

# Dissociating the neural bases of repetition-priming and adaptation in the human brain for faces

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**Kaiser D, Walther C, Schweinberger SR, Kovács G.** Dissociating the neural bases of repetition-priming and adaptation in the human brain for faces. *J Neurophysiol* 110: 2727–2738, 2013. First published October 2, 2013; doi:10.1152/jn.00277.2013.—The repetition of a given stimulus leads to the attenuation of the functional magnetic resonance imaging (fMRI) signal compared with unrepeatable stimuli, a phenomenon called fMRI adaptation or repetition suppression (RS). Previous studies have related RS of the fMRI signal behaviorally both to improved performance for the repeated stimulus (priming) and to shifts of perception away from the first stimulus (adaptation-related aftereffects). Here we used identical task (sex discrimination), trial structure [stimulus 1 (S1): 3,000 ms, interstimulus interval: 600 ms, stimulus 2 (S2): 300 ms], and S2 stimuli (androgynous faces) to test how RS of the face-specific areas of the occipito-temporal cortex relates to priming and aftereffects. By varying S1, we could induce priming (significantly faster reaction times when S1 and S2 were identical compared with different images) as well as sex-specific aftereffect [an increased ratio of male responses if S1 was a female face compared with ambiguous faces or to Fourier-randomized noise (FOU) images]. Presenting any face as S1 led to significant RS of the blood oxygen level-dependent signal in the fusiform and occipital face areas as well as in the lateral occipital cortex of both hemispheres compared with FOU, reflecting stimulus category-specific encoding. Additionally, while sex-specific adaptation effects were only observed in occipital face areas, primed trials led to a signal reduction in both face-selective regions. Altogether, these results suggest the differential neural mechanisms of adaptation and repetition priming.

adaptation; face; fMRI; priming

STIMULUS REPETITION HAS SEVERAL consequences, on both the behavior of a subject and neural responses. Behaviorally, the prior presentation of a related or identical stimulus can lead to faster and more accurate responses for a given target. This effect is known as priming and is studied extensively for both low-level (Magnussen 2000) and high-level stimuli, such as faces. In the latter case, priming effects were typically investigated for familiarity or identity decisions in long-term (e.g., Ellis et al. 1987, 1996) and immediate repetition contexts (e.g., Bindemann et al. 2008; Brooks et al. 2002; Schweinberger et al. 2002). Additionally, in various paradigms the preceding stimulus (the adaptor) has been shown to bias the decisions about a target, leading to contrastive adaptation-related aftereffects (Clifford et al. 2007; Thompson and Burr 2009). Such aftereffects have been found for a wide range of stimuli from

oriented lines (Campbell and Maffei 1971; Clifford 2002) and moving patterns (Anstis et al. 1998; Sekuler and Ganz 1963) to high-level visual stimuli such as faces (e.g., Webster and MacLin 1999; for a review, see Webster and MacLeod 2011). In such paradigms of aftereffects for example, the sex classification of an androgynous face was found to be biased toward male decisions following prolonged adaptation to a female face and toward female decisions following adaptation to a male face (Kloth et al. 2010; Kovács et al. 2006, 2007; Webster et al. 2004). Despite the clear differences in their behavioral outcomes, both priming and aftereffects are currently associated with similar neural effects, predominantly with a reduction of neural activation for a repeated stimulus compared with a nonrepeated one, a phenomenon termed as repetition suppression (RS).

Although priming effects can also be observed for the repetition of semantically related nonidentical stimuli, in the present study we focus on the case of identical image repetition priming, since there is evidence that both phenomena rely on different neural processes (Schweinberger et al. 1995). For the repetition of identical stimuli, several extracellular single-cell studies have shown RS of the neural response in the monkey brain (Desimone 1996; Gross et al. 1972; Miller et al. 1991). The neural effects of stimulus repetition have also been studied extensively in human subjects using functional magnetic resonance imaging (fMRI). The blood oxygen level-dependent (BOLD) signals of the extrastriate visual areas have been shown to decrease for repeated compared with nonrepeated stimulation, a phenomenon currently considered as the neuroimaging equivalent of the RS observed on the single-cell level. This phenomenon has become known as fMRI adaptation (fMRIa) and is currently widely applied in the cognitive neurosciences (for reviews, see Grill-Spector and Malach 2001; Grill-Spector et al. 2006; Krekelberg et al. 2006) to infer neural stimulus tuning by manipulating the adaptor stimuli and monitoring the changes of response attenuation in very different behavioral paradigms (Grill-Spector et al. 2006; Kourtzi and Kanwisher 2001; Malach 2012). However, due to the large variety of applied designs, it is not yet clear how RS and certain behavioral effects relate to each other. Moreover, although several models have been suggested in the past to explain the neural mechanisms of fMRIa and RS (De Baene and Vogels 2010; Grill-Spector et al. 2006; Sawamura et al. 2006), it is also unclear as yet if a single, unified model can explain the response attenuation of different cortical areas elicited by various methods.

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As for paradigms related to priming, identical stimulus repetition leads to RS of the BOLD signal in extrastriate regions of the visual cortex (Buckner et al. 1998; Henson 2003; Koutstaal et al. 2001). This RS is usually the most pronounced for immediate stimulus repetitions (Sayres and Grill-Spector 2006), but has also been shown after longer delays, even after several days (van Turennout et al. 2000). For face stimuli, repeated presentation of a certain face elicits reduced BOLD signals in face-selective cortical regions (Andrews and Ewbank 2004; Henson et al. 2002; Summerfield et al. 2008), such as the occipital face area (OFA; Gauthier et al. 2000) and the fusiform face area (FFA; Kanwisher et al. 1997), but also in the object-selective lateral occipital cortex (LO; Malach et al. 1995). These regions have been connected to different functions within the face-processing network (Haxby et al. 2000), with FFA being associated with face processing at a configurational level (Kanwisher et al. 1998), which is supported by a lack of a disruption in RS by low-level changes in this region (Andrews and Ewbank 2004) or by changes in other aspects of the face stimuli, such as their expression (Winston et al. 2004). A study using morph continua between two famous faces (Rotshtein et al. 2005) found that RS in the FFA was only present if the category boundary between the two presented stimuli was crossed, reflecting the neural basis for the effect of categorical perception of face identity (Beale and Keil 1995). In contrast, RS in OFA was largely driven by physical changes in the stimuli, regardless of the location of the individual stimuli in the morph continuum (Rotshtein et al. 2005). The authors also found that anterior regions of the face-processing network reflect greater sensitivity to identity changes (i.e., greater BOLD-signal differences for pairs that fall within one identity and pairs crossing the categorical boundary) for faces that were more familiar to the subjects. Indeed, RS has been shown to depend on face familiarity: while reduced responses in face-selective regions can be observed for familiar faces, enhanced responses can be observed for unfamiliar stimuli (Henson et al. 2000). Although most of these studies of RS did not employ behavioral measures of processing efficiency (such as faster reaction times for primed vs. unprimed conditions), it is possible that RS of the BOLD signal is related to the behaviorally observed effects in repetition priming paradigms (for a review, see Henson 2003). Nevertheless, a causal link between behavioral priming and RS has not been determined [see Buracas et al. (2005) for the general problem of linking fMRI responses to behavior], and so far only a few neuroimaging studies have attempted to make such correlations. In fact, some studies have raised doubts about RS being the neural equivalent of priming, as either RS was not specific to their “primed” conditions (Ganel et al. 2006), or its magnitude did not correlate with the amount of behaviorally observed effects (Sayres and Grill-Spector 2006). RS has also been linked favorably to rapid response learning rather than priming (Dobbin et al. 2004; Horner and Henson 2008).

