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Broadly Tuned Face Representation in Older Adults Assessed by Categorical Perception

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Studies of face recognition in older adults (60 years of age and older) report increases in false alarms over younger adults (usually 18–30 years of age), but no age differences in hits. To examine this phenomenon, we compared older and younger adults in categorical perception of faces. We hypothesized that face representations in older adults would be broadly tuned, resulting in overlapping representations, manifested by a shallower slope in identity categorization than in younger adults, and age-related reductions in the advantage for between-categories, as compared with within-category, face discrimination. We morphed faces to change linearly from one identity to another. We used familiar or unfamiliar faces in separate conditions to examine the role of familiarity. Categorical perception was assessed in an identity-classification task and a discrimination task. Older adults showed a shallower slope and poorer discrimination compared with younger adults, and both groups exhibited better performance with familiar than unfamiliar faces. Enhanced discriminability for between-categories as compared with within-category faces was seen for both familiar and unfamiliar faces in younger adults, but only for familiar faces in older adults. The more broadly tuned representations of unfamiliar faces in older adults may lead to misidentification and greater false alarms for unfamiliar faces, but not for familiar faces.

Keywords: categorical perception, aging, face perception, face recognition, broad tuning

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Normal aging is associated with face perception and recognition deficits (e.g., Boutet & Faubert, 2006; Grady, McIntosh, Horwitz, & Rapoport, 2000; Habak, Wilkinson, & Wilson, 2008; Lee, Paleja, Grady, & Moscovitch, 2014; Searcy, Bartlett, & Menon, 1999). One common complaint among older adults (usually 60 years and older) is that even unfamiliar faces look familiar. Indeed, many studies have reported that older adults successfully detected target faces (hits) but falsely recognized lures as targets (more false alarms; e.g., Boutet & Faubert, 2006; Grady, Bernstein, Beig, & Siegenthaler, 2002; Lee et al., 2014; see a review in Searcy et al., 1999, for earlier studies). False identification of a lure face may be related to increased feelings of familiarity that older adults tend to have, a problem that is not unique to faces (Bartlett, Strater, & Fulton, 1991). Neuroimaging evidence suggests that distinctiveness of visual cortical representations is reduced with age (Burianová, Lee, Grady, & Moscovitch, 2013; Carp, Park, Polk, & Park, 2011; Goh, Suzuki, & Park, 2010; Park et al., 2004; Schiavetto, Köhler, Grady, Winocur, & Moscovitch, 2002). For instance, in our recent functional MRI (fMRI) study using unfamiliar faces (Lee, Grady, Habak, Wilson, & Moscovitch, 2011), older adults showed equivalent neural responses in the face-sensitive area of the fusiform gyrus to both repetitions of the same face and different faces, thus showing no adaptation to face repetitions, unlike younger adults. The findings suggest that different neuronal populations that are supposed to be tuned to different identities are responding less distinctively and have overlapping representations, what is termed *broad tuning*. In a different study, older adults showed neural adaptation to lures as much as to targets (Goh et al., 2010), again suggestive of broader tuning. The goal of the present study was to inquire more deeply whether face representations are broadly tuned in older adults (see Figure 1 top).

We addressed this question by testing *categorical perception* (CP). CP is the perceptual distortion when linear, continuous physical changes of a stimulus have nonlinear perceptual effects

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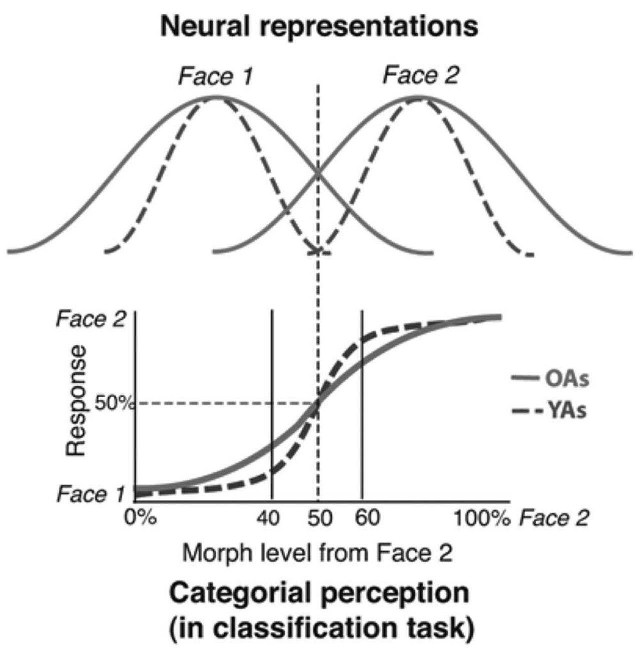

Figure 1. Hypothesis with unfamiliar faces. We hypothesized that if face representations are broadly tuned in older adults, they will have the same boundary location as younger adults but a shallower slope at the boundary, showing less advantage of between-categories discrimination. The top figure depicts hypothetical representation of neural tuning to a pair of faces in older and younger adults. The bottom figure shows corresponding classification performance.

(Harnad, 1987). For example, visible light varies continuously in terms of wavelengths but is perceived as discrete categories of color bands of the rainbow. Likewise, CP operates in speech perception so that linear changes in the acoustic signal are perceived discontinuously as discrete phonemes. The role of CP is to simplify our perception of events by putting them into discrete categories that share some common properties (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). CP has been demonstrated for facial identity (Beale & Keil, 1995), facial expressions (Etcoff & Magee, 1992), and face gender (Campanella, Chrysochoos, & Bruyer, 2001).

One way of demonstrating categorical perception of faces is by morphing two faces linearly so that the resulting stimulus contains input ranging from 0% to 100% from one face with the remainder from the other. Given the morph continua between two face identities, CP is evident by abrupt transitions in categorization of identity (see Figure 1). In addition, CP is defined by enhanced discriminability for between-categories as compared with within-category stimuli; that is, discrimination between pairs of faces that straddled the boundary between categories is better than that for equidistant pairs drawn from the same category. In Figure 2C, for example, discrimination between 40% Jen and 60% Jen (i.e., between-categories faces) is easier than discrimination between 60% Jen and 80% Jen, even though these pairs of faces are equally distant from each other by 20% (also see Figure 1 bottom).

Neuroimaging studies have shown changes in brain activation corresponding to CP of facial identities. Using faces of famous people, Rotshtein, Henson, Treves, Driver, and Dolan (2005) found that the fusiform gyrus, a region especially sensitive to face stimuli, showed reduced activation to repeated stimulation by nonidentical face stimuli as long as they were drawn from samples within a category boundary. In contrast, the fusiform gyrus showed recovery from adaptation when presented with faces that cross category boundaries, even though the physical difference between within-category and across-categories faces was the same. These results indicated that faces that cross category boundaries are processed as distinct identities, whereas faces within the category are processed as the same identity. Campanella et al. (2000) demonstrated similar adaptation effects to within- category and between-categories faces in the N170 component of the event-related potential, which also is face-sensitive (Bentin, Allison, Puce, Perez, & McCarthy, 1996).

