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Effects of aging on face identification and holistic face processing

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ABSTRACT

Several studies have shown that face identification accuracy is lower in older than younger adults. This effect of aging might be due to age differences in holistic processing, which is thought to be an important component of human face processing. Currently, however, there is conflicting evidence as to whether holistic face processing is impaired in older adults. The current study therefore re-examined this issue by measuring response accuracy in a 1-of-4 face identification task and the composite face effect (CFE), a common index of holistic processing, in older adults. Consistent with previous reports, we found that face identification accuracy was lower in older adults than in younger adults tested in the same task. We also found a significant CFE in older adults that was similar in magnitude to the CFE measured in younger subjects with the same task. Finally, we found that there was a significant positive correlation between the CFE and face identification accuracy. This last result differs from the results obtained in a previous study that used the same tasks and which found no evidence of an association between the CFE and face identification accuracy in younger adults. Furthermore, the age difference was found with subtraction-, regression-, and ratio-based estimates of the CFE. The current findings are consistent with previous claims that older adults rely more heavily on holistic processing to identify objects in conditions of limited processing resources.

1. Introduction

Holistic processing is thought to be a critical component of face recognition in younger adults (e.g., Maurer, Le Grand, & Mondloch, 2002; Rossion & Boremanse, 2008). A common index of holistic processing is the composite face effect (CFE), sometimes referred to as the composite face illusion (Hole, 1994; Konar, Bennett, & Sekuler, 2010; Le Grand et al., 2004; Young, Hellawell, & Hay, 1987), and the most common way to estimate the CFE is to measure performance in a task that requires participants to discriminate faces composed of the top and bottom halves of different faces (Le Grand et al., 2004). Participants typically are shown two successive faces, and are instructed to judge whether the top halves of the two faces are the same or different. The bottom halves of the faces differ on every trial, and therefore provide no useful discrimination information. Performance is measured in an aligned condition, in which the top and bottom halves are aligned and therefore are perceived as a single face, and a misaligned condition, in which the top and bottom halves are shifted horizontally relative to each other. When the faces are upright, performance on "same" trials in the aligned condition typically is worse than in the misaligned condition, presumably because holistic processing produces greater interference when the top and bottom halves form a single perceptual unit. The CFE commonly is defined as the difference between response accuracy and/or response times (RTs) measured in aligned and misaligned conditions.

A common assumption in the face perception literature is that holistic processing is associated with adults' ability to recognize upright faces (Maurer, Le Grand, & Mondloch, 2002; Rossion, 2008). Konar, Bennett, and Sekuler (2010) tested this assumption by measuring the correlation between the magnitude of the CFE and face identification accuracy in 125 younger adults. Surprisingly, Konar et al. found that there was no correlation between the two measures. Using measures similar to the ones used by Konar et al., other investigators also have found small and non-significant correlations between the CFE and accuracy in face identification and recognition tasks (e.g., Richler, Cheung, & Gauthier, 2011). These results suggest that holistic processing, as indexed by the CFE, may not constrain accuracy in these face identification tasks. Alternatively, the subtraction-based CFE may not be a good measure of holistic processing, and indeed several investigations have described alternative measures of the CFE that may be better indices of holistic processing (DeGutis et al., 2013; Richler, Cheung, & Gauthier, 2011; Wang et al., 2012). One purpose of the current paper is to examine if the failure of Konar et al. to find a significant association between the CFE and face identification depends on the definition of the CFE.

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The current study also examines whether holistic processing remains intact across the adult lifespan, and whether the relationship between holistic processing, as indexed with CFE, and face identification changes with age. Many studies have shown that face processing deteriorates during normal aging (e.g., Grady, 2002; Grady et al., 2000; Grady et al., 1995; Habak, Wilkinson, & Wilson, 2008; Owsley, Sekuler, & Boldt, 1981; Resnick et al., 1995; Rousselet et al., 2009; Rousselet et al., 2010; Searcy, Bartlett, & Memon, 1999). These effects may reflect the fact that older adults are less sensitive to the information conveyed by horizontal facial contours (Obermeyer et al., 2012), which are especially important for identifying faces (Goffaux & Dakin, 2010; Pachai, Sekuler, & Bennett, 2013). Alternatively, these age-related changes in face perception may be due, in part, to age-related changes in holistic and/or configural processing, although the evidence on this point is equivocal. For example, older adults are generally less sensitive to changes in the spacing among face parts (Murray, Halberstadt, & Ruffman, 2010), and especially insensitive to changes in the horizontal separating between the two eyes (Chaby, Narme, & George, 2010). Also, using a memory-based version of the CFE similar to the one described by Young, Hellawell, and Hay (1987); which required participants to memorize names of faces and then identify the top halves of composite faces, Boutet and Faubert (2006) found evidence for holistic processing in younger, but not older, adults. On the other hand, Boutet and Faubert found that the face inversion effect, which some researchers (e.g., Rossion, 2008) have argued is an index of holistic processing (but see Gaspar, Sekuler, & Bennett, 2008; Pachai, Sekuler, & Bennett, 2013; Sekuler et al., 2004, for an alternative view), did not differ between age groups. Boutet and Faubert also found that the whole-part effect, another common index of holistic face processing (Tanaka & Farah, 1993), did not differ between younger and older adults. Finally, using a very different paradigm, Dror, Schmitz-Williams, and Smith (2005) found evidence suggesting that older adults are more likely than younger adults to use holistic processing of non-face objects in mental rotation tasks.

Given the conflicting accounts of the effects of aging on holistic processing and new evidence that older adults process facial information differently from young adults (Chaby, Narme, & George, 2010; Murray, Halberstadt, & Ruffman, 2010; Obermeyer et al., 2012), we used the methods described by Konar, Bennett, and Sekuler (2010) to examine whether older observers show evidence of holistic processing using a common metric of holistic face processing – i.e., the composite face task (Le Grand et al., 2004), and whether older observers make use of holistic processing differently than younger observers in the context of face identification.

2. Methods

2.1. Participants

A group of 49 older adults (60–82; $M = 68.6$, $SD = 5.93$; 21 male) participated in this experiment. All had normal or corrected-to-normal visual acuity (Snellen decimal acuity: $M = 0.96$; $SD = 0.23$), and each received $10/h for participation. All older adults except for one completed the Mini-Mental State Exam (MMSE) with a mean (*SD*) score of 29.04 (1.13) out of 30. The one person who did not complete the MMSE performed well (28/30) on the Montreal Cognitive Assessment. None of the participants reported having any neurological diagnoses that would interfere with the experiment, nor did they take centrally-acting medications. Results from 77 younger adults (17–25; $M = 19.25$, $SD = 1.78$; 22 male) previously tested in an identical experiment (Konar, Bennett, & Sekuler,2010, Experiment 2) were used for age comparisons.