Interestingly, aftereffects in face perception have been associated with RS in face-selective regions as well (Cziraki et al. 2010; Furl et al. 2007; Löffler et al. 2005). Sex adaptation has been shown to lead to lower BOLD signals in OFA and FFA compared with control conditions using phase-randomized adaptors (Kovács et al. 2008). This result is consistent with the N170/M170 modulations in event-related potentials (ERPs) that have been observed following adaptation (Harris and

Nakayama 2007; Kovács et al. 2005, 2007) and is thought to reflect the structural encoding stages of face processing (Bentin et al. 1996; Rossion et al. 1999). Reduced activity in extrastriate body area (Downing et al. 2001) and FFA has also been found in a study of face vs. hand category adaptation (Cziraki et al. 2010). In this study, face or hand adaptors biased the perception of ambiguous test stimuli in opposite directions: while hand adaptation led to RS in extrastriate body area, face adaptation led to RS in FFA, showing that adaptation aftereffects are category specific on a neural level. In studies of face-sex aftereffects, RS seems to be associated with the behavioral effect of biased sex perception: RS was shown to occur in conditions in which sex perception was altered due to prior adaptation (Kovács et al. 2008). However, a recent ERP study (Kloth et al. 2010) comparing the effects of sex-specific and face-specific adaptations failed to show a clear connection between N170 modulations and sex-specific adaptation: the same N170 modulations were found for test stimuli following any face adaptors (ambiguous as well as unambiguous) compared with phase-randomized noise adaptors. This suggests that the N170 modulation effect is due to adaptation to the category of faces, irrespective of sex, and reflects the neural processes related to generic face configuration processing rather than sex-specific encoding mechanisms.

The similarity between findings from neuroimaging studies of priming and aftereffects is somewhat surprising because of the distinct behavioral implications of the two phenomena. Although there are studies that have tried to elicit priming and aftereffects in subjects' behavior by manipulating temporal properties, predominantly the length of the interstimulus interval (motion aftereffect: Kanai and Verstraten 2005; Pavan et al. 2009; high-level object aftereffects: Daelli et al. 2010), no study has compared the fMRI-correlates of priming and adaptation within the same subjects and paradigm, as of yet. Such a comparison could shed light on the question of whether RS, as it is associated with both behavioral phenomena, reflects different mechanisms or a common underlying system.

Eliciting both effects within a single paradigm is not entirely straightforward due to the fundamental differences between commonly used priming and aftereffect paradigms. First, the timing parameters between priming and aftereffect studies differ: while priming paradigms typically employ short *stimulus 1* (S1) (prime) durations or even masked presentation of the prime (Henson 2003; Sayres and Grill-Spector 2006), aftereffect paradigms typically use longer S1 (adaptor) durations (although relatively shorter durations can lead to aftereffects as well; see Kovács et al. 2007). Second, the behavioral tasks vary for studies of priming and aftereffects: tasks in typical priming studies are usually based on features necessary for recognition, which are suitable for quantifying processing efficiency (e.g., deciding if a person is a famous person or not), whereas tasks in studies of aftereffects always have to include the adapted stimulus feature to see the behavioral aftereffect (e.g., deciding if a face is male or female after being adapted to a male or female face).

In a recent EEG study (Walther et al. 2013), we used a face identity adaptation paradigm, where we manipulated the ambiguity of the test stimulus on a continuum between two famous male faces. We observed behavioral aftereffects for ambiguous test stimuli; however, if the test stimuli were less ambiguous (i.e., they were closer to the veridical adaptor

faces), priming started to emerge. In addition to showing that both effects can be evoked within the same paradigm and subjects, we were able to identify ERP components that reflect priming and aftereffects separately. Priming was reflected by a modulation of components as early as 90 ms, with the most pronounced effect in the N250r range (Schweinberger et al. 2002). In contrast, category-specific adaptation effects were the largest on the N170 component, while identity-specific adaptation effects emerged only at around 205–255 ms poststimulus onset. These results suggested that exclusive, temporally separate mechanisms might underlie identity-specific priming and aftereffects as well as category-specific adaptation processes.

In our present study, we used fMRI to disentangle brain regions mediating priming and aftereffects. We used a sex-adaptation paradigm (Kovács et al. 2006, 2008) with familiar face stimuli to demonstrate that priming and adaptation to face-category can be observed within the same subjects and paradigm simultaneously. In contrast to our previous experiment (Walther et al. 2013), we manipulated priming and aftereffects by changing the S1 image rather than the S2 test stimulus. Using this paradigm, we were able to confirm that both priming and category-specific adaptation effects are related to the RS of face-selective regions. Additionally, we show that priming and aftereffects differ in their neural correlates and are therefore likely to employ different neural mechanisms and systems.

## MATERIALS AND METHODS

### Subjects

Seventeen healthy university students participated in the experiment (mean age: 22.9 yr, SD: 2.7 yr, 11 women, all right-handed). All participants had normal or corrected-to-normal vision and provided their written consent. The experiment was carried out in accordance with the Declaration of Helsinki and approved by the Ethical Committee of the University of Regensburg.

### Stimulation and Procedure

We collected images of 25 female and 25 male celebrities from the public domain of the world-wide web. The celebrities were selected based on their popularity in Germany and were therefore familiar to all subjects. Images were full-frontal and with a neutral expression. We then created 25 female-male stimulus pairs. For each pair we created the 50%:50% intermediate androgynous morph image, using Sierra Morph 2.5 (Sierra Home). All images were converted to grayscale, fit behind a shield-mask [to avoid any heuristic-based decisions of the outer features, see Goshen-Gottstein and Ganel (2000) for a similar procedure], and subjectively equated for luminance and contrast using Adobe Photoshop CS5 (Adobe Systems, San Jose, CA). All original male images were Fourier-phase randomized using the algorithm of Näsänen (1999), which replaces the phase spectrum with random values (ranging from 0 to 360), leaving the amplitude spectrum of the image intact. These images were used as control (“Fourier”) stimuli. All images (mean luminance: 18 cd/m<sup>2</sup>) were presented centrally and subtended a visual angle of 7° vertically and 6° horizontally. Stimuli were back-projected via an LCD video projector (JVC, DLA-G20, Yokohama, Japan, 72 Hz, 800 × 600 resolution) onto a translucent circular screen (30° diameter), placed inside the scanner bore at 63 cm from the observer. Stimulus presentation was controlled via Matlab (The MathWorks, Natick, MA), using Psychtoolbox (version 3.0.8). The experiment was composed of three runs of a sex-decision task (similar to that of Kovács et al. 2008).