Categorical perception, however, can be influenced by experience. If the stimuli are not familiar to the observer, the advantage of discriminating between-categories faces compared with within-category faces is weaker. CP is stronger for familiar than unfamiliar faces (Beale & Keil, 1995; Campanella, Hanoteau, Seron, Joassin, & Bruyer, 2003) and for upright faces than for inverted faces, where it may be absent entirely (Levin & Beale, 2000; McKone, Martini, & Nakayama, 2001), although familiarity may not account for the entirety of the inversion effect.

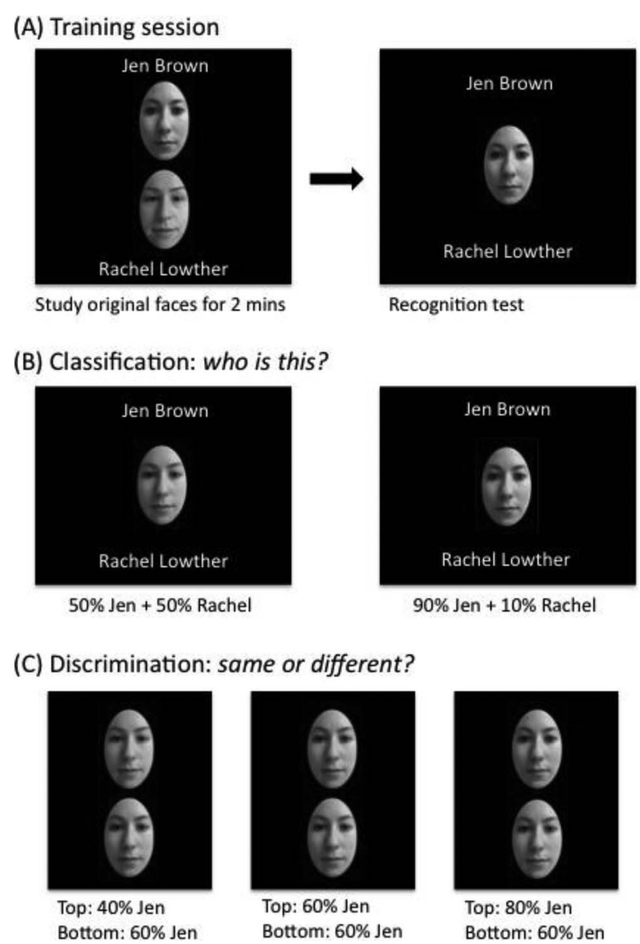

Figure 2. Experimental procedure. The figure illustrates the nonfamous (NNy) condition.

Age-related reductions in face perception and recognition may be associated with broadening of neuronal bandwidths, which would result in overlapping representations between different facial identities (Lee et al., 2011; Wilson, Mei, Habak, & Wilkinson, 2011). Broadly tuned neurons were observed in the middle temporal area of old monkeys (Liang et al., 2010), in line with other evidence that functional degradation of cells, rather than massive cell loss, is responsible for behavioral decline in monkeys and humans during normal aging (Burke & Barnes, 2006, for review; Morrison & Hof, 1997). Broadly tuned neurons in senescent monkey middle temporal area exhibited decreased direction selectivity as well as increases in peak activity and noise, suggesting degradation of inhibitory intracortical circuits (Liang et al., 2010) probably due to decreased GABAergic inhibition (Leventhal, Wang, Pu, Zhou, & Ma, 2003). CP could be an effective *behavioral* measure to test tuning curves of face representations in older adults. CP is consistent with population coding of facial identities, as distinct identity categories involve different neuronal populations (e.g., Betts & Wilson, 2010; also see discussion in Lee, Matsumiya, & Wilson, 2006) and CP is reflected at the cortical level (Campanella et al., 2000; Rotshtein et al., 2005; also see Bidelman, Moreno, & Alain, 2013, for correspondence between the auditory cortex and behavior in CP of speech).

Thus far, only one study has examined CP of facial identity in older adults (Kiffel, Campanella, & Bruyer, 2005), with results suggesting that CP for unfamiliar faces is diminished or absent in older adults. The authors found no advantage for between-categories as compared with within-category discrimination in older adults, but revealed a similar boundary location between older and younger groups. The Kiffel et al. (2005) study differs from the present study in two ways. First, they did not test CP of familiar faces but concluded, nonetheless, that "older people do not access familiar representations" (p. 140). In the present study, we tested CP for familiar faces and unfamiliar faces to study the effects of long-term face representations on performance. Second, Kiffel et al. used only the classification task to define within-category and between-categories faces. The present study investigated both classification and discrimination performance to better understand face representation in aging.

We hypothesized that if face representations are broadly tuned in older adults, they will have the same boundary location as younger adults, but a shallower slope at the boundary in classification, as well as a reduced advantage for between-categories as compared with within-category discrimination (see Figure 1). We also assessed the role of experience in modulating CP by presenting faces that recently became famous, faces that became famous long ago, and faces that were not famous but learned in the lab. Our question was whether even very old representations deteriorate with age, or whether age differences apply only to recently acquired representations. Compared with unfamiliar faces, representation of famous faces involves large networks of multiple regions (Leveroni et al., 2000) and less activation in the occipitotemporal cortex (Rossion, Schiltz, Robaye, Pirenne, & Crommelinck, 2001), potentially making them less vulnerable to the effects of aging.

To control for the so-called *own-age bias* (i.e., better recognition memory for faces of one's own age compared with faces of a different age), nonfamous faces that were learned in the lab were of either old or young people. Studies that examined the interaction of participant age and facial stimulus age in face recognition have produced mixed results: Some studies have found this bias to exist in old participants but not in younger participants (Anastasi & Rhodes, 2005; Lamont, Stewart-Williams, & Podd, 2005; Perfect & Harris, 2003), whereas others have found the opposite, with younger, but not older, participants demonstrating own-age bias (Bäckman, 1991; Bartlett & Leslie, 1986; Fulton & Bartlett, 1991; Wiese, Schweinberger, & Hansen, 2008). Therefore, we used four experimental conditions with famous face pairs (FF) of older fame (FFo) or recent fame (FFr) and nonfamous face pairs (NN) of aged people (NNa) or young people (NNy).