2.2. Procedure

Each participant completed the CFE task first, followed immediately by the face identification task.

2.3. Composite face effect task

We used the same composite face task as Konar, Bennett, and Sekuler (2010), which utilized composite faces, consisting of the tops and bottoms of different faces, that were created by Le Grand et al. (2004, see Fig. 1a). There were 48 aligned and 48 misaligned trials, each trial consisting of two faces. In each alignment condition there were 24 *same* and 24 *different* top halves of faces (12 male in each case). An Apple G3 computer controlled stimulus presentation and response collection using Matlab, the Psychophysics and Video Toolboxes (Brainard, 1997; Pelli, 1997), and a 21-in. Apple Studio Display (75 Hz; 1152×870 pixels; $22.6° \times 17.1°$). From the viewing distance of 100 cm, the width and height of the aligned faces subtended visual angles of 5.4×8.2 deg, respectively. In the misaligned condition, the faces subtended 8.2×8.2 deg.

As in Konar, Bennett, and Sekuler (2010, Experiment 2), participants completed three blocks of aligned and misaligned trials, with each block consisting of 96 trials (48 trials per alignment). Sets of aligned and misaligned stimuli alternated during the experiment, and half of the participants started with aligned stimuli. On each trial, participants determined, as quickly and accurately as possible, whether the tops of two stimuli were the same or different. The bottoms differed on every trial, and therefore provided no information about the correct response. Participants were informed that the bottom halves were not informative, and so they should try to ignore the bottom halves and focus attention on the top halves of faces. The dependent measures were response time (RT) and accuracy, the latter indexed by d'. d' in the aligned and misaligned conditions were estimated from correct and incorrect responses using standard formulae for Same-Different designs (MacMillan & Creelman, 1991). To test whether younger and older adults had different response biases, we used the formula $-0.5 \times [z(\text{Hit}) + z(\text{FA})]$ to calculate the response criterion, c, a common measure of response bias (MacMillan & Creelman, 1991). Note that $c < 0$ corresponds to a bias to respond "same," whereas $c > 0$ corresponds to a bias to respond "different."

Two measures of the CFE, one based on response time (CFE*RT*) and another based on d'(CFE*d*), were estimated for each participant. CFE*RT* was calculated, as in most studies (e.g., Hole, 1994; Konar, Bennett, & Sekuler, 2010; Le Grand et al., 2004), by subtracting the median RT for correct misaligned trials from that for aligned trials for same trials only. CFE*d* was calculated by subtracting d' for aligned trials from d' for misaligned trials. We used d' rather than percent correct to reduce the influence of response bias, which may differ between younger and older adults (Searcy, Bartlett, & Memon, 1999). For both CFE measures, positive values indicate poorer performance in the aligned condition and negative values indicate poorer performance in the misaligned condition. The standard view of holistic face processing predicts that both measures should be positive. CFE*d* and CFE*RT* were calculated separately for each block, and then averaged across blocks.

2.4. Face identification task

The stimuli and task were the same as those used by Konar, Bennett, and Sekuler (2010, Experiment 2). The faces were displayed on a Sony Trinitron monitor with a resolution set to 1280×1024 pixels, which subtended 30.9×23.6 deg of visual angle at the viewing distance of 70 cm. For each of the 80 target-present stimuli used by Bruce et al. (1999); we constructed 11 images: a target face, a correct match, and nine distracters. On average,

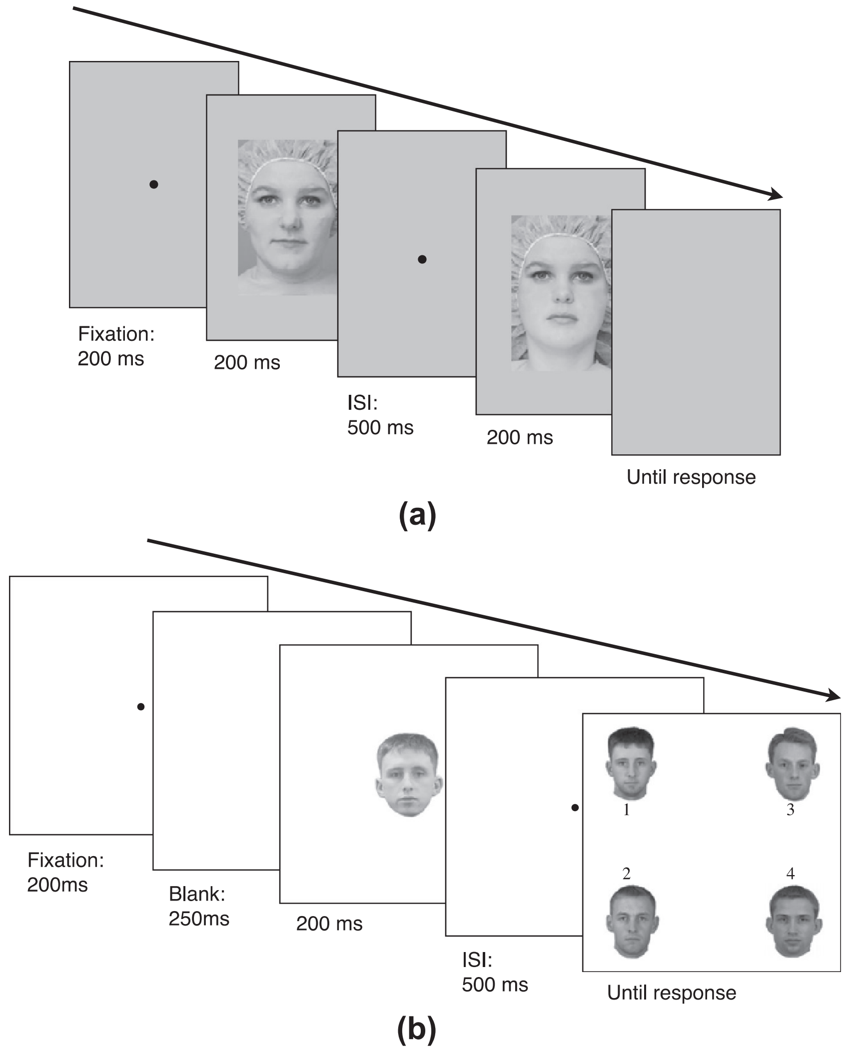

Fig. 1. (a) Example of an aligned trial in the composite face task. Stimuli were created by splitting grey-scale frontal-view faces (24 male and 24 female) horizontally across the middle of the nose and recombining top and bottom halves within gender (see Le Grand et al., 2004 for details). The two face halves were spatially aligned or misaligned. Aligned and misaligned stimuli were presented in separate blocks of 48 trials, and the order of the aligned and misaligned conditions was counterbalanced across participants. (b) Example of a trial from the 4-AFC identification task used in Experiment 2. A correct match was always present.