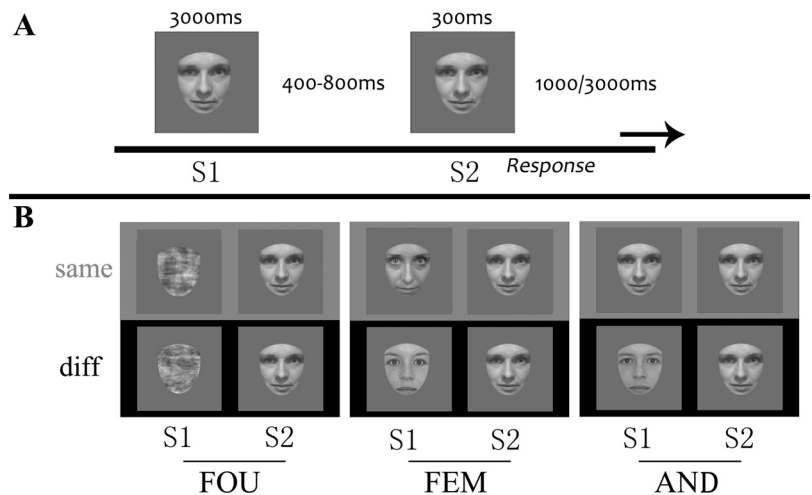
The order of the different blocks was counterbalanced between participants. Participants had to perform a two-alternative forced choice sex discrimination task, in which they were required to decide whether the androgynous target stimulus [*stimulus 2* (S2), presented for 300 ms] was male or female by pressing a button with either their index or middle finger. In each run (100 trials per run), the S2 was preceded by different adaptor stimuli (S1), which were presented for 3,000 ms. The different conditions appeared in random order within a given run. S1 and S2 were always separated by an interstimulus interval varying randomly between 400 and 800 ms, and the trials were followed by a 1- to 3-s long intertrial interval. To minimize local feature adaptation, the size of the S2 was reduced by 10% relative to S1, so that the S2 subtended a visual angle of 6.3° vertically and 5.4° horizontally. Each S2 image was repeated four times within a block. In the “Fourier run” (FOU), S1 was always a Fourier phase-randomized image. In one-half of trials, this image was the Fourier phase-randomized version of the male image used to create the S2 (FOU-S), while in the other one-half it was the phase-randomized version of another, unrelated original male face (FOU-D). In the “androgynous run” (AND), the S1 on one-half of the trials was the image of the same ambiguous androgynous face as the S2 (primed trial, AND-S), while on the other one-half of trials the S1 was an ambiguous image of another face pair (unprimed trial, AND-D). In the “female run” (FEM), on one-half of trials the S1 was the original female face that was used to create the ambiguous S2 (adaptation same trial, FEM-S), while on the other one-half of trials the S1 was an original female face that was unrelated to the S2 (adaptation different trial, FEM-D). Note that, despite the changes of S1, the S2 and the task that subjects had to perform, were identical for every block. These three runs were designed in a way that FOU, where S1 was always the Fourier phase-randomized version of S2, served as a control condition to estimate face category-specific effects (Kloth et al. 2010). AND, where S1 was either identical to S2, or it was another androgynous face, was designed to elicit image-repetition and image-priming effects. Finally FEM was used for testing sex-specific adaptation effects (Kloth et al. 2010; Kovács et al. 2008). See Fig. 1 for stimulus and trial examples. The reasons to apply our mixed block- and event-related design were the following. First, previous studies on aftereffects have presented trials in a blocked fashion (Cziraki et al. 2010; Kovács et al. 2008), while previous priming studies tended to present primed and unprimed trials randomly intermixed within the same block (e.g., Eger et al. 2005; Schweinberger et al. 1995, 2002, 2004). To make our study comparable to those studies of both priming and adaptation, we used a between-block comparison as a measure of aftereffects and a within-block comparison for priming. Second, this separation allowed us to reduce influences of primed trials on subsequent aftereffects trials and vice versa, and consequently helped us to obtain more independent measures of either effect.

### Parameters and Data Analysis

Imaging was performed using a 3-Tesla MR Head scanner (Siemens Allegra, Erlangen, Germany). For the functional series, we continuously acquired images (34 slices, 10° tilted relative to axial, T2\* weighted echo-planar imaging sequence, repetition time = 2,000 ms; echo time = 30 ms; flip angle = 90°; 64 × 64 matrices; in-plane resolution: 3 × 3 mm; slice thickness: 3 mm). High-resolution T1-weighted images were acquired using a magnetization-prepared rapid gradient-echo sequence (repetition time = 2250 ms; echo time = 2.6 ms; 1 mm isotropic voxel size) to obtain a three-dimensional structural scan. Details of preprocessing and statistical analysis are given elsewhere (Cziraki et al. 2010; Kovács et al. 2008). Briefly, the functional images were realigned, normalized to the Montreal Neurological Institute (MNI)-152 space, resampled to 2 × 2 × 2 mm resolution, and spatially smoothed with a Gaussian kernel of 8 mm full-width half maximum (SPM8, Wellcome Department of Imaging Neuroscience, London, UK). Regions of interests (ROI) analysis was



Fig. 1. **A**: timing parameters of a single trial. This example shows an androgynous run primed trial (AND-S) trial. **B**: overview of all conditions used in the experiment. Note that the stimulus 2 (S2) is identical in every condition, while the stimulus 1 (S1) varies. In the same-condition, the S1 is related or identical to the S2 (see MATERIALS AND METHODS), in the diff-condition, the S1 is unrelated to the S1. Fourier run (FOU), androgynous run (AND), and female run (FEM) were grouped in runs, while the same and diff trials were presented randomly during each run. Note that, in the experiment, famous face images were used. Due to publication restrictions, here we illustrate the conditions with unfamiliar face images from our own database.



based on the results of a separate functional localizer run (480 s long, 20-s epochs of stimulation). For this localizer scan, blocks of faces (different from those used than in the main experiment), nonsense objects and their Fourier phase-randomized versions were presented, interleaved with 20 s of blank periods (stimulus presentation rate: 2 Hz; 300-ms exposition time; 200-ms blank). MARSBAR 0.42 toolbox for SPM (Brett et al. 2002) was used for the ROI data analysis. One subject was excluded from the ROI analysis due to bad localizer data.

The location of face-responsive areas was determined individually as areas responding more strongly to faces than to objects and to Fourier noise images in the functional localizer scans ( $P_{\text{uncorrected}} < 10^{-6}$ ;  $T = 4.86$ ,  $df = 273$ ), FFA [average MNI coordinates ( $\pm SE$ ):  $-40 \pm 1$ ,  $-57 \pm 2$ ,  $-19 \pm 1$  and  $41 \pm 1$ ,  $55 \pm 2$ ,  $-17 \pm 1$  for the left ( $n = 14$ ) and right hemispheres ( $n = 15$ ), respectively] and the OFA [average MNI coordinates ( $\pm SE$ ):  $-41 \pm 1$ ,  $-78 \pm 2$ ,  $-12 \pm 1$  and  $43 \pm 1$ ,  $-77 \pm 1$ ,  $-12 \pm 1$  for the left ( $n = 14$ ) and right ( $n = 13$ ) hemispheres]. Areas selectively responding to objects were determined by similar functional localizer scans comparing the activity obtained for nonsense objects vs. their Fourier randomized versions and faces ( $P_{\text{uncorrected}} < 10^{-6}$ ;  $T = 4.86$ ;  $df = 273$ ) and area LO [average MNI coordinates ( $\pm SE$ ):  $36 \pm 2$ ,  $-79 \pm 2$ ,  $7 \pm 2$  and  $37 \pm 2$ ,  $-79 \pm 2$ ,  $4 \pm 2$  for left ( $n = 11$ ) and right ( $n = 11$ ) hemispheres]. The ROIs were selected individually on the single-subject level from these thresholded T-maps. Areas matching our anatomical criteria and lying closest to the corresponding reference clusters (based on the results of the previous literature) were considered as their appropriate equivalents on the single-subject level. All ROI analyses were performed on regions defined as spheres with a radius of 4 mm, centered at the localizer peak coordinates. The convolution of a reference canonical hemodynamic response function with box-car functions, representing the onsets and durations of the experimental conditions, was used to define the regressors for a general linear model (GLM) analysis. All trials were analyzed and modeled at the onset of the S2 stimuli. For the ROI analysis, we then computed %signal change separately for each event and ROI, using the regressors of the GLM. In addition to the above-described ROI analysis, we also conducted a random-effects whole-brain analysis (with a threshold  $P$  family-wise error  $< 0.05$ ) using the GLM model of the ROI analysis to search for additional areas, modulated by adaptation or priming. Finally, since recent studies suggest that, in adaptation paradigms the cortical response can depend on the behavioral response of the subjects (Cziraki et al. 2010), we performed a second random-effects whole-brain analysis where subjects' decisions were included in the GLM model as a regressor. For this analysis, we split the data of FEM-S/FEM-D according to whether adaptation biased perception away from the sex of the adaptor in a certain trial, or whether it did not lead to such contrastive biases. Similarly, we split the data of the AND-S/AND-D conditions as well into trials where the reaction times were