We assessed CP in two ways: with a binary identity-classification task and with a discrimination task (Beale & Keil, 1995). The identity-classification task was used to measure abrupt transitions in categorization of identity (i.e., assess the sigmoid function) and to determine the predicted category boundary and slope at the boundary for each participant. The discrimination task was used to determine whether discrimination of between-categories faces was better than that of within-category faces. The discrimination task did not require prior knowledge of the endpoint (original) face identities but a same or different perceptual judgment of two simultaneously presented morphs. The discrimination task, nonetheless, assumes that an observer makes a decision based on two factors: (a) the identity category label (e.g., as evident in enhanced discriminability of between-categories faces) and (b) differences in perceptual features (i.e., operating to distinguish within-category faces; Liberman, Harris, Hoffman, & Griffith, 1957; Pisoni & Lazarus, 1974). The accuracy score directly measured from the discrimination task is termed the *obtained* discrimination score. In addition, discrimination scores can be derived from the classification task with the assumption that the observer's response is solely based on the outcome of category labeling and no other (Liberman et al., 1957; Pollack & Pisoni, 1971). We calculated the *predicted* discrimination score from classification functions to estimate discrimination performance, which is based only on the ability to classify (or label) facial identity. A match of the obtained and predicted discrimination would represent "pure" CP (Pisoni & Lazarus, 1974). If the obtained score were better than the predicted discrimination, it would suggest reliance on perceptual features, whereas if the obtained score were worse than that predicted by discrimination, it would indicate degradation in perceptual processes (Liberman et al., 1957).

Method

Participants

Twenty-four younger adults (12 women) and 24 older adults (12 women) were recruited to participate in the study. Younger adults were an average age of 23 years old (range: 18–30 years) and had an average of 16 years of total education. All younger adults were healthy graduate or undergraduate students attending the University of Toronto. They had normal or corrected-to-normal vision, no neurological or psychiatric disorders, and never experienced a concussion or any other head injury.

Older adults were recruited from the adult volunteer pool of the Department of Psychology at the University of Toronto. They were an average age of 69 years (range: 61–75 years) and had an average of 16 years of education. All older adults were carefully screened through a phone interview to ensure that they had a minimum of 13 years of education and no psychiatric or neurological problems. They all had normal or corrected-to-normal vision, no eye diseases, and had attended an optometrist or ophthalmologist appointment within the past 2 years (the average time since the most recent eye examination = 11.13 months, SD = 8.24). The average Mini-Mental State Examination score for older adults was 29.91 (SD = 0.29).

All participants were tested individually after providing informed consent, and participated in two 1-hr sessions (each on separate days). The present study was approved by the University of Toronto Research Ethics Board.

Apparatus

All participants were tested using a Dell Dimension 8200 computer (Intel Pentium 4) and a 15-in. monitor with 1,024 × 768 pixel spatial resolution, 60 Hz refresh rate, and 32-bit/pixel grayscale. The monitor subtended 31.5 degrees × 23.9 degrees of visual angle from a viewing distance of 60 cm. Stimuli were displayed using E-Prime 1.0 by Psychology Software Tools.

Stimuli

Forty famous and 40 nonfamous faces (half women) were collected from the Internet. We obtained faces that were presented approximately in a frontal view. Famous faces were chosen from Canadian and American celebrities (movie stars, singers, politicians, etc.) from a wide range of time periods from the 1950s to the present day. We collected two groups of famous faces (20 each): those who were famous and remained so continuously on Canadian media for a long time (e.g., Queen Elizabeth II; FFo) and those who became famous within the past 15 years (e.g., Canadian Prime Minister Stephen Harper; FFr). We purposely used middle-aged famous people rather than very young faces in FFr as not to confound the own-age bias with recency. All face stimuli were of neutral affect and free of accessories, such as glasses, hats, and so forth.

Using Adobe Photoshop CS3, we created a face mask to crop out an oval region of each person's face. The circumference of the oval included only the areas spanning vertically from close to the top of the forehead to close to the bottom of the chin, and horizontally from 0.5 cm leftmost to the left eye to 0.5 cm rightmost to the right eye; thus, hair and ears were excluded. In addition, the face mask enabled the consistent positioning of each person's face within the oval region, which minimized variations in facial structures across the face images (e.g., differences in the size or position of the eyes, nose, and mouth). Each face image was centered at a 3.0 degree × 4.7 degree oval region of the face mask template. As a result, the cropped oval faces were prepared to be similar in size and perspective before morphing.

We morphed one face image with another using Face Morpher Lite software, which allowed us to match all of the facial feature coordinates of one face to those of the other face. The endpoint faces (100% original faces) in each pair were chosen to be similar to each other (same sex and race, similar age and attractiveness, similar facial features and configurations). For each pair of faces morphed together (e.g., Jen and Rachel), resulting morph images differed by 10% on a continuum from 10% to 90%, with a 50% morph having an equal percentage of each of the two faces. The 0% and100% morphs indicate original images. Intermediate stimuli on the face continua were labeled in terms of the percentage of Face 2 in the pair (i.e., 0% = 100% Face 1 and 0% Face 2; 70% = 30% Face 1 and 70% Face 2; 100% = 0% Face 1 and 100% Face 2; see Figure 1). All face stimuli were presented on a black background. This morphing procedure created 20 pairs of famous faces (10 pairs of older fame in FFo, 10 pairs of recent fame in FFr) and 20 pairs of nonfamous faces (10 pairs of aged faces in NNa, 10 pairs of younger faces in NNy). Each participant was tested with two pairs of faces in each condition (one pair of male faces, one pair of female faces), which were chosen from the set of 10 pairs of that condition; presentation of the face pairs was counterbalanced across participants.

Procedure

Each participant performed two tasks on two separate days, a classification task on the first day and a discrimination task on the second day. Before the classification task, each participant underwent a famous individual recognition test, which allowed us to choose famous faces known by the participant to serve as stimuli for the upcoming tasks. In this phase, participants were shown a set of famous faces, including an original picture of each famous individual with full hair, as well as its cropped picture (i.e., endpoint faces). If participants could recognize all or most of the faces shown, they continued to the classification task. If they did not know two or more famous faces from the set, a different selection of famous faces was chosen and presented. A total of eight famous faces (i.e., two pairs from FFo, two pairs from FFr) were used for each participant; however, only morphs, not original images, were presented during actual tasks. To counterbalance the famous faces set used across participants, we tested some participants on one or two famous faces that they did not recognize, as the famous face pairs were predetermined for morphing. To control for this, we excluded individually any unknown famous faces from data analysis of the participant. The famous individuals who were recognized in this phase of the study were used throughout the classification and discrimination tasks.

Classification task. The classification task of each pair of faces began with a training session (see Figure 2A), in which participants were presented with two cropped original faces (endpoint faces) of different identities that were used in a morph pair. One face was placed on the top of the other at the center of the screen. Names of the faces were also stated on the screen. All nonfamous faces were given fake names. The participants were asked to study the faces for 2 min. After the study screen disappeared, the participants went through a brief recognition test in which they had to identify each face. During this recognition test, one face with two names was shown on the screen at a time, and the participant would either press the *up* or *down arrow* on the keyboard to categorize the face as either that of the name written above the face or that written below (see Figure 2A). These faces were the original endpoint faces that appeared in the study screen, not morphs. To reinforce learning, participants received feedback as to whether they were correct or incorrect after their response to each face. This session was completed when the participant correctly named each face in three consecutive trials to ensure that the participant had successfully learned each identity.