target faces subtended 5.8 × 8.2 deg and selection faces subtended 4.5 × 6.7 deg (see Fig. 1b). Target stimuli were presented for 200 ms, and were then followed by a display comprising four faces arranged in a 2 × 2 array. The participant's task was to select the face that matched the target. Importantly, the face that matched the target was taken with a different camera under slightly different lighting conditions, and therefore the task was not an image matching task. Auditory feedback was provided after each trial. Each participant completed three blocks of 80 trials, for a total of 240 trials. Proportion correct was estimated from all 240 responses.

3. Results

Data were analyzed with R (R Development Core Team,2011). The results are summarized in Table 1. Confidence intervals for CFE*RT* and CFE*d* were calculated using a bootstrap method described by Konar, Bennett, and Sekuler (2010).

In the face identification task, accuracy was significantly lower in older adults than younger adults ($t(124) = 5.74$, $p < 0.001$). In the CFE task, older adults had longer response times than younger adults in both the aligned ($t(124) = 6.72$, $p < 0.001$) and misaligned ($t(124) = 5.44$, $p < 0.001$) conditions. Older adults also had lower d' in both conditions (aligned: $t(124) = -5.52$, $p < 0.001$; misaligned: $t(124) = -4.94$, $p < 0.001$).

Table 1
Summary of results obtained with older and younger adults. The younger adults' data are from Konar, Bennett, and Sekuler (2010, Experiment 2).

	Mean	95% CI	Range
Older			
Face ID	62.9	(60, 65)	(38, 79)
RT (aligned)	878	(803, 953)	(565, 2006)
RT (misaligned)	785	(698, 818)	(451, 1565)
d' (aligned)	2.18	(2.01, 2.35)	(0.86, 3.53)
d' (misaligned)	2.59	(2.33, 2.86)	(−0.52, 4.49)
CFERT	120.1	(80, 160)	(−167, 579)
CFEd	0.42	(0.20, 0.64)	(−2.59, 1.85)
Younger			
Face ID	71.9	(70, 74)	(46, 88)
RT (aligned)	652	(627, 677)	(466, 1030)
RT (misaligned)	611	(590, 631)	(385, 912)
d' (aligned)	2.75	(2.63, 2.88)	(1.41, 4.06)
d' (misaligned)	3.28	(3.14, 3.43)	(0.42, 4.59)
CFERT	41.8	(27, 57)	(−154, 342)
CFEd	0.53	(0.40, 0.67)	(−2.42, 1.57)

The mean CFE*d* and CFE*RT* scores in younger and older participants were significantly different from zero (in both cases, $t \geqslant 3.8$, $p < 0.001$). Hence, both age groups exhibited significant CFEs. The CFE*d* scores in the two age groups did not differ significantly from each other ($t(124) = 0.94$, $p = 0.35$). There was, however, a group difference on CFE*RT*, with larger values in the older group ($t(124) = -4.22$, $p < 0.001$).

A measure of response bias, *c*, was calculated for each participant after averaging performance across the three blocks of the CFE task (Fig. 2). On average, the bias measures were slightly negative, which means that subjects had a slight bias to respond "same". The bias measures were analyzed with a 2 (Age) × 2 (Alignment) mixed-design ANOVA. The main effects of Age ($F(1,124) = 10.9$, $p = 0.0012$) and Alignment ($F(1,124) = 21.9$, $p < 0.001$) were significant, as was the Age × Alignment interaction ($F(1,124) = 50.4$, $p < 0.001$). In younger subjects, the mean value of *c* differed from zero ($F(1,76) = 30.06$, $p < 0.001$), but the simple main effect of Alignment was not significant ($F(1,76) = 0.56$, $p = 0.46$). In older subjects, the mean value of *c* also differed from zero ($F(1,48) = 43.6$, $p < 0.001$), but, for this group, the simple main effect of Alignment was significant ($F(1,48) = 78.7$, $p < 0.001$): *c* differed from zero for misaligned stimuli ($t(48) = -11.8$, $p < 0.001$), but not for aligned stimuli ($t(48) = -0.353$, $p = 0.76$). In summary, subjects had an overall bias to respond "same", and among older adults, but not younger adults, that bias was significantly greater in the misaligned condition.

Finally, we examined whether any of the above measures were correlated with age, expressed in years, separately in each age group. None of the correlations were significant except for the correlation between identification accuracy and age, which was significant in older adults ($r = -0.35$, $t(47) = -2.56$, $p = 0.014$) but not in younger adults ($r = 0.035$, $t(75) = 0.31$, $p = 0.76$).

3.1. Identification accuracy vs. *d′*

To assess the association between face identification accuracy and *d′* separately in the aligned and misaligned conditions of the CFE task, we constructed linear models that included identification accuracy as the dependent variable, and age, *d′*, and the age × *d′* interaction as predictor variables (Fig. 3). Note that this measure of *d′* is an index of sensitivity in each of the aligned and misaligned conditions; it is not a measure of holistic processing, CFE*d*, which requires a comparison across those conditions. Association strength was expressed as η^2, which is the proportion of the total variation in the dependent variable that is accounted for by a predictor variable. In both conditions, the effect of age was significant ($F(1,122) \geqslant 37$, $p < 0.001$, $\eta^2 = 0.21$), reflecting the fact that identification accuracy was lower in older adults. In each condition, after controlling for the effect of age, the effect of *d′* (aligned: $F(1,122) = 19.5$, $p < 0.001$, $\eta^2 = 0.11$; misaligned: $F(1,122) = 36.4$, $p < 0.001$, $\eta^2 = 0.18$) was significant, but the age × *d′* interaction was not (aligned: $F(1,122) = 0.01$, $p = 0.92$, $\eta^2 < 0.0001$; misaligned: $F(1,122) = 0.15$, $p = 0.70$, $\eta^2 = 0.0007$). These results indicate that face identification accuracy was linearly associated with sensitivity in face discrimination in the separate components of the CFE task—*d′* accounted for 11% and 18% of the variation in identification accuracy in the aligned and misaligned conditions—but that the association did not differ between age groups.

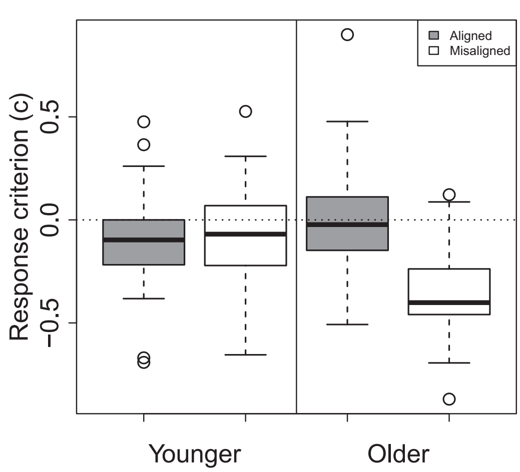

Fig. 2. Boxplots summarizing response criteria for younger and older adults. Bias to respond 'same' is indicated by negative values. Bias to respond 'different' is indicated by positive values. The median values of *c* are indicated by the horizontal lines in each boxplot.

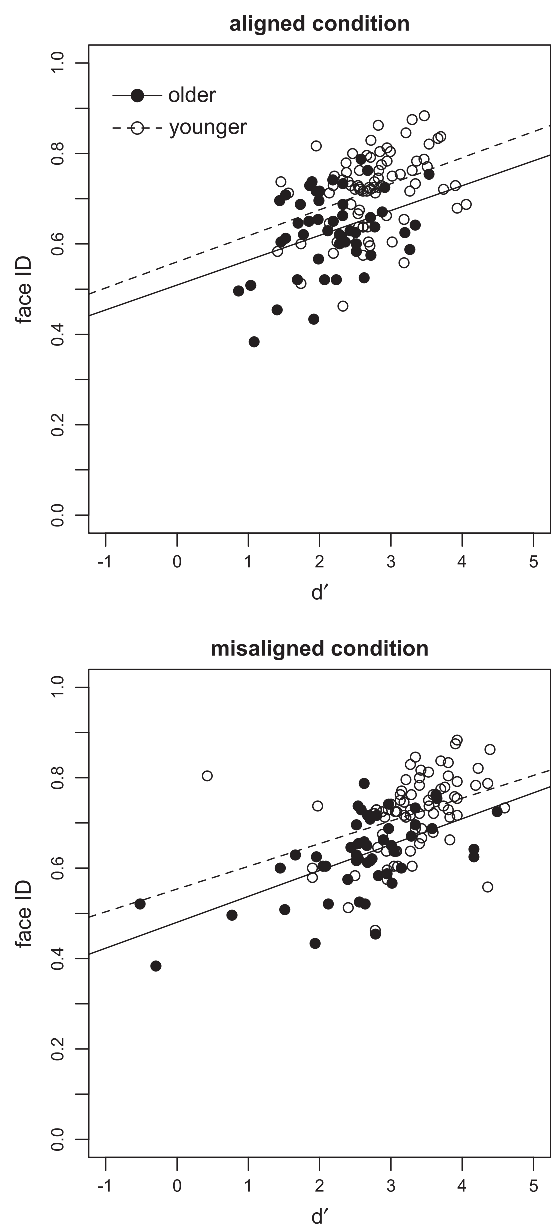

Fig. 3. Identification accuracy (proportion correct) plotted against *d′* in the aligned and misaligned conditions. In each plot, the dotted and dashed lines illustrate the fits of a linear model that contained an effect of age, *d′*, and the age × *d′* interaction. In each condition, the effects of age and *d′* were significant, but the interaction was not (i.e., the slopes of the lines did not differ significantly). Data from younger adults are from Konar, Bennett, and Sekuler (2010, Experment 2).

To examine if face identification was linked to the measure of holistic processing – CFE*d*, which is the difference between d' in the aligned and misaligned conditions – we altered the linear models by replacing the d' and age × d' predictor variables with CFE*d* and the age × CFE*d* interaction. After controlling for the effect of age ($F(1,122) = 34.9$, $p < 0.001$, $\eta^2 = 0.21$), the effect of CFE*d* ($F(1,122) = 6.96$, $p = 0.009$, $\eta^2 = 0.04$) and the age × CFE*d* interaction ($F(1,122) = 3.93$, $p = 0.05$, $\eta^2 = 0.023$) were significant (Fig. 4).

Separate analyses of the two age groups revealed that the effect of CFE*d* was significant in older adults ($F(1,47) = 11.47$, $p = 0.0014$, $\eta^2 = 0.20$), but not younger adults ($F(1,75) = 0.19$, $p = 0.66$, $\eta^2 = 0.003$). Next, we calculated the correlation between identification and CFE*d* in each age group. As a measure of association, we prefer Spearman's ρ because it is based on ranks, and therefore is less influenced by outliers. To facilitate comparison with other studies, however, we also include Pearson's r. The correlation between identification accuracy and CFE*d* was significant in older adults ($\rho = 0.43$, $S = 11{,}164$, $p = 0.002$; $r = 0.44$, $t(47) = 3.39$, $p = 0.0014$), but not in younger adults ($\rho = 0.13$, $S = 66{,}177$, $p = 0.26$; $r = 0.05$, $t(75) = 0.45$, $p = 0.66$). Inspection of Fig. 4 shows that two older subjects and one younger subject had very low CFE*d* scores that may have had an unusually strong influence on the correlations. However, removing these cases did not alter the main results: the correlation between accuracy and CFE*d* remained significant in older adults ($\rho = 0.37$, $S = 10{,}949$, $p = 0.01$; $r = 0.30$, $t(45) = 2.09$, $p = 0.04$) and non-significant in younger adults ($\rho = 0.16$, $S = 61{,}137$, $p = 0.16$; $r = 0.14$, $t(74) = 1.24$, $p = 0.22$) even after the three outliers were removed.

In the previous section we noted that identification accuracy was negatively correlated with age, in years, in older adults. To determine if the association between accuracy and CFE*d* in older adults remained after accounting for this association between accuracy and age, we compared two nested linear models, one that included only age (in years) as a predictor variable and another that included age and CFE*d*. Adding CFE*d* as a second predictor variable improved the fit significantly ($F(1,46) = 10.34$, $p = 0.0024$), which indicates that the association between accuracy and CFE*d* persists even after accounting for the linear association between accuracy and age.

In summary, face identification accuracy in both age groups was associated with d' in the separate aligned and misaligned conditions of the CFE task, but face identification accuracy was associated with the holistic index CFE*d* (i.e., the *difference* between d' in the aligned and misaligned conditions) only in older adults.

3.2. Identification accuracy vs. response times

Analyses similar to the ones described in the previous section were used to assess the association between face identification accuracy and response time (RT) in the aligned and misaligned conditions of the CFE task (Fig. 5). In each condition, after controlling for the effect of age ($F(1,122) \approx 32$, $p < 0.001$, $\eta^2 = 0.21$), the effects of RT (aligned: $F(1,122) = 0.01$, $p = 0.92$, $\eta^2 < 0.0001$; misaligned: $F(1,122) = 0.02$, $p = 0.89$, $\eta^2 = 0.0001$) and the age × RT interaction (aligned: $F(1,122) = 0.005$, $p = 0.94$, $\eta^2 < 0.0001$; misaligned: $F(1,122) = 0.18$, $p = 0.67$, $\eta^2 = 0.001$) were not significant. Hence, we found no evidence that identification accuracy was associated with response times in the aligned or misaligned conditions.

The association between face identification and CFE*RT* was assessed with a linear model that included age, CFE*RT*, and age × CFE*RT* as predictor variables. After controlling for the effect of age ($F(1,122) = 32.2$, $p < 0.001$, $\eta^2 = 0.21$), the effects of CFE*RT* ($F(1,122) = 0.15$, $p = 0.69$, $\eta^2 = 0.001$) and the age × CFE*RT* ($F(1,122) = 0.56$, $p = 0.45$, $\eta^2 = 0.004$) interaction were not significant. Finally, in older adults the correlation between identification accuracy and CFE*RT* was not significant ($\rho = 0.054$, $S = 18526.2$, $p = 0.71$; $r = 0.10$, $t(47) = 0.70$, $p = 0.48$), a result that is similar to the one reported by Konar, Bennett, and Sekuler (2010, Experiment 2) for 77 younger participants ($\rho = 0.04$, $S = 73{,}034$, $p = 0.73$; $r = -0.052$, $t(75) = -0.45$, $p = 0.65$).

In summary, we found no evidence of an association between face identification accuracy and CFE*RT* for either age group.

3.3. Identification accuracy vs. response criterion (c)

Analyses similar to the ones described in the previous two sections were used to assess the association between identification accuracy and response criterion (c). Fig. 6 shows the data and

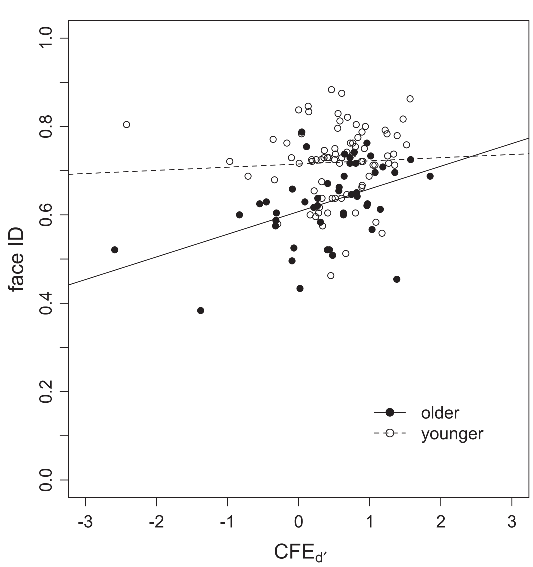

Fig. 4. Identification accuracy (proportion correct) plotted against CFE*d*. The dotted and dashed lines illustrate the fits of a linear model that contained an effect of age, CFE*d*, and the age × CFE*d* interaction. The interaction was significant (i.e., The effects of age and d' differed significantly from zero. Data from younger adults are from Konar, Bennett, and Sekuler (2010, Experiment 2).

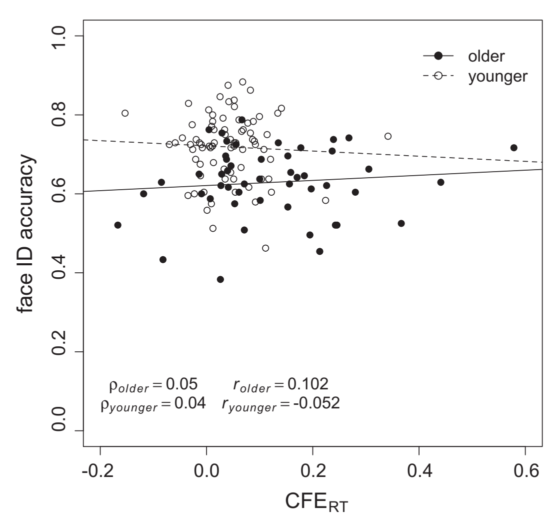

Fig. 5. Identification accuracy (proportion correct) plotted against CFE*RT*. The dotted and dashed lines illustrate the fits of a linear model that contained an effect of age, CFE*RT*, and the age × CFE*RT* interaction. Only the effect of age was significant: The slopes of the two lines did not differ significantly from zero or from each other. Data from younger adults are from Konar, Bennett, and Sekuler (2010, Experiment 2).

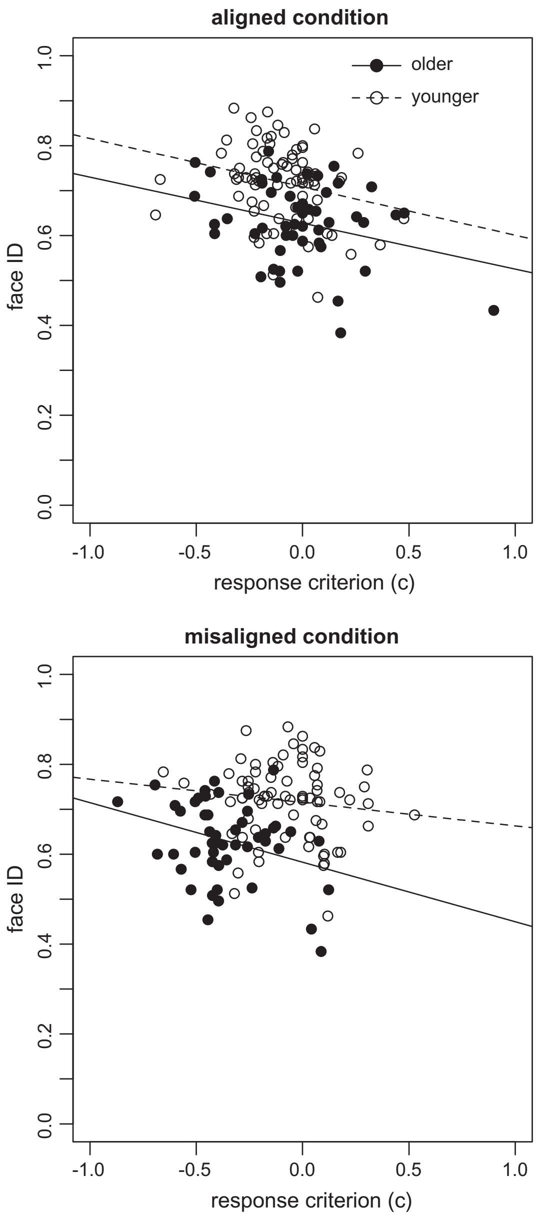

Fig. 6. Identification accuracy (proportion correct) plotted against *c* in the aligned and misaligned conditions. In each plot, the dotted and dashed lines illustrate the fits of a linear model that contained an effect of age, *c*, and the age × *c* interaction. In each condition, the effects of age and *c* were significant, but the interaction was not (i.e., the slopes of the lines did not differ significantly). Data from younger adults are from Konar, Bennett, and Sekuler (2010, Experiment 2).

best-fitting linear models for the aligned and misaligned conditions of the CFE task. In each condition, the effects of age ($F(1,122) > 33$, $p < 0.001$, $\eta^2 = 0.21$) and *c* (aligned: $F(1,122) = 9.32$, $p = 0.003$, $\eta^2 = 0.056$; misaligned: $F(1,122) = 5.18$, $p = 0.025$, $\eta^2 = 0.032$) were significant, but the age × *c* interaction was not (aligned: $F(1,122) = 0.01$, $p = 0.94$, $\eta^2 < 0.001$; misaligned: $F(1,122) = 1.15$, $p = 0.29$, $\eta^2 = 0.007$). Thus, *c* was associated with face identification accuracy – accounting for 5.6% and 3.2% of the variation in identification accuracy in the aligned and misaligned conditions – but the association did not differ between age groups.

Fig. 7 shows identification accuracy plotted against the difference between *c* in the aligned and misaligned conditions (Δc). After controlling for the effect of age ($F(1,122) = 32.2$, $p < 0.001$, $\eta^2 = 0.21$), the effect of Δc ($F(1,122) = 0.43$, $p = 0.51$, $\eta^2 = 0.003$) and the age × Δc interaction ($F(1,122) = 0.005$, $p = 0.94$,

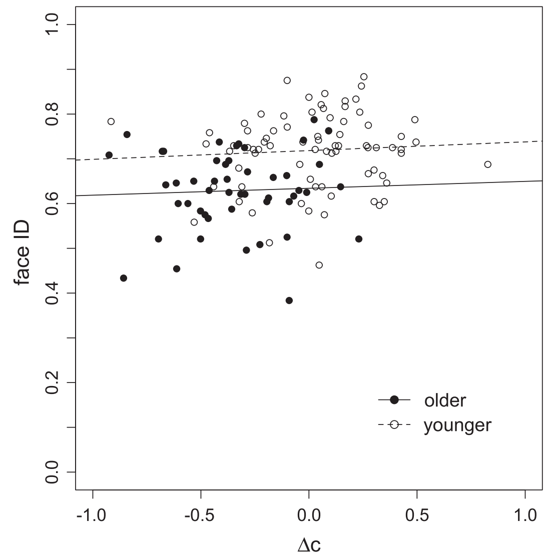

Fig. 7. Identification accuracy (proportion correct) plotted against Δc (i.e., the difference between *c* in the aligned and misaligned conditions of the CFE task). The dotted and dashed lines illustrate the fits of a linear model that contained an effect of age, Δc, and the age × Δc interaction. Only the effect of age was significant: the slopes of the two lines did not differ significantly from zero or each other. Data from younger adults are from Konar, Bennett, and Sekuler (2010, Experiment 2).

$\eta^2 < 0.001$) were not significant. The correlation between identification accuracy and Δc was not significant in older adults ($\rho = 0.057$, $S = 18478.74$, $p = 0.69$; $r = 0.047$, $t(47) = 0.32$, $p = 0.75$) or younger adults ($\rho = 0.056$, $S = 71{,}817$, $p = 0.63$; $r = 0.067$, $t(75) = 0.58$, $p = 0.56$).

In summary, these analyses show that face identification accuracy in both age groups was related to *c* in both the aligned and misaligned conditions of the CFE task, but not to the difference between *c* in the two conditions (i.e., Δc).

3.4. CFE vs. response criterion (*c*)

Some researchers have suggested that the values of CFE*d* estimated from the methods used in this study are susceptible to response bias (Richler, Cheung, & Gauthier, 2011), despite the fact that CFE*d* is derived from measures of d' which should reduce the effects of bias. To test this prediction, we correlated CFE*d* with Δc for each group separately. Neither group of participants had a significant correlation between CFE*d* and Δc (Younger adults: $\rho = 0.007$, $p = 0.95$; Older adults: $\rho = -0.27$, $p = 0.06$). As mentioned above, two older participants had very low CFE*d* scores and may have strongly influenced the correlation analysis. However, after removing the two outliers the correlation between CFE*d* and Δc remained non-significant ($\rho = -0.19$, $p = 0.20$).

In summary, the correlation between CFE*d* and Δc was not significant for either group, indicating that the CFE*d* measure was not associated significantly with response bias in our tasks.

3.5. Confidence intervals for CFE correlations

We found that CFE*d* is correlated with face identification accuracy in older subjects, but not younger subjects. To what extent might this age difference simply be the result of higher variance in the younger subjects' results? To address this issue, we used the bootstrap method described by Konar, Bennett, and Sekuler (2010) to calculate 95% confidence intervals for the correlations between face identification accuracy and CFE*d*, CFE*RT*, and Δc. The results are shown in Table 2. Three results are noteworthy.

Table 2
95% Confidence intervals for correlations (ρ) between face identification (ID) accuracy and CFE*d*, CFE*RT*, and Δc.

ρ	Older	Younger
ID & CFEd	(0.18, 0.48)	(−0.09, 0.17)
ID & CFERT	(−0.09, 0.24)	(−0.16, 0.09)
ID & Δc	(−0.13, 0.20)	(−0.09, 0.18)

First, the confidence interval for the CFE*d*-based correlation was slightly wider in older adults than younger adults. Therefore, the failure to find a significant correlation in the younger group cannot be due to our measures being less precise in those subjects. Second, the extent to which confidence intervals were wider for older adults compared to younger adults (23%) was nearly identical to the 25% difference predicted by the difference in sample size – suggesting that the precision of our measures was approximately the same in the two age groups. Third, in both age groups the widths of the three confidence intervals were nearly the same. This last result suggests that the failure to find significant correlations between identification and CFE*RT* and Δc was not caused by higher error with the RT and c measures.

3.6. Alternative measures of the CFE

As has been done in most previous studies, we defined the CFE as the difference between performance (i.e., d' or reaction time) measured in the aligned and misaligned conditions. However, other definitions are possible. One alternative CFE measure that has been used in some studies (e.g., de Heering & Rossion, 2008; Wang et al., 2012) is based on the ratio (misaligned − aligned)/(misaligned + aligned). More recently, DeGutis et al. (2013) described a regression-based measure that may be a better estimate of the CFE than the standard subtraction measure. The regression-based CFE is estimated by computing the best-fitting line that relates performance in the misaligned and aligned conditions, and then, for each subject, calculating the difference between predicted and observed performance in the misaligned condition. In a series of experiments, DeGutis et al. found that the regression-based estimate of the CFE was a better predictor of face recognition accuracy in young adults than was the subtraction-based measure.

To determine if our results depended on the definition of the CFE, we calculated ratio- and regression-based CFEs for our subjects. The correlations between estimates of CFE*d* were quite high, as were the correlations between measures of CFE*RT*, but the correlations between accuracy- and RT-based CFEs were much lower (Table 3). The correlations between face identification accuracy and the various CFEs are shown in Table 4. Statistical significance was assessed using Holm's sequential Bonferroni procedure, with familywise Type I error set to 0.05. We expected the correlations to be positive; to increase power, we therefore used one-tailed tests to evaluate the null hypothesis $\rho \leqslant 0$. Using this procedure,

Table 3
Correlations (Spearman's ρ) between various CFE measures. sCFE, regCFE, and ratCFE are, respectively, subtraction-, regression-, and ratio-based estimates of the CFE. (Note: Statistical significance was assessed using Holm's sequential Bonferroni test with familywise Type I error rate set to 0.05, one-tailed. Significant correlations are indicated by †.)

	regCFEd	ratCFEd	sCFERT	regCFERT	ratCFERT
sCFEd	0.972†	0.958†	0.241	0.253	0.242
regCFEd		0.878†	0.179	0.199	0.186
ratCFEd			0.296†	0.300†	0.289†
sCFERT				0.972†	0.988†
regCFERT					0.985†

Table 4
Correlations Correlations (Spearman's ρ) between face identification accuracy and various CFE measures. (Note: † indicates a significant correlation assessed using Holm's sequential Bonferroni test with familywise Type I error rate set to 0.05, one-tailed.).

Group	sCFEd	regCFEd	ratCFEd	sCFERT	regCFERT	ratCFERT
Younger	0.127	0.216	0.043	0.036	0.042	0.046
Older	0.430†	0.480†	0.347	0.055	0.051	0.030

only the correlations between identification accuracy and the subtraction- and regression-based CFE*d* in older adults were significant. However, it is worth noting that, in younger subjects, the correlation between accuracy and the regression-based CFE*d* was 70% higher than the correlation between accuracy and the subtraction-based CFE*d*. If we had not corrected for multiple comparisons, the correlation between accuracy and regression-based CFE*d* would have been significant ($\rho = 0.216$, $S = 59{,}465$, $p = 0.03$, one-tailed).

4. General discussion

The current experiment measured holistic face processing using a CFE task. In the CFE task, older adults had lower d' scores and longer response times in both the aligned and misaligned conditions. Nonetheless, unlike Boutet and Faubert (2006) who did not find a significant CFE*d* in older participants, we found that both CFE*d* and CFE*RT* were significantly greater than zero in older adults; CFE*RT* scores were larger in older adults than younger adults, but CFE*d* scores did not differ between age groups. Note, however, that the CFE tasks used in the current study and by Boutet and Faubert differed considerably. Most critically, Boutet and Faubert required subjects to first memorize the names of faces and then recall the names corresponding to the top or bottom halves of composite faces, whereas the current study relied on perceptual comparisons that presumably minimized the memory load. Faubert (2002) has argued that, in general, age-related changes are greater in tasks that engage more extensive and/or complex neural networks. According to this hypothesis, the greater age difference in CFEs reported by Boutet and Faubert reflects the fact that their CFE task engaged more complex and/or extensive neural networks than the CFE task used in the current paper.

The current study also found that d' in both aligned and misaligned conditions of the CFE task had a significant linear relationship with identification accuracy for both age groups, and there was no difference in the strength of the relationship between the groups. In contrast, the difference between d's in the aligned and misaligned conditions – which corresponds to CFE*d* and is interpreted as an index of holistic face processing – was significantly related to identification accuracy in older adults only. Response times in aligned and misaligned conditions were not associated with identification accuracy for either age group, and CFE*RT* also was not related to identification accuracy in either age group. Thus, our analyses suggest that quantifying CFE with d's may be a more sensitive measure of the way in which holistic processing relates to face identification, and that holistic processing, as indexed by CFE*d*, is more strongly associated with face identification accuracy in older adults. Finally, these results did not change markedly when regression- or ratio-based estimates of the CFE were used instead of the subtraction-based estimate, although there was some evidence to suggest that the regression-based estimate of CFE*d* might yield a higher identification-CFE correlation in younger subjects.

Face identification accuracy was significantly lower in older adults than younger adults, a result that is consistent with previous studies (see Searcy, Bartlett, & Memon, 1999, for a review). One potential explanation for this finding is that holistic processing, which is thought to improve the perception of upright faces, is less effective in older adults. Our results are inconsistent with this explanation. First, we found no evidence that the strength of holistic processing, as indexed by the CFE, was reduced in older adults. Second, we found that the CFE*d* was positively correlated with identification accuracy in older, but not younger, subjects. If anything, our results suggest that the influence of holistic processing on face identification is stronger, not weaker, in older adults. Therefore, the decline in identification accuracy must be due to some other factor, such as reduced sensitivity to information conveyed by horizontal facial contours (Obermeyer et al., 2012; Pachai, Sekuler, & Bennett, 2013) and/or the horizontal spacing between features such as the eyes (Chaby, Narme, & George, 2011).

4.1. Partial vs. complete experimental designs

Several investigators have differentiated CFEs that are measured in experiments using partial and complete experimental designs (Cheung et al., 2008; Richler et al., 2011; Richler, Cheung, & Gauthier, 2011). In a so-called partial design, like the one used in the current experiment, the irrelevant half of the face (e.g., the bottom) changes across intervals on every trial, and holistic processing is indexed by the difference in performance measured in aligned and misaligned conditions. In a complete design, the irrelevant half of the face changes on only 50% of the trials: on congruent trials, both the top and bottom halves are the same or different, whereas on incongruent trials one part of the face is the same and the other is different. In a complete design, holistic processing is indexed by the congruency effect (i.e., the performance difference on congruent and incongruent trials), which typically is larger for aligned faces than misaligned faces.

In comparing the partial and complete designs, Richler, Cheung, and Gauthier (2011) suggested that a CFE measured with partial designs may not be an accurate index of holistic processing because the results of partial designs may be affected by response bias. Cheung et al. (2008), for example, demonstrated that response bias differed significantly in aligned and misaligned conditions, and therefore suggested that changes in percent-correct were not an accurate measure of the underlying CFE. However, it is not clear why CFE*d* calculated in a partial design, which is based on differences in d' in the aligned and misaligned conditions, should be affected strongly by response bias. Compared to a measure of accuracy like percent correct, d' ought to be relatively stable despite changes in response criterion. Consistent with this idea, we found that the correlation between CFE*d* and Δc was not significant in either age group.

Moreover, the effects of stimulus alignment on response criterion have been inconsistent across several experiments. Cheung et al. (2008) measured congruency effects in younger subjects with low spatial frequency (LSF), high spatial frequency (HSF), and full-spectrum upright faces, and found a significant bias to respond "different", but only for aligned LSF and full-spectrum faces. Richler et al. (2011), on the other hand, found a greater tendency to respond "same" for aligned full-spectrum faces at short (50 ms) and medium (183 ms) stimulus durations. At a long (800 ms) stimulus duration, which was similar to the 600 ms stimulus duration used by Cheung et al., Richler et al. reported a small bias to respond "same" (i.e., $c \approx -0.1$) that did not vary significantly with alignment. This lack of an alignment effect is similar to the one we obtained with younger subjects. However, the current experiment also found that older adults had a neutral response criterion when shown aligned stimuli and a significant bias to respond "same" for misaligned stimuli, a pattern of results that differs from those reported by Cheung et al. and Richler et al. In summary, although stimulus alignment sometimes affects response bias, the direction of those effects has varied across conditions, age groups, and experiments, and the current experiment found no evidence that changes in response bias across alignment conditions were correlated with CFE*d* or face identification accuracy. Thus, any effects of the partial design on response bias cannot account for our results.

4.2. Relation to previous studies using younger subjects

Using a partial design CFE task, Konar, Bennett, and Sekuler (2010) found that neither CFE*d* ($r = 0.05$) nor CFE*RT* ($r = -0.05$) were correlated with face identification accuracy in younger adults. This finding was replicated by Richler, Cheung, & Gauthier, 2011 in an experiment that used a complete CFE design: analyzing a subset of trials that corresponded to those that would have been included in a partial design, Richler et al. found no evidence of a correlation between face identification and CFE*d* ($r = 0.09$) or CFE*RT* ($r = 0.16$). Using all of the trials in the complete design, Richler et al. again found no evidence of a correlation between face identification accuracy and the congruency $\times$ alignment interaction that was measured with d' ($r = 0.031$), but the correlation was significant when the congruency measure was based on response time ($r = 0.48$). Hence, the evidence presented by Richler et al. suggests that, in younger subjects, there is no significant correlation between face identification and CFE*d* or a related congruency measure based on d'.

Interestingly, Richler et al. did find significant correlations between congruency effects measured with both d' ($r = 0.39$) and response times ($r = 0.33$) and accuracy on the Cambridge Face Memory Test (CFMT). Using a complete CFE design, DeGutis et al. (2013) also found that accuracy on the CFMT was correlated with a subtraction-based estimate of the congruency effect measured with d' ($r = 0.33$) and a regression-based estimate of the congruency effect ($r = 0.36$). Finally, using a partial CFE design and a very large sample size ($N = 337$), Wang et al. (2012) found a small but significant correlation ($r = 0.13$) between a ratio-based estimate of CFE*RT* and face recognition ability (FRA), defined as the difference between accuracy in old-new recognition tasks using faces and flowers; the correlation between a ratio-based estimate of CFE using proportions correct and FRA was not significant ($r = 0.03$). In summary, three studies have now reported correlations between congruency effects and accuracy on face recognition tasks, which presumably were constrained more by memory than the face identification task used in the current experiment. This result suggests that holistic processes may play a more significant role in face processing in tasks that place greater emphasis on memory.

4.3. Greater holistic processing and limited cognitive resources

In contrast to these previous results obtained with younger subjects, the current experiment found that CFE*d* was correlated significantly with face identification in older adults ($r = 0.44$), which suggests that older adults may have a greater reliance on holistic processing of faces. Why would older adults rely more on holistic processing? Dror, Schmitz-Williams, and Smith (2005) suggested that using holistic representations and processes could, in some circumstances, reduce the perceptual and cognitive load associated with recognizing objects presented at different viewpoints (at the cost of reducing response accuracy). Furthermore, they argued that age-related reductions in cognitive resources would force older adults to rely on this less-taxing type of processing in a wider range of conditions than younger adults. According to this hypothesis, older adults relied more on holistic processing because identification of upright faces placed a greater demand on their cognitive resources (Craik & Byrd, 1982), perhaps because face perception engages complex neural networks that are more likely to be compromised by aging (Bennett et al., 2001; Della-Maggiore et al., 2000; Faubert, 2002; McIntosh et al., 1999). If this idea is correct, then younger subjects ought to rely more on holistic processing in an upright face identification task that was made more difficult, perhaps by reducing stimulus duration or by including a secondary task, and in such conditions younger adults may exhibit a significant correlation between identification accuracy and the CFE. Indeed, such an account could explain why Richler, Cheung, and Gauthier (2011) found a relationship between CFE*d* and face recognition but not face identification; the face memory task may require additional cognitive resources and therefore force subjects to rely more on holistic processing.

In summary, we found evidence that holistic processing, as indexed by subtraction-, regression- and ratio-based estimates of the CFE, is related to face identification in older adults, but not in younger adults. The current results are consistent with the idea that the extent to which holistic processing influences upright face identification may depend on the relative difficulty of the task: people may rely more on holistic processing under conditions that decrease recognition, and rely less on holistic processing under conditions in which we recognize faces easily and well.

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