.

Thus, the experiment indicates that increasing the number of “tokens” for a particular emotional face does not induce noticeably stronger perceptual representation of that expression. That is, the redundancy gain in facial expression aftereffects is negligible. The redundancy gain shown in Experiments 1 and 2 is likely attributable to increased accuracy in sampling an emotion, rather than stronger perceptual representation of an expression.

5. General discussion

Humans live in an environment with constant social interaction with multiple people. Previous research on emotional processing has primarily focused on the processing of a single emotional face. Studies that used multiple emotional faces have presented faces of different emotions, such as a happy and an angry face (Sweeny et al., 2009), or a happy and a fearful face (Tamietto et al., 2006), or faces involving different intensity of an emotion (Haberman & Whitney, 2007, 2009). These previous studies provided evidence for perceptual averaging, as people could rapidly and accurately estimate the mean facial expression of multiple faces. The present study examined processing of multiple faces that share the same facial expression, a situation often encountered in daily life. We tested whether multiple same-expression faces would induce a redundancy gain, as expected from a summation model, whether they would induce a redundancy cost, as expected from a competition and suppression model, or whether they would lead to the same processing as a single emotional face, as expected from simple perceptual averaging. Our data revealed a pattern of redundancy gain, therefore ruling out perceptual averaging and visual suppression as adequate accounts for how multiple, redundant faces interact in their neural representation.

Because the redundancy gain was very strong in the *redundant-same-identity* condition, and was equivalent for the *redundant-same-identity* and the *redundant-different-identity* conditions, our data do not support the race model as a complete account for redundancy gain. Instead, the data are consistent with the co-activation model, according to which neural signals from multiple

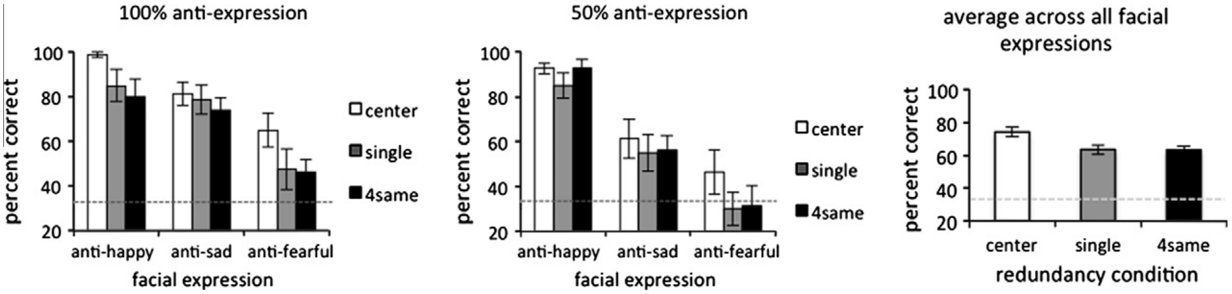

Fig. 8. Facial expression aftereffects in Experiment 3. Higher accuracy indicates a stronger aftereffect. 4same: redundant-same-identity. Half of the participants were adapted to 100% anti-expression faces, whereas the other half were adapted to 50% anti-expression faces. Dashed line indicates chance performance. Error bars show ±1 S.E. of the mean.

redundant stimuli summate. But what is the nature of that summation? In Experiment 3, we examined and rejected the idea that the redundancy gain originated from stronger perceptual representation of a facial expression. Facial expression aftereffects were equally strong for a single face and for four identical faces. This finding does not support a perceptual summation model. Rather, it suggests that there is statistical summation – an increase in the accuracy of representation for a specific facial expression, without a concomitant change in perceptual strength.

It is important to note that our study is not incompatible with previous studies revealing perceptual averaging of facial expressions. Had we found evidence for perceptual summation, our results would have been inconsistent with findings of perceptual averaging. Instead, what we have revealed is statistical summation, which is orthogonal to perceptual averaging. In particular, perceptual averaging corresponds to the central tendency of a sample of faces, but statistical summation corresponds to the reliability of the sample estimation. Our data are therefore compatible with ensemble coding models that incorporate both central tendencies and sample reliability (Alvarez, 2011; Parkes et al., 2001). The key idea in our study is that besides an ability to extract the central tendency, people's perception of facial expressions is also sensitive to the redundancy (statistical reliability) of a specific expression.

Our study leaves open the neural mechanisms that support redundancy gain. For example, it is unclear how redundancy gain relates to effects of within- and between- hemisphere processing. Because we used four faces occupying all four quadrants, we do not know whether the redundancy gain originates primarily from faces within a hemifield, faces from different hemifields, or both. We cannot rule out the possibility that summation occurs primarily for unilateral stimuli, and that (weaker) averaging or competition occurs primarily for bilateral stimuli (Sweeny et al., 2009).

In sum, by comparing face processing of a single face with that of multiple faces, our study demonstrated a redundancy gain in the processing of multiple faces of the same expression. Furthermore, the gain was substantial even when the multiple faces were identical. However, because multiple identical faces did not strengthen the facial expression aftereffects, the redundancy gain could not reflect perceptual summation. Our study supports the idea that when presented with multiple visual objects (such as faces), visual perception is sensitive not only to the mean of the sample, but also to the sample dispersion. Statistical summation of neural representation for multiple faces enhances the accuracy, but not the perceptual strength, of that representation.

Author contribution

Bo-Yeong Won designed the study, collected the data, analyzed the data, and wrote the paper. Yuhong Jiang designed the study, analyzed the data, and wrote the paper.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.visres.2012. 11.013.

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