After the training session, participants were then given the classification task in which they were shown morphed faces between the two distinct identities that were studied (see Figure 2B). In each trial, given one morphed face, which was randomly selected from nine morphed images (10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% of Face 2), the participant was asked to categorize each morph as either identity by pressing the *up* or *down arrow* keys. Each morph was presented for up to 4 s but disappeared on the participant's response. If the participant did not respond in 4 s, the morph disappeared but the identity names remained on the screen until the participant made a response. No feedback was given. Each morph was presented five times, amounting to 45 trials for one pair of faces. These two sessions (training and classification) were repeated for eight pairs of faces in four conditions (FFo, FFr, NNa, NNy).

Discrimination task. As this task was administered on the second day, participants repeated the training session and recognition test for each pair of faces. This training session and recognition test were identical to those of the classification task described above, as were the pairs of faces that were used. After the training, the participant was then given instructions for the discrimination task. In each trial, participants were shown two morphs simultaneously for 4 s (see Figure 2C). Participants decided whether the two images were identical or whether they differed in any way. In the *different* trials, morphs differed by 20%, that is, 10% versus 30%, 20% versus 40%, 30% versus 50%, 40% versus 60%, 50% versus 70%, 60% versus 80%, 70% versus 90%, each of which was presented five times for a total of 35 trials for each morph pair. In the *same* trials, morphs were identical: 10% versus 10%, 20% versus 20%, 30% versus 30%, 40% versus 40%, 50% versus 50%, 60% versus 60%, 70% versus 70%, 80% versus 80%, 90% versus 90%; each was presented three times for a total of 27 trials (about 44% of the total trials) for each morph pair. Same trials were included so as to not bias participants' responses, but were excluded from analysis. Note that in both classification and obtained discrimination, the participant's response function was based on the same number of trials, that is, each point in the response function for one pair of faces was from an average of five trials. In the discrimination task, participants were instructed to focus on *images* rather than identity. Participants were told that many faces might look like those of the same person, but in fact, there could be very subtle differences between them. To answer, participants pressed either the *left* or *right arrow* key, indicating either a *same* or *different* response, respectively. These two phases (training and discrimination) were repeated for the same eight pairs of faces presented in the classification task. The order of face pairs was randomly chosen by E-Prime for each participant.

Analysis

Accuracy was computed by percentage correct trials divided by the total number of trials. The sigmoid function was fitted to the classification accuracy data of each participant to estimate the predicted category boundary (x_c) and slope at the boundary for the individual (k = slope of the tangent at x_c, or derivative at x_c, defined as $0 < k < 1$ in the current study, using custom routines coded in MATLAB, MathWorks, Natick, MA). The sigmoid fit provided an optimal description of the perceptual distortion underlying CP (McKone et al., 2001). A simple sigmoid equation is as follows (Eq. 1):

$$y = \frac{1}{1 + e^{-k(x - x_c)}}. \tag{1}$$

Predicted percentage correct discrimination $P_{c(a,b)}$ (Eq. 2) for a pair of two stimuli, *A* and *B*, which were separated by two steps (e.g., 10% and 30% as in the present study), was derived from the classification data in each participant, using the procedures described in Strouse, Ashmead, Ohde, and Grantham (1998) (originally, Pollack & Pisoni, 1971):

$$P_{c(a,b)} = \frac{[(1 - P_{a1})^2 + (1 - P_{b2})^2]}{2} + P_{a1}P_{b2}, \tag{2}$$

where P_{a1} is the probability that the first stimulus (e.g., *A*) in the pair is identified as a member of a given category and P_{b2} is the probability that the first stimulus in the pair is identified as a member of another category. The equation is based on the extreme assumption that the observer's discrimination response is based solely on the outcome of the categorical labeling (Pollack & Pisoni, 1971); that is, when the stimulus pair comes from the same category, the predicted score is at chance (50%), and when the pair of stimuli is from two different categories, the predicted score is greater than chance. If an observer uses only the categorical label of a stimulus to make a discrimination judgment, the decision should be completely binary; for example, discrimination of two stimuli just flanking a CP boundary should always be 100% because they are given two different and unique labels.

Obtained discrimination accuracy was directly measured from the discrimination task. Analysis of obtained discrimination performance included only different pairs. Reaction times were not used as difficult trials (e.g., 10% vs. 30% discrimination) were highly variable and sometimes did not yield any correct responses.

Results

Figure 3 plots the average group results in classification (see Figure 3A) and discrimination (see Figure 3B) for famous faces pairs (FFo and FFr) and nonfamous faces pairs (NNa and NNy). Note that in Figure 3, for illustration only, the sigmoid function (in classification) and the derivative of the sigmoid function (in discrimination) were fitted to *averaged* group accuracy. However, for results reported below, we fitted the sigmoid function (Eq. 1) to each participant's data *individually* to obtain slope (k) and boundary (x_c) values of each participant, and entered individual values into analyses of variance (ANOVAs) and Bonferroni t tests. Homogeneity of variance was examined with Mauchly's test for ANOVAs; in case of violation of this assumption, the Greenhouse–Geisser estimates were used. Multiple comparisons used Bonferroni t tests.

Table 1 shows values of slope and boundary from classification averaged across the participants in each group. Table 2 shows average accuracy in discrimination tasks. One older adult did not recognize any famous faces used in FFr and was excluded from analyses of that condition.

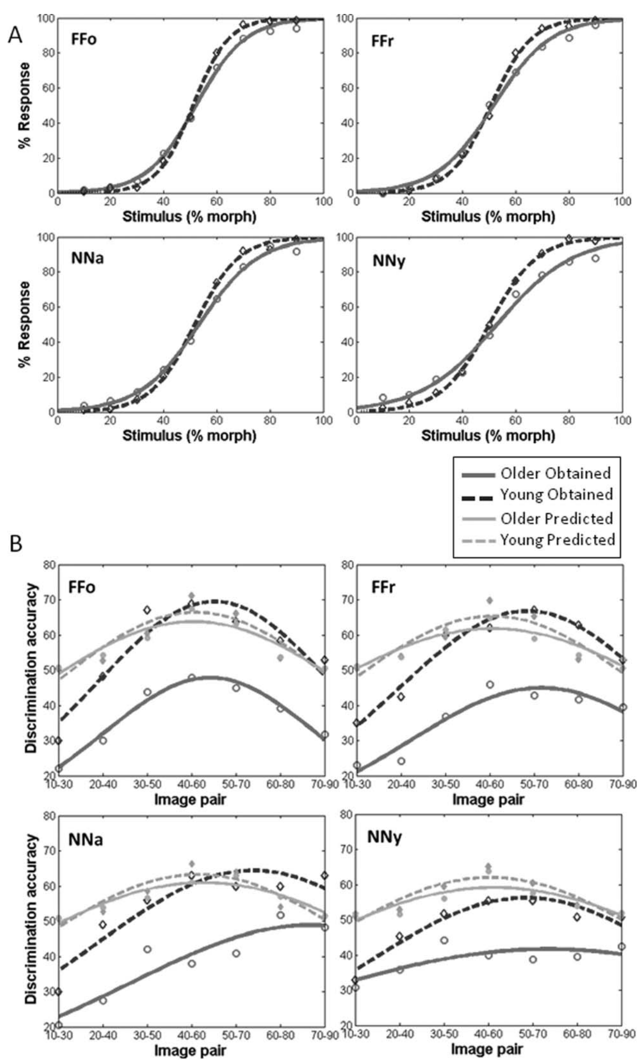

Figure 3. Average group performance in classification (A) and discrimination (B) performance for famous faces (FFo, FFr) and nonfamous faces (NNa, NNy). For illustration only, the sigmoid function (Eq. 1 for classification) and the derivative of the sigmoid function (for discrimination) were fitted to *averaged group data*. Note that analyses of variance were performed with values from the sigmoid function fitted *individually* in each participant. In (A), the older participants show shallower slopes compared with the younger participants. In (B), the sigmoid derivative is defined as

$$y = \frac{h}{e^{w(x-x_c)} + 2 + e^{-w(x-x_c)}},$$

where x_c = position of peak, h = height of peak, and w = width of peak (McKone et al., 2001). We calculated a proportion of variance (R^2) that is accounted for by the sigmoid derivative (R^2_{sd}) and by a linear regression function (R^2_{lin}). If CP is present, R^2_{sd} should be greater than R^2_{lin}. As expected, FFo shows R^2_{sd} = .97, R^2_{lin} = .16 in older adults group and R^2_{sd} = .89, R^2_{lin} = .24 in younger adults group; FFr shows R^2_{sd} = .91, R^2_{lin} = 0.59 in older and R^2_{sd} = .97, R^2_{lin} = .44 in younger; NNa shows R^2_{sd} = .86, R^2_{lin} = .83 in older and R^2_{sd} = .87, R^2_{lin} = .67 in younger; NNy shows R^2_{sd} = .56, R^2_{lin} = .42 in older and R^2_{sd} = .92, R^2_{lin} = .45 in younger. Hence, even the sigmoid-derivative function fitted to the group data reflects analysis of variance results reported in the text. The predicted discrimination scores are plotted in lighter gray. Older adults showed poorer obtained than predicted discrimination in all conditions. Dark solid line = older obtained, dark dashed line = young obtained, lighter solid line = older predicted, lighter dashed line = young predicted.

Table 1
Boundary and Slope Values From Classification

Group	Boundary (x_c)				Slope (k)			
	FFo	FFr	NNa	NNy	FFo	FFr	NNa	NNy
Older adults	50.88 (6.27)	50.76 (8.49)	50.75 (7.00)	53.87 (11.92)	0.19 (0.13)	0.15 (0.08)	0.14 (0.12)	0.10 (0.06)
Young adults	50.80 (5.43)	50.56 (6.78)	51.70 (5.40)	49.61 (6.87)	0.23 (0.13)	0.21 (0.13)	0.18 (0.13)	0.14 (0.06)

Note. k = a slope of a tangent at x_c, which equals the derivative of the function at x_c. Hence, k is not equivalent to the slope value of a line. FFr = recent famous face pairs; FFo = old famous face pairs; NNy = young nonfamous face pairs; NNa = aged nonfamous pairs. Values are averaged across participants in the group. Standard error appears within parentheses.

Classification

First, to examine whether older and younger participants learned and correctly identified faces, we compared classification accuracy of endpoint faces (10% and 90% of Face 2) between the two groups in each condition (FFo, FFr, NNa, NNy) with t tests (two-tailed) without correction for multiple comparisons (to be liberal to detect any group difference). There was no group difference except in classification of 90% faces of NNy (p = .03). However, this difference was not significant if corrected for multiple comparisons using Bonferroni's method.

Mixed-factors ANOVAs were conducted with group (older adults, younger adults) and conditions (e.g., familiarity comparing FF vs. NN, recency comparing FFo vs. FFr, face age comparing NNa vs. NNy) as independent variables, and boundary (x_c) or slope (k) as the dependent variable. With boundary values, 2 × 2 ANOVAs did not find any significant effect in any conditions, suggesting that decision criteria were similar between the two groups (see Table 1). Thus, only the results of slope (k) are reported here. It is noted that because faces in the FFr condition were not always those of younger individuals (e.g., Stephen Harper), a three-way ANOVA, for example, with Group × Familiarity (FF vs. NN) × Face Age (old vs. young) was not appropriate in this study.

The effect of familiarity (FF vs. NN) on slopes was assessed with a 2 × 2 mixed-factors ANOVA (Group × Familiarity). FFo and FFr were averaged for FF, as were NNa and NNy for NN. The main effects of familiarity, $F(1, 46) = 11.27$, $p = .002$, $\eta_p^2 = .20$, and group, $F(1, 46) = 7.78$, $p = .01$, $\eta_p^2 = .15$, were significant, but the interaction was not ($F < 1$), showing that both groups were better at classification of famous faces, whereas older adults were poorer than younger adults overall.

Additional analyses were conducted within each familiarity condition to examine the effects of recency and face age separately. In the famous conditions (FF), a 2 × 2 mixed ANOVA examined the effect of group and recency (FFo vs. FFr) on slope. The results showed a marginal group effect, $F(1, 45) = 3.6$, $p = .07$, $\eta_p^2 = .07$, no effect of recency, $F(1, 45) = 1.73$, $p = .20$, $\eta_p^2 = .04$, and no interaction ($F < 1$). With famous faces, older adults' slope was somewhat shallower than that of younger adults, but the difference did not reach significance, indicating that, like younger adults, their classification of famous faces was relatively sharp.

In the nonfamous conditions (NN), a 2 × 2 mixed-factors ANOVA examined the effect of group and face age (NNa vs. NNy). The effect of group was significant, $F(1, 46) = 4.7$, $p = .04$, $\eta_p^2 = .09$, but neither face age, $F(1, 46) = 2.87$, $p = .10$, $\eta_p^2 = .06$, nor the interaction ($F < 1$) was significant. Hence, the older adults had shallower slopes than the younger adults for nonfamous faces, suggesting classification deficits for faces that they recently learned. No effect of face age indicates that our participants did not demonstrate an own-age bias with nonfamous faces.

In summary, these results suggest that older adults show a shallower slope than younger adults in all face classification conditions, with both groups benefitting from familiarity, and older adults showing a tendency to benefit somewhat more. This benefit that familiarity confers on CP in older adults becomes more evident in the discrimination task.

Discrimination

For ANOVA, three morph steps (10–30%, 40–60%, 70–90%) were chosen representing within-category face pairs (10–30%, 70–90%) and between-categories face pairs (40–60%); the dependent variable was discrimination accuracy. Figure 3B shows averaged discrimination accuracy in each group for all conditions.

First, the effect of familiarity (FF vs. NN) was assessed with a 2 × 2 × 3 mixed-factors ANOVA (Group × Familiarity × Morph Step). The effect of familiarity was not significant (F <1). There were significant main effects of group, $F(1, 46) = 13.42$, $p = .001$, $\eta_p^2 = .23$, and morph step, $F(2, 92) = 56.08$, $p < .001$, $\eta_p^2 = .55$, and an interaction of Familiarity × Morph Step, $F(2, 92) = 7.87$,

Table 2
Obtained Discrimination Accuracy (Percentage Correct)

Image	Older adults				Young adults			
	FFo	FFr	NNa	NNy	FFo	FFr	NNa	NNy
10–30	22.08 (4.38)	22.92 (4.32)	20.42 (3.83)	29.58 (4.01)	30.00 (4.58)	35.00 (5.07)	30.42 (3.69)	33.33 (3.84)
40–60	47.92 (4.96)	45.83 (4.92)	37.92 (5.07)	40.00 (4.70)	68.75 (5.01)	62.08 (4.62)	63.33 (5.00)	55.42 (4.17)
70–90	31.67 (5.17)	39.58 (6.27)	48.33 (5.64)	42.50 (5.78)	53.33 (3.44)	53.33 (4.11)	63.33 (4.77)	50.83 (4.89)

Note. FFr = recent famous face pairs; FFo = old famous face pairs; NNy = young nonfamous face pairs; NNa = aged nonfamous pairs. Values are averaged across participants in the group. Standard error appears within parentheses.

p = .001, η_p^2 = .15. These results show that the older adults had poorer discrimination, but in both groups, familiarity differentially affected within-category and between-categories discrimination. Moreover, an interaction of Group × Morph Step was marginally significant, $F(2, 92) = 2.51$, $p = .087$, $\eta_p^2 = .05$, suggesting that the groups exhibited different patterns of categorical perception.

Given the significant Familiarity × Morph Step interaction, we examined the two familiarity conditions separately. In the famous conditions (FFo, FFr), a 2 × 2 × 3 ANOVA (Group × Recency × Morph Step) revealed a significant effect of group, $F(1, 46) = 11.71$, $p = .001$, $\eta_p^2 = .20$, and morph step, $F(2, 92) = 40.08$, $p < .001$, $\eta_p^2 = .47$, but no other effects. Both groups showed a characteristic shape of discrimination reflecting categorical perception (see Figure 3B), in which discrimination was better across the boundary than within category. Older adults, however, showed overall poor discrimination compared with younger adults.

In the nonfamous conditions (NNa, NNy), a 2 × 2 × 3 ANOVA showed a significant effect of group, $F(1, 46) = 8.76$, $p = .005$, $\eta_p^2 = .16$, and morph step, $F(2, 92) = 40.15$, $p < .001$, $\eta_p^2 = .47$, a significant interaction of Morph Step × Face Age, $F(2, 92) = 4.78$, $p = .01$, $\eta_p^2 = .09$, and a marginal interaction of Group × Morph Step, $F(2, 92) = 2.98$, $p < .06$, $\eta_p^2 = .06$. Although older adults had poorer discrimination than younger adults, the two groups showed different patterns in discrimination of within-category versus between-categories faces. No interaction between group and face age suggests no own-age bias.

Moreover, to characterize the pattern of discrimination performance across the three morph steps (10–30%, 40–60%, 70–90%), we performed a trend analysis and Bonferroni tests for each condition separately in each group. With famous faces, older adults demonstrated enhanced discrimination of between-categories faces (40–60%) compared with within-category faces (10–30%, 70–90%). Specifically, in FFo, older adults' data were approximated better by a quadratic function, $F(1, 23) = 20.12$, $p < .001$, $\eta_p^2 = .47$, than by a linear relationship, $F(1, 23) = 3.70$, $p = .07$, $\eta_p^2 = .14$. In Bonferroni tests, older adults showed better discrimination of 40–60% compared with 10–30% (mean difference or $MD = 25.8$, $p < .001$) or 70–90% ($MD = 16.3$, $p = .009$). In FFr, older adults' data demonstrated both quadratic, $F(1, 23) = 14.24$, $p = .001$, $\eta_p^2 = .38$, and linear, $F(1, 23) = 5.91$, $p = .02$, $\eta_p^2 = .20$, trends: They performed better in 40–60% than in 10–30% ($MD = 22.9$, $p < .001$), although discrimination in 40–60% was not significantly better than in 70–90% ($MD = 6.3$, $p = .85$). (It is noted that no difference between 40–60% and 70–90% was also demonstrated in younger adults, and we discuss this at the end of this section.) However, with nonfamous faces, older adults did not show enhanced discrimination of between-categories faces (40–60%; see Figure 3B). In NNa, there was a significant linear trend, $F(1, 23) = 20.69$, $p < .001$, $\eta_p^2 = .47$, but no quadratic relationship ($F < 1$). Similarly, in NNy, only a linear trend was significant, $F(1, 23) = 4.98$, $p < .04$, $\eta_p^2 = .18$, but not a quadratic relationship, $F(1, 23) = 1.04$, $p = .32$, $\eta_p^2 = .04$.

Younger adults showed enhanced discrimination of between-categories faces compared with within-category faces with famous faces. In FFo, the data showed both quadratic, $F(1, 23) = 25.16$, $p < .001$, $\eta_p^2 = .52$, and linear, $F(1, 23) = 17.34$, $p < .001$, $\eta_p^2 = .43$, trends. Bonferroni tests revealed an advantage of between-categories faces: 40–60% versus 10–30% ($MD = 38.8$, $p < .001$), and 40–60% versus 70–90% ($MD = 15.4$, $p < .04$). In FFr, younger adults demonstrated both quadratic, $F(1, 23) = 11.59$, $p = .002$, $\eta_p^2 = 0.34$, and linear, $F(1, 23) = 9.50$, $p = .005$, $\eta_p^2 = .29$, trends, with a better discrimination of 40–60% compared with 10–30% ($MD = 27.1$, $p = .002$), although the difference in 40–60% versus 70–90% was not significant ($MD = 8.8$, $p = .30$). In NNa, there was a significant quadratic pattern, $F(1, 23) = 15.30$, $p = .001$, $\eta_p^2 = .40$, and linear trend, $F(1, 23) = 43.04$, $p < .001$, $\eta_p^2 = .65$: Discrimination of 40–60% was better than that of 10–30% ($MD = 32.9$, $p < .001$), although no difference was found between 40–60% and 70–90% ($p = 1$). In NNy, similarly, there was a significant quadratic relationship, $F(1, 23) = 7.83$, $p = .01$, $\eta_p^2 = .25$, as well as linear, $F(1, 23) = 11.86$, $p = .002$, $\eta_p^2 = .34$, with a better discrimination of 40–60% compared with 10–30% ($MD = 22.1$, $p < .001$). There was no difference between 40–60% and 70–90% ($MD = 4.6$, $p = 1$). Thus, younger adults demonstrated an advantage for between-categories pairs across all conditions.

Figure 3B shows that discrimination accuracy is better at the end (70–90%) of the continua than the beginning (10–30%), which was also observed in other studies using unfamiliar faces (Angeli, Davidoff, & Valentine, 2008; Kikutani, Roberson, & Hanley, 2008; Levin & Beale, 2000; McKone et al., 2001). Such trends were obscured as we implemented some controls: First, participants were specifically instructed to look for "image" differences, not identity differences; second, presentation location (top or bottom) of faces in each pair was randomized across trials; and third, endpoint morphs (e.g., 70%, 90% of Face 1) would have a similar familiarity as morphs in the beginning (e.g., 10%, 30% of Face 2 = 90%, 70% of Face 1) because we included only those faces that were known to the participant and different famous face pairs were used across participants. The trend was even stronger in the NN condition, which is not explained by familiarity. Although we employed some controls as described above, and made an effort to match two endpoint faces in terms of similarity, it is possible that one of the endpoint faces in a pair was preferred as a reference or was relatively easier to discriminate.[1] Despite these possibilities, the differential patterns of performance between older and younger adults in the NN condition suggest reduced categorical perception in older adults (see the online Supplemental Materials).

Obtained Versus Predicted Discrimination

To compare obtained and predicted discrimination accuracy in two groups, we conducted a 2 × 2 × 7 mixed ANOVA with group, discrimination type (obtained vs. predicted), and morph step (10–30%, 20–40%, 30–50%, 40–60%, 50–70%, 60–80%, 70–90%) in each condition. Because morph step was included as a factor to take account of all discrimination accuracy, but was not

[1] Previous studies discussed this artifact such that one of the endpoint faces might have been used as a base for comparison (Levin & Beale, 2000) or was distinctive (Angeli et al., 2008). However, it should be noted that unlike the present study, these previous studies employed a better likeness task (e.g., "Which of these faces looks more like Jen?"), which forced the participants to use one of the endpoint faces as a reference. For this reason, their explanation would not be applicable directly to the present study. In Kikutani et al. (2008), an X–AB match-to-sample discrimination task was used. McKone et al., 2001 used a similarity rating (e.g., "How similar are A and B?"), which did not require an endpoint face to be a reference, but still observed asymmetry in some of their participants.

of interest to our analysis (because our goal was to examine group differences in obtained and predicted discrimination), the main effect or interaction involving morph step is not reported here.

The ANOVA revealed differences in the way in which perceptual features and identity labels (memory components) are used in older and younger participants (see Figure 3B and Table 3). In each of the conditions, all effects were significant (except a marginal interaction in NNy): In FFo, group, $F(1, 46) = 18.30$, $p < .001$, $\eta_p^2 = .29$; type, $F(1, 46) = 23.37$, $p < .001$, $\eta_p^2 = .34$; Group × Type, $F(1, 46) = 14.98$, $p < .001$, $\eta_p^2 = .25$. In FFr, group, $F(1, 46) = 16.36$, $p < .001$, $\eta_p^2 = .27$; type, $F(1, 46) = 22.92$, $p < .001$, $\eta_p^2 = .34$; Group × Type, $F(1, 46) = 13.23$, $p = .001$, $\eta_p^2 = .23$. In NNa, group, $F(1, 46) = 11.75$, $p = .001$, $\eta_p^2 = .20$; type, $F(1, 46) = 18.28$, $p < .001$, $\eta_p^2 = .28$; Group × Type, $F(1, 46) = 11.44$, $p = .001$, $\eta_p^2 = .20$. In NNy, group, $F(1, 46) = 5.11$, $p = .03$, $\eta_p^2 = .10$; type, $F(1, 46) = 23.39$, $p < .001$, $\eta_p^2 = .34$; Group × Type, $F(1, 46) = 3.59$, $p = .06$, $\eta_p^2 = .07$. Figure 3B demonstrates the interaction between group and discrimination type, with older participants showing poorer obtained than predicted discrimination, and younger participants showing similar obtained than predicted discrimination. That is, when older adults' discrimination is predicted solely on the basis of their ability to classify (or label) facial identity, their obtained (actual) discrimination performance is consistently worse than predicted. These results imply that older adults may not use perceptual cues to perform discrimination as effectively as younger adults do, a matter we consider further in the discussion.

Discussion

Summary of the Results

The present study assessed categorical perception of famous and nonfamous faces to examine the effects of aging and familiarity on face perception and representation. First, classification across a progressive series of morphs between two faces showed that the slope of older adults was shallower than that of younger adults, whereas both groups were better at classifying famous faces than nonfamous faces. These results indicate that older adults were less able to distinguish different categories compared with younger adults, with a hint that the deficit was more pronounced when the faces were unfamiliar than familiar. Such results suggest that face representation is more broadly tuned in older adults (Wilson et al., 2011; also see Liang et al., 2010). Nonetheless, the location of the category boundary was not affected by age in any of the conditions, indicating that decision criteria do not change with age (Kiffel et al., 2005).

Second, discrimination tasks revealed that older adults showed reduced sensitivity to differences between faces compared with younger adults across all conditions. However, older adults still showed a better discrimination of famous faces across the boundary (advantage for between-categories discrimination), the hallmark of CP, thereby lending credence to the age-related familiarity effect that was noted in classification. With nonfamous faces, older adults demonstrated less enhancement in discrimination across the boundary (Kiffel et al., 2005) compared with younger adults.

Third, obtained discrimination was lower than predicted discrimination in older adults, but equivalent in younger adults across all conditions, including famous faces. This suggests that older adults are limited in their use of perceptual features (e.g., see Strouse et al., 1998, for auditory domain) but could perform better if relying on category labels or memory. Their classification performance, although worse than that of younger adults, remains adequate as it relies primarily on categorical information that is not sensitive to subtle differences of within-category faces. Discrimination, however, takes those into account, which is why obtained performance in the older adults is worse than predictions based on classification. We now discuss in more detail the implications of these results with regards to aging and perceptual representations.

Face Representation Is Broadly Tuned in Old Age

As we predicted, face representation was less precise in older, than in younger, adults. The slope of the older adults' classification responses was shallower than that of younger adults and, although both groups benefitted from familiarity, older adults did so somewhat more. This reduction in classification performance with age, and the increased benefit conferred by familiarity, is reflected in their discrimination performance. Indeed, older adults showed less of an advantage for between-categories faces with nonfamous faces than they did for familiar faces.

For a number of reasons, older adults' poor performance with unfamiliar faces is not likely due to their difficulty in learning the face–name associations, which was part of the procedure. First, they performed as well as younger adults in classifying endpoint faces (10% or 90%) with great accuracy. Second, older adults exhibited higher predicted discrimination estimated from classification data, which also required face–name associations, than that obtained from actual discrimination tasks. Third, the category boundary of nonfamous faces did not differ between the two age groups, indicating that older adults built different (albeit weaker) representations even for the faces that they just learned. Lastly, and perhaps most important, the

Table 3
Obtained Versus Predicted Discrimination Averaged Across Morph Steps (Percentage Correct)

	Older adults				Young adults			
Discrimination	FFo	FFr	NNa	NNy	FFo	FFr	NNa	NNy
Obtained	37.08	36.21	38.39	38.45	55.59	54.70	54.70	49.00
Predicted	57.03	56.74	56.32	55.20	57.81	57.50	56.79	56.31

Note. FFr = recent famous face pairs; FFo = old famous face pairs; NNy = young nonfamous face pairs; NNa = aged nonfamous pairs. Values are averaged across participants and across morph steps, reflecting the analysis of variance results reported in the Results section.

discrimination task required a same or different *perceptual* judgment of simultaneously presented faces, not naming. Intriguingly, a shallower slope in classification and worse obtained than predicted discrimination is not limited to visual tasks in older adults, as such phenomena also have been observed in the auditory domain, in which older adults were less able to distinguish phoneme categories (/ba/ and /pa/; Strouse et al., 1998).

Our results may reflect the broader tuning of neurons to facial identity in the brains of older adults and possibly to stimuli in other domains, as was evident in perception of orientation (Leventhal et al., 2003), motion (Liang et al., 2010), and speech (Strouse et al., 1998). At the perceptual level, even neural representation for well-known faces might also be broadly tuned, as indicated by lower obtained than predicted discrimination across all conditions. In this context, better performance with famous faces is interpreted as older adults benefitting from prior knowledge of the faces that they can identify, or the ability to use labels to sharpen the representations and perceptions. We return to this point in the next section. Such broad tuning, especially for unfamiliar faces, would account for the greater tendency of older, than younger, adults to misclassify a novel face as familiar (i.e., false alarm errors; Bartlett et al., 1991; Lee et al., 2014). By comparison, the greater CP among familiar than unfamiliar faces suggests that mistaking one familiar face for another is less likely to occur as one ages (i.e., intact hits; Bartlett et al., 1991; Lee et al., 2014), but is still more likely than in younger adults.

Our findings are consistent with those reported in studies of old monkeys that show broadly tuned neurons in the middle temporal area (Liang et al., 2010) and V1, perhaps due to reductions in GABA-mediated lateral inhibition (Leventhal et al., 2003). In these studies, decreases in neuronal selectivity are accompanied by increases in neural noise and peak response. Functional degradation of neurons at early visual processing stages, such as V1, could cascade downstream to higher processing stages, such as those for faces and objects. In our fMRI study (Lee et al., 2011), older adults' fusiform gyrus responded equivalently to faces across different conditions of facial identity and viewpoints, that is, they showed no face-specific or viewpoint-specific selective adaptation, as did younger adults (also see Burianová et al., 2013). Reduced neural specialization is not limited to face recognition but extends to processing of other visual categories in the occipitotemporal cortex (Burianová et al., 2013; Park et al., 2004). A neural model based on human psychophysical data (Wilson et al., 2011) also has suggested broadening of cortical bandwidths for facial orientation in older adults. Such overlapping representations as a result of broad tuning could lead to false identification often observed in older adults (Bartlett et al., 1991). Age-related broad tuning is likely a general phenomenon encompassing perception of other visual objects.

Memory Could Aid Perception in Older Adults

Although older adults' discrimination performance is poorer overall than that of younger adults, it is illuminating that older adults showed between-categories discrimination advantage for famous faces but not for nonfamous faces. These results argue against Kiffel and colleagues' (2005) conclusions that "older people do not access familiar representations" and "older people would rely on other facial cues (than identity) to perform discrimination" (p. 140). Our finding indicates that older adults can use stored information about faces they know well, either in the form of stored representations or identity labels, to aid their between-categories discrimination performance. That there was no added advantage for faces that became famous long ago rather than recently suggests that this benefit did not arise from information consolidated when the older adults were much younger, but can be acquired even recently. The latter finding suggests, as well, that with time and experience, older adults can convert novel faces to familiar faces and reap the accompanying benefits in recognition and perception, probably using their spared semantic processing (e.g., St-Laurent, Abdi, Burianová, & Grady, 2011).

The interaction between memory and perception is evident from other studies in the literature. Li, Mayhew, and Kourtzi (2009) showed that following category learning, activity in the prefrontal areas and ventral visual regions reflected the younger observers' behavioral shift in perceived category boundaries as a result of learning. It has also been shown that learning enhances neuronal responses and sharpens the neuronal tuning (i.e., narrower tuning curves) in monkey V4 (Yang & Maunsell, 2004). These changes in ventral visual regions as a result of learning are likely influenced by the top-down signal from frontal areas (Bar, 2009; Bar et al., 2006). Because it has been shown that high-performing older adults use the frontal areas to compensate for face perception deficits (Burianova et al., 2013; Grady et al., 2002; Lee et al., 2011; also see Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008), it would be valuable to know whether similar areas are implicated in the familiarity advantage that we observed in older adults, and whether these areas are recruited when novel items become familiar in both age groups.

Our data may also speak to research on the proactiveness of the brain with aging, namely, the idea that the ability to use information stored in memory to generate predictions and guide our decisions given uncertain external input (Bar et al., 2006) may be relatively maintained in the aging brain. Bar (2009) has proposed that we not only interpret our world by analyzing incoming information, but we also "try to understand it" by linking external input to existing representation in memory (p. 1235). He argues that one role of memory is to predict and guide our behavior by associating previous experience with external input and generating a novel mental scenario. A recent study using fMRI and multivariate pattern analysis has also revealed that expectation sharpened sensory representations in the primary visual cortex and facilitated perception (Kok, Jehee, & de Lange, 2012). The brain shows a remarkable ability to adapt to uncertain situations by referring to existing representations. However, it may not always be correct. In the aging brain, due to broad tuning functions, poor visual representation of a novel face at the level of perception could be wrongly associated with memory of a known face and could lead to false identification (Bartlett et al., 1991), a phenomenon also associated with damage to anterior and medial temporal regions, such as perirhinal cortex, in humans and rodents (Yeung, Ryan, Cowell, & Barense, 2013) and rodents (McTighe, Cowell, Winters, Bussey, & Saksida, 2010).

Conclusion

Using a behavioral CP paradigm, our study provides insights into neural representations of faces in old age. Broad tuning could result in two types of behavioral errors, false alarms and misses, and the literature indicates that older adults are likely to make more false alarms but show equivalent hits to those of younger adults (e.g., Bartlett et al., 1991; Lee et al., 2014; Searcy et al., 1999). Our results suggest that reduced identification and discrimination of faces are due to less precise face representations in older adults, consistent with the idea that older age is associated with broader tuning of neural responses to faces, making it more difficult for older adults to identify faces and to discriminate between old and new faces. Semantic memory helps perceptual discrimination in older adults, leading to correct identification of familiar faces, whereas representations that are newly acquired are not robust enough to help perception, leading to poorer identification and discrimination characterized by greater false alarms, as older adults tend to categorize lures as targets.

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