shorter than the respective subject's median reaction time (i.e., priming was present) and trials where the subject's reaction time was above his or her median reaction time (i.e., no priming is manifest).

For sex discrimination performance and reaction time, we performed a two-way within-subjects ANOVA with run type (3: FOU, FEM, AND) and trial type (2: same or different) as factors. In addition, we estimated the magnitude of aftereffect using the following formula:  $\text{Perf}_A = (\text{Perf}_{\text{FEM-S}} + \text{Perf}_{\text{FEM-D}})/2 - \text{Perf}_{\text{AND-D}}$  ( $\text{Perf}_{\text{FEM-S}}$ ,  $\text{Perf}_{\text{FEM-D}}$ , and  $\text{Perf}_{\text{AND-D}}$  are the percentage endorsed as male in the FEM-S, FEM-D, and AND-D conditions, respectively). Similarly, the magnitude of priming was calculated by  $\text{RT}_p = \text{RT}_{\text{AND-D}} - \text{RT}_{\text{AND-S}}$  ( $\text{RT}_{\text{AND-S}}$  and  $\text{RT}_{\text{AND-D}}$  are the average reaction times of the subjects for AND-S and AND-D, respectively). All post hoc analyses were performed by Fisher least significant difference tests.

## RESULTS

### Behavioral Results

**Aftereffect.** Subjects' sex discrimination performance (Fig. 2A) depended significantly on the nature of the S1 [main effect of run:  $F(2,32) = 23.71$ ;  $P < 0.001$ , without a significant main effect of trial-type or run  $\times$  trial interaction] in the sense that the mean proportion of "male" responses was significantly higher for FEM-S and FEM-D compared with the other conditions (where it was around chance level). This shows that prior presentation of a female face biases the perception of an ambiguous androgynous face toward male responses and leads to sex-specific face aftereffects, confirming previous results (Kloth et al. 2010; Kovács et al. 2006, 2008). On the other hand, FEM-S and FEM-D were not significantly different ( $P = 0.28$ ), suggesting that the identity of the adaptor stimulus had no effect on the sex decision bias. The same was true for FOU-S and FOU-D as well ( $P = 0.98$ ). Finally, it is worth mentioning that the average sex decisions in the AND-S and AND-D conditions were not significantly different from the performance in the FOU-S or FOU-D conditions either ( $P > 0.50$  for all comparisons). Since S1 was an androgynous face in both AND-S and AND-D, this confirms previous data that show no aftereffects following the presentation of neutral stimuli (Webster and MacLin 1999).

**Image repetition priming.** We found a significant difference in reaction times (Fig. 2B) between S1 conditions [main effect of run:  $F(2,32) = 4.03$ ;  $P = 0.03$ , main effect of trial:  $F(1,16) =$

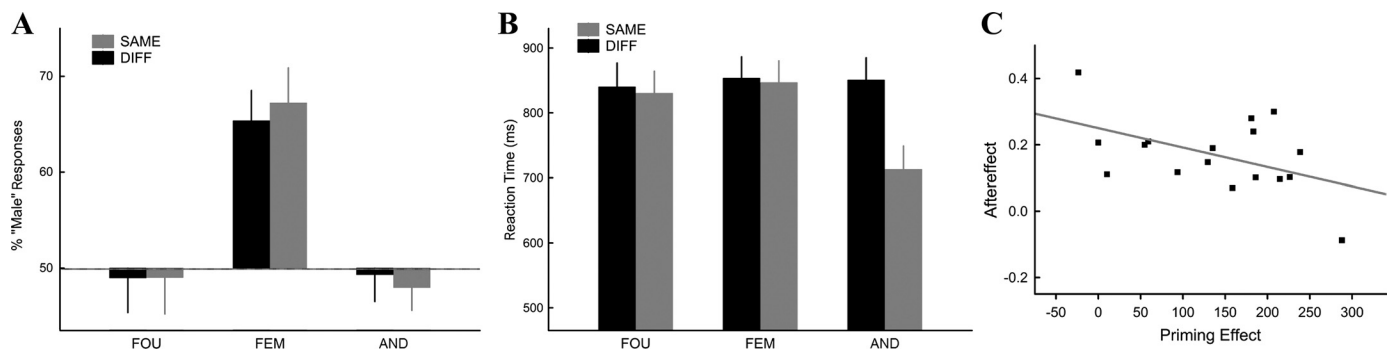


Fig. 2. Behavioral results. *A*: sex responses as proportions of “male” classifications. Only in the FEM conditions are responses biased (toward more “male” classifications), while in all other conditions the proportion of male responses is around 50%. *B*: reaction times. Reaction times were faster in the AND-S condition, which reflects a behavioral priming effect. *C*: correlation of priming and adaptation effect magnitudes. Subjects showing larger priming effects tended to show weaker adaptation effects and vice versa. Aftereffect magnitude was computed as the difference of FEM and androgynous run unprimed trial (AND-D) responses proportions, while priming effects were computed as the reaction time difference of AND-D and AND-S (see MATERIALS AND METHODS).

23.00;  $P < 0.001$ , run  $\times$  trial interaction:  $F(2,32) = 36.23$ ;  $P < 0.001$ ]. Responses were significantly faster in AND-S trials compared with any other S1 condition ( $P < 0.001$  for all comparisons), as revealed by post hoc tests. This suggests that repetition of the same stimulus [note that S1 and S2 were identical images in the AND-S condition, but S1 and S2 differed in size by  $\sim 10\%$  (see MATERIALS AND METHODS)] leads to shorter reaction times in the sex decision task, a manifestation of the behavioral priming effect. Furthermore, there was no significant difference between any of the other conditions ( $P > 0.10$  for all comparisons of FOU-S, FOU-D, FEM-S, FEM-D and AND-D).

Interestingly, we found a significant negative correlation between the magnitude of priming ( $RT_p$ ; expressed as the reaction time difference between AND-S and AND-D; see MATERIALS AND METHODS) and sex aftereffect (the difference of proportion of “male” responses between FEM-S/FEM-D and FOU-S/FOU-D; see MATERIALS AND METHODS; Fig. 2C;  $r = -0.48$ ,  $P = 0.05$ ). Subjects with larger priming showed weaker aftereffect and vice versa. This suggests that behavioral aftereffects and repetition priming effects are related to each other, despite the fact that priming and aftereffect are manifest after different S1 images (note that the aftereffect is measured by comparing AND-D vs. FEM S1 trials, while priming is measured by comparing the reaction times of the AND-S and AND-D S1 trials). Previous theoretical accounts (Theodoni et al. 2011) suggest that higher levels of neural adaptations lead to quicker decisions. Thus it is likely that, for participants who show strong adaptation aftereffects, their faster reaction times are not improved further by priming. This explanation is supported by the fact that subjects with greater adaptation effects tended to show lower overall reaction times as well ( $r = -0.36$ ,  $P = 0.15$ ).

### Neuroimaging Results

**ROI analysis.** For all ROI analyses, we computed a two-way repeated-measures ANOVA with run and trial as factors (see MATERIALS AND METHODS) for each ROI separately. We chose this procedure instead of including ROI and hemisphere as factors in the ANOVA as well, due to the varying number of subjects for each ROI and hemisphere (see MATERIALS AND METHODS). To illustrate the different aspects of priming and adaptation effects, we focused on particular comparisons within this analysis (see Table 1).

**ROI analysis: category-specific adaptation.** To quantify RS associated with the processing of stimulus category we focused on the difference between the FOU-S/D and the FEM-S/D conditions. We expected significant response reductions for the FEM-S and FEM-D conditions, similar to previous findings of adaptation studies with peripheral faces (Kovács et al. 2008) and other high-level stimuli (Cziraki et al. 2010). Figure 3 shows the results of this comparison for each ROI. We observed significant adaptation-related response reductions in the left FFA [main effect of run:  $F(2,26) = 18.28$ ;  $P < 0.001$ ], right FFA [main effect of run:  $F(2,28) = 20.12$ ;  $P < 0.001$ ] and left OFA [main effect of run:  $F(2,26) = 21.85$ ;  $P < 0.001$ ] and right OFA [main effect of run:  $F(2,24) = 7.84$ ;  $P = 0.0024$ ]. Similar results were also obtained for left LO [main effect of run:  $F(2,20) = 3.46$ ;  $P = 0.051$ ] and right LO [main effect of run:  $F(2,20) = 6.36$ ;  $P = 0.0073$ ]. These effects were due to the fact that both FOU-S and FOU-D were significantly different from FEM-S as well as FEM-D ( $P < 0.01$  for all comparisons), in that responses to FEM trials were lower than those to FOU trials. For all these regions, however, post hoc tests showed that the FOU-S and FOU-D conditions did not differ from each other (all  $P > 0.10$ ). Similarly, FEM-S and FEM-D conditions evoked similar BOLD signals ( $P > 0.60$  for all comparisons). Altogether this comparison shows that our paradigm led to a significant face category-specific adaptation of the response in several areas of the occipito-temporal cortex. This confirms previous findings with peripheral stimulus presentations (Kovács et al. 2008).

Table 1. Comparisons used in the neuroimaging analyses to access different aspects of priming and adaptation

| Contrast                     | Interpretation  |
|------------------------------|---|
| FOU > FEM                    | Face-specific adaptation  |
| AND-D > AND-S                | Image repetition priming  |
| FEM vs. AND-S                | Differential responses for adaptation and priming                   |
| Adaptation vs. no adaptation | Difference between trials with and without perceptual aftereffect   |
| Priming vs. no priming       | Difference between high and low reaction time benefit primed trials |

FOU, Fourier run; FEM, female run; AND-D, androgynous run unprimed trial; AND-S, androgynous run primed trial.

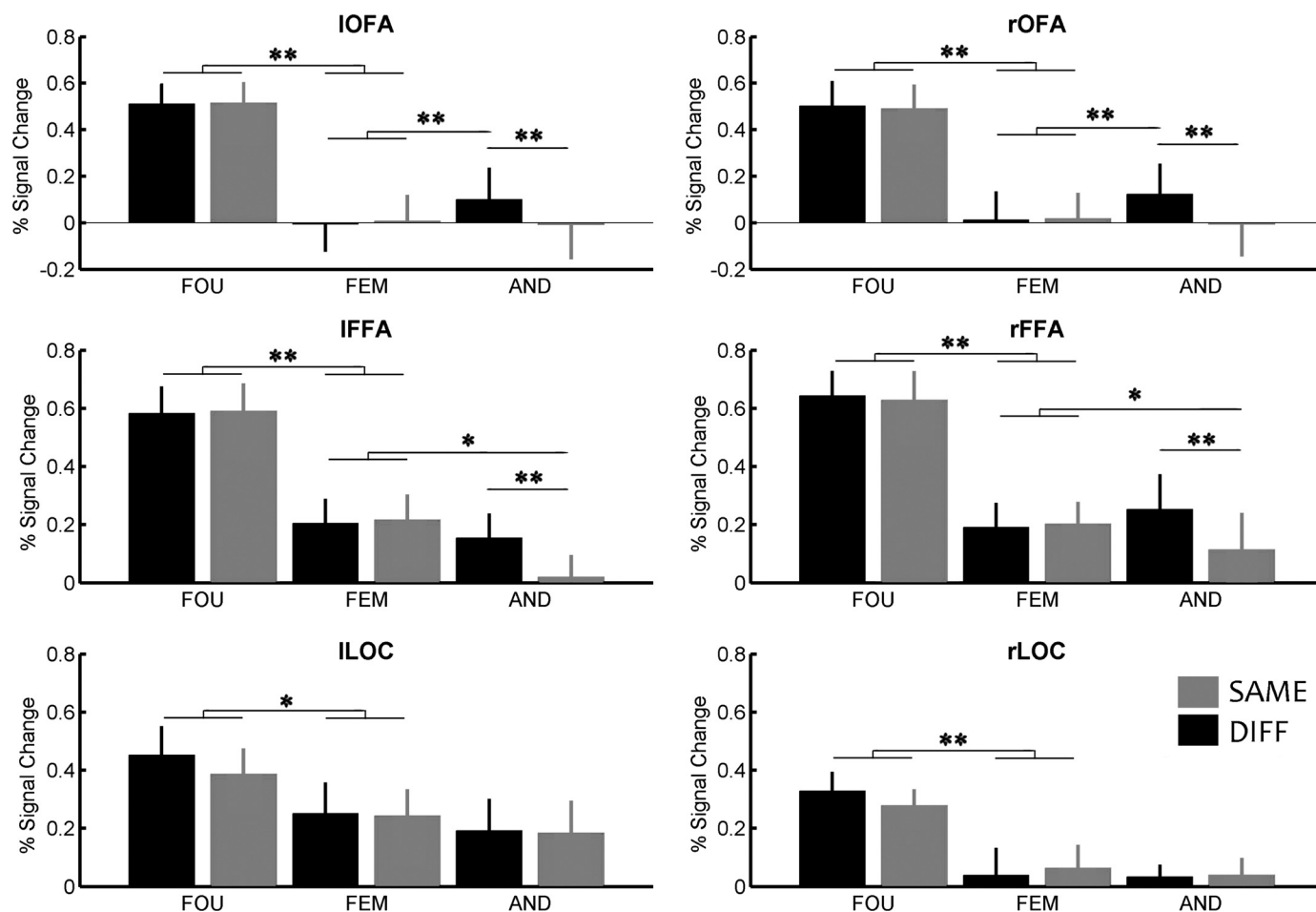


Fig. 3. Results of the region of interest (ROI) analysis. Face-specific adaptation effects (FOU vs. FEM) were found in all ROIs. Priming effect (AND-D vs. AND-S) can only be observed in the face-selective regions. While occipital face area (OFA) showed a sex-specific adaptation effect (AND-D vs. FEM), fusiform face area (FFA) was the only region that allowed differentiation between primed and adapted trials (FEM vs. AND-S). l, Left; r, right; LOC, lateral occipital cortex. \* $P < 0.05$ . \*\* $P < 0.001$ .

**ROI analysis: sex-specific adaptation.** The comparison of FOU and FEM illustrates the sensitivity of a given area to the category of face stimuli per se, suggesting “generic” face sensitivity, in a similar way to Kloth et al. (2010). However, we also found a significant response reduction for AND-S and AND-D trials in left and right FFA and OFA when comparing them to the FOU-S and FOU-D conditions ( $P < 0.001$  for all comparisons). This indicates that the S1 being a face is sufficient to elicit the effect. To test the more specific sex-related changes of the BOLD signal, one should compare two face stimuli conditions, where the one leads to specific aftereffects and the other fails to do so. Hence, we tested if there was a difference between the BOLD signal in the AND-D condition and that of the FEM-S/D conditions. In the AND-D condition, S1 was an androgynous face, different from S2, that neither leads to bias of sex decisions, nor to reaction time benefits in our behavioral data (see Fig. 2, A and B). In the FEM conditions, S1 was a female face, leading to a behavioral aftereffect. In contrast to the lack of such findings in previous ERP studies (Kovács et al. 2006; Kloth et al. 2010), we found a response reduction in FEM compared with AND-D in the left and right OFA, as indicated by significant run  $\times$  trial interactions [left:  $F(2,26) = 4.94$ ;  $P = 0.015$ ; right:  $F(2,24) = 4.01$ ;  $P = 0.031$ ]. For both hemispheres, the AND-D condition

led to greater responses than the FEM conditions (all  $P < 0.01$ ). This suggests that OFA is involved in sex-specific face processing.

**ROI analysis: priming effects.** To assess repetition priming effects, we measured the magnitude of RS by comparing a condition where S1 and S2 were identical images to a condition where S1 and S2 were different faces, following from previous neuroimaging studies (see Henson 2003). Thus we measured priming related RS by comparing two conditions where S1 was an androgynous face, identical to (AND-S) or different from (AND-D) S2 (Fig. 3), a modulation that reflects the RS typically associated with stimulus repetition related priming processes (Grill-Spector et al. 2006). We found a significant modulation of the BOLD signal bilaterally in the FFA [significant interaction of run  $\times$  trial type:  $F(2,26) = 8.30$ ;  $P < 0.001$  and  $F(2,28) = 11.25$ ;  $P < 0.001$ , for the left and right hemispheres, respectively], in that the responses of both left and right FFAs were weaker for AND-S than for AND-D trials (both  $P < 0.001$ ). The same pattern was found in bilateral OFA [significant interaction of run  $\times$  trial type:  $F(2,26) = 4.94$ ;  $P = 0.015$  and  $F(2,24) = 4.01$ ;  $P = 0.031$ , for the left and right hemispheres, respectively]. Responses were also weaker for AND-S than for AND-D trials in OFA ( $P = 0.0016$  and  $P = 0.0014$ , for left and right hemispheres, respectively). No such

response reduction was found in LO (no significant run  $\times$  trial interaction in this ROI).

**ROI analysis: comparing priming and adaptation effects.** As we were primarily interested in disentangling the phenomena of priming and aftereffects, we also checked for regions that showed different responses for the AND-S and FEM-S/FEM-D conditions. We found that the left and right FFA were the only ROIs where responses to these conditions were different. Both FEM-S and FEM-D elicited greater responses than AND-S in left FFA ( $P < 0.05$  for both comparisons) and right FFA (FEM-S vs. AND-S:  $P = 0.041$ ; FEM-D vs. AND-S:  $P = 0.093$ ). This suggests that FFA might be differentially involved in repetition priming- and sex aftereffect-related processes.

**Whole-brain analysis.** On the whole brain level (Fig. 4A), we found a face category-specific effect, as revealed by the comparison of FOU conditions with all other conditions where S1 was a face (FEM-S/FEM-D and AND-S/AND-D), which can be seen in an extended region covering occipito-temporal parts of the visual cortex bilaterally. On the right side we found a cluster of 976 voxels ( $P_{\text{cluster}} < 0.001$ ;  $T_{\text{peak}} = 7.92$ ; peak coordinates:  $x = 32$ ;  $y = -82$ ;  $z = 8$ ), and on the left side a cluster of 599 voxels ( $P_{\text{cluster}} < 0.001$ ;  $T_{\text{peak}} = 9.02$ ; peak coordinates:  $x = -36$ ;  $y = -86$ ;  $z = 16$ ). This shows that large areas in the extrastriate cortex seem to contribute to face-repetition-related response reductions. No area showed re-

sponse reduction related to priming (when tested by comparing AND-D  $>$  AND-S) on the whole-brain level. Interestingly, however, we found a region that allowed us to distinguish between image repetition priming- and face adaptation-related activations (expressed by the FEM  $>$  AND-S contrast; 70 voxels;  $P_{\text{cluster}} = 0.003$ ;  $T_{\text{peak}} = 4.20$ ; peak coordinates:  $x = -4$ ;  $y = 28$ ;  $z = 36$ ). This cluster, located in the anterior cingulate cortex (ACC), showed stronger activation in the FEM-S/FEM-D than in the AND-S condition.

Since previous studies suggest that the neural activation during an adaptation paradigm depend on the perceptual bias of the subjects (Cziraki et al. 2010), we also performed a second whole-brain analysis with a reestimated design that included the behavioral responses of the subjects as regressors. For this analysis, we split the FEM trials based on whether behavioral aftereffects were observed or not, and we split the AND-S trials according to the effectiveness of priming (see MATERIALS AND METHODS for details). With this analysis we could show that different brain regions are involved in the extent and success of the behavioral priming and adaptation outcomes, which also suggests different mechanisms underlying priming and after-effects (Fig. 4B). The trials leading to aftereffects were related to lower activations than those where adaptation led to no perceptual biases in three areas: 1) right middle frontal gyrus (135 voxels;  $P_{\text{cluster}} = 0.034$ ;  $T_{\text{peak}} = 5.68$ ; peak coordinates:

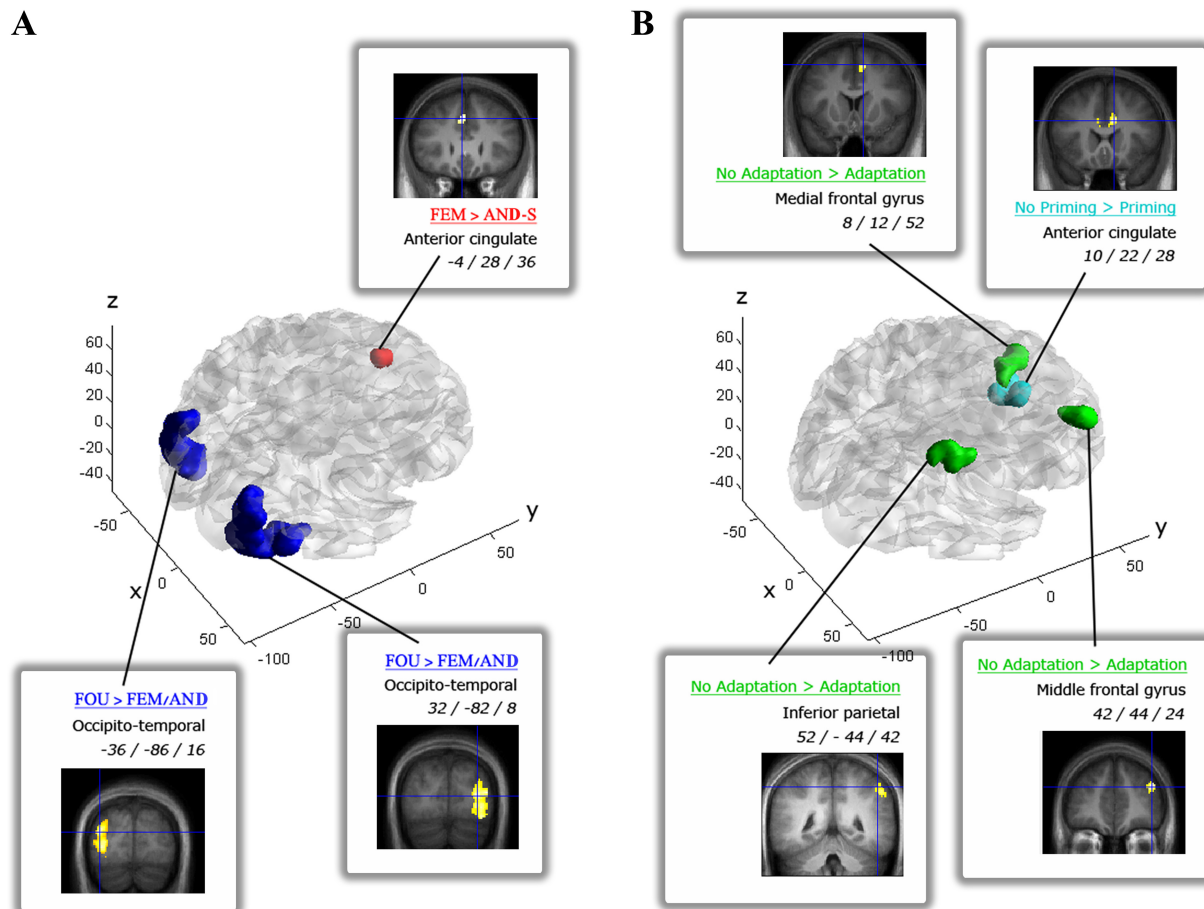


Fig. 4. Results of the whole-brain analysis. A: location of clusters showing response reduction related to face repetition (FOU  $>$  FEM/AND; again FOU is the mean of FOU-S and FOU-D, FEM/AND is the mean of FEM-S, FEM-D, AND-S, and AND-D), and a cluster showing differential responses for priming and adaptation (FEM  $>$  AND-S). B: clusters obtained from the split dataset. Three areas showed larger responses if adaptation was effective than if it was ineffective (No Adaptation  $>$  Adaptation), and one cluster showed larger activation for effective priming than for ineffective priming (No Priming  $>$  Priming).



$x = 42$ ;  $y = 44$ ;  $z = 24$ ); 2) right inferior parietal lobe (173 voxels;  $P_{\text{cluster}} = 0.010$ ;  $T_{\text{peak}} = 5.42$ ; peak coordinates:  $x = 52$ ;  $y = -44$ ;  $z = 42$ ); and 3) the right medial frontal gyrus and right supplementary motor area (181 voxels;  $P_{\text{cluster}} = 0.008$ ;  $T_{\text{peak}} = 5.30$ ; peak coordinates:  $x = 8$ ;  $y = 12$ ;  $z = 52$ ). We found weaker activation on trials with strong priming effects (i.e., shorter reaction times than the median, see MATERIALS AND METHODS) than on trials without priming in the ACC (201 voxels;  $P_{\text{cluster}} = 0.006$ ;  $T_{\text{peak}} = 6.03$ ; peak coordinates:  $x = 10$ ;  $y = 22$ ;  $z = 28$ ), located close to the previously described medial frontal activation. The differential activations in these regions could indicate more efficient processing in the case of effective priming or aftereffects by reduced response conflicts.

## DISCUSSION

The major result of the current experiment is the dissociation of neural processes underlying repetition priming, category-specific and sex-specific adaptation phenomena. In addition, our behavioral results support the results of our previous ERP study (Walther et al. 2013) in the sense that repetition priming and face sex-specific aftereffects can be induced within the same paradigm and subjects.

On a neural level we were able to show that both priming and adaptation effects are related to RS in specific face- and object-selective regions of the visual cortex. The largest and most extensive RS was achieved for generic face category-specific adaptation effects (as assessed by a response reduction for the repetition of a face compared with the FOU condition). This is reflected in RS in early and late regions of the object and face-processing network (LO, OFA, FFA). The RS we found when comparing FOU and FEM conditions was not specific for the biased perception on a behavioral level, as the same effect was also present when comparing FOU with AND condition (where no decision shift was observed in sex classification). This unspecific nature of RS is also visible in the response reduction of large bilateral occipito-temporal regions observed in the whole-brain analysis when contrasting the FOU conditions and all other conditions. The RS of this large bilateral occipito-temporal cluster can be related to previous ERP and magnetoencephalographic findings of face-adaptation effects on the N170, an early occipito-temporal, negative component of the ERP. It has been shown that the N170, as well as its magnetoencephalographic equivalent, the M170, show a reduction in amplitude following prolonged adaptation, for example, to the sex of a given face in a category-specific manner (Harris and Nakayama 2008; Kovács et al. 2005, 2006, 2007). It has been suggested that this reduced and delayed N170 reflects the adaptation of mechanisms that are sensitive to the detection of any face-like stimuli (irrespective of specific information such as gaze, sex, configuration or identity; Kloth et al. 2010; Schweinberger et al. 2007). The scalp distribution of this categorical adaptation effect is centered on the occipito-temporal electrodes, such as P9/10, P7/P8, PO7/PO8 (Amihai et al. 2011; Maurer et al. 2008; Walther et al. 2013) corresponding, at least qualitatively, to the bilateral occipito-temporal activation of the present study in the FOUR vs. FEM contrast. Therefore we suggest that the comparison of FOU and FEM conditions reflects a generic face category-specific effect in the sense that it is sensitive to the repetition of stimuli belonging to the category of faces. Whether it is the detection

of individual face parts or of the configural and holistic features of a face that drives such sensitivity is currently under debate (Eimer et al. 2010; Jacques and Rossion 2006; Rossion and Jacques 2008; Schweinberger et al. 2007) and will require further studies.

We also analyzed the differences between generic face category- and face sex-specific adaptation processes. Sex-specific aftereffects (Webster et al. 2004) were observed as a male bias in sex perception following female adaptation (FEM-S/FEM-D) compared with androgynous (AND-S/AND-D) or noise adaptation (FOU). In contrast to a previous ERP study, which could not find any effects of sex-adaptation on early ERP components (Kloth et al. 2010), we found that bilateral OFA showed differences between the androgynous S1 condition (a condition where no sex-adaptation is apparent, only generic face-adaptation) and the conditions where subjects were adapted to the sex of female faces. Thus our findings indicate that OFA is specifically involved in sex adaptation processes. The absence of such sex-specific adaptation in FFA can be explained by considering FFA as an identity encoding area (Nestor et al. 2011; Pourtois et al. 2005; Rotshtein et al. 2005). Assuming primarily identity-specific representations in FFA, it is not surprising that its response profile follows identity changes in the stimuli. Indeed, face identity changed between S1 and S2 in every condition, except for the AND-S condition. This could lead to a release from adaptation, explaining higher responses in the FEM compared with AND-D condition. While the absence of any sex-specific adaptation effects in FFA corresponds to the identity-coding role of FFA, it is at odds with some recent studies showing sex-specific processing in FFA (Freeman et al. 2010; Podrebarac et al. 2013). However, in contrast to these studies, in the present study we used facial identities that were familiar to participants. Therefore, it is possible that the identity recognition processes, activated by the familiarity of our stimuli, might imply sex categorization already, and therefore could override the sex-specific effects in FFA. Another, possible explanation of the lack of sex-specific adaptation effect in FFA is the possibility that neurons encoding the different sexes (to a certain extent) differentially are intermixed with each other within FFA. Finally, it is also possible that female and male specific neurons are spatially separated from each other, but only to such an extent that is not visible with current standard neuroimaging techniques. High-resolution fMRI experiments, using variations of pattern analysis, targeting directly the issue of sex processing and adaptation in the FFA are required to decide which explanation is valid.

Using a sex decision task, priming was manifest in reduced reaction times when S1 and S2 were identical stimuli in the AND-S compared with any other condition. This novel effect of repetition of the same androgynous face might be, at least to some extent, related to findings of priming reported for veridical faces (for the case of familiarity decisions, see Ellis et al. 1996; and for the case of sex decisions, see Goshen-Gottstein and Ganel 2000). Several studies also suggested that there are image specific and identity specific contributions to priming effects in face perception (Bindemann et al. 2008; Schweinberger et al. 2002), with the former presumably playing a larger role in the present paradigm. On a neural level, priming effects were found in bilateral FFA and OFA, but not in LO, indicating that the RS effect is specific to face-processing areas. Such a



dissociation of RS effects for object- and face-selective visual cortex has been indicated before by intact RS for objects but not for faces in acquired prosopagnosic patients (Schiltz et al. 2006).

Some previous studies (Dobbins et al. 2004; Horner and Henson 2008) have argued that priming-related RS could merely be explained by rapid response learning. In this case, perceptual processing of the S2 could be largely overcome in the case of a repetition, as the decision has already covertly been made on the S1. However, priming-related RS would then be predicted for LO in the present study, too. The fact that the observed RS was restricted to OFA and FFA indicates that the effect involves other mechanism as well. Nevertheless, the lower decision effort in the case of primed trials might indeed be reflected in changes in regions that are connected to executive control and ambiguous decision making, as revealed by our whole-brain analysis.

Bilateral FFA was the only area that allowed to disentangle the activations of the priming and aftereffect conditions, in that only this region showed a significantly smaller activation for the repeated image condition (AND-S) compared with FEM. This finding is in agreement with the assumption that FFA primarily encodes face identity (Nestor et al. 2011; Pourtois et al. 2005; Rotshtein et al. 2005), as there was an identity change in the FEM conditions, but not in the AND-S condition. The identity change between S1 and S2 can, in fact, be defined as a hallmark of either effect: priming relies on the repetition of the same image, while aftereffects rely on the differences between S1 and S2 stimuli. In addition to FFA, our whole-brain analysis also revealed that there are differences between priming and aftereffect related activation in regions outside the visual cortex. We found that the ACC is activated stronger for the adapted compared with the primed condition. This higher activation for adapted trials points toward higher decision efforts and uncertainty in the FEM condition (maybe due to the perceptual aftereffects) compared with the lower effort that is needed to make a decision in the primed trials, where the same stimulus is presented twice (Botvinick et al. 2004). However, recent studies suggest that adaptation can in fact also reduce decision uncertainty (Oruc and Barton 2011; Rhodes et al. 2010; Theodoni et al. 2011). Thus a direct comparison of decision difficulty during priming and aftereffect trials can be an exciting topic of future experiments. Nevertheless, our findings suggest that there are cortical regions that show differential responses during the two perceptual phenomena, suggesting the recruitment of different neural mechanisms.

Compared with the pattern in FFA, OFA shows priming effects and also sex-specific adaptation effects. This is not surprising, since OFA has been shown to be sensitive to face sex, as it is activated during sex categorization tasks (Wiese et al. 2012), and transcranial magnetic stimulation on OFA disrupts sex categorization (Dzhelyova et al. 2011). Altogether, OFA seems to respond differentially to conditions that help to resolve the ambiguity of the test stimulus via priming or aftereffects. Furthermore, there was no difference between the repetition of the same androgynous face in the AND-S condition and the FEM conditions. This result indicates that OFA is not only driven by physical stimulus properties, but processing in OFA seems to go beyond these physical properties, allowing a more flexible parsing of structural face-information to reduce ambiguity.

Our split-analysis also supports the view of different neural correlates for priming and adaptation. If the two processes recruited the same neural systems, their outcome magnitude would likely be mediated by activation changes within the same areas. However, when we contrasted “effective” and “ineffective” priming or adaptation trials, we found different results. For priming, ACC showed greater activations for trials where priming did not lead to shorter RTs, a finding which has been related to response conflicts between prime and target in recent priming studies (D’Ostilio and Garraux 2012). Here, implicit categorization of the S1 as male or female can also lead to relatively longer reaction times in case the S2 is initially perceived as the opposite sex (although being physically the same). In the case of “ineffective” adaptation (in trials when adaptation did not lead to opposite aftereffects), activation was stronger than for “effective” adaptation in medial frontal regions. These regions previously have been connected to ambiguous decision making (Krain et al. 2006). Clearly, in the case of effective adaptation, the ambiguity of stimuli is reduced by adaptation processes (Clifford et al. 2007). In the case of a “female” response after female adaptation, the ambiguity of the test stimulus may not be reduced sufficiently by adaptation. This is supported by the inferior parietal activation showing the same pattern (i.e., higher activation for unsuccessful compared with successful adaptation), which can be interpreted as a reflection of higher decision uncertainty in trials where faces have been classified as female (Vickery and Jiang 2009). However, making a “female” decision in the adaptation block also requires larger cognitive control, since the more frequent “male” classification answer needs to be inhibited. This might be reflected in the higher activations in the medial frontal gyrus and the supplementary motor areas for “female” responses, which areas are associated with response inhibition (Sharp et al. 2010). These findings suggest that effective priming and adaptation lead to less investment of cognitive control (as reflected by lower activations in frontal regions), and are also in line with studies reporting behavioral benefits after face adaptation on classification performance (Oruc and Barton 2011; Rhodes et al. 2010) or response time measures (Walther et al. 2013). However, it seems that this benefit is related to different cortical circuits.

Another possible explanation of the observed differential activations of the frontal cortex comes from theories of predictive coding. Recently, image repetition-related RS of the BOLD signal has been related to the predictive coding model (Rao and Ballard 1999) in the sense that RS reflects the residual error reduction of subsequent bottom-up/top-down processing iterations within a hierarchical system (Kveraga et al. 2007). The results of several studies support the role of top-down connections in RS of the FFA for face stimuli [Egner et al. 2010; Kovács et al. 2012; Larsson and Smith 2012; Summerfield et al. 2008; note, however, the lack of such evidences for object stimuli in the macaque inferior temporal cortex (Kaliukhovich and Vogels 2011) and in the human LO (Kovács et al. 2013)]. Specifically, Summerfield et al. (2006), using functional connectivity analysis, could show that the top-down connectivity of medial frontal cortex, with coordinates close to those of the currently described ACC, was enhanced toward the FFA during perceptual decisions about faces. Thus it is also possible that the observed frontal cortical activations of the present study reflect the differential connec-

tivity of frontal areas toward face sensitive areas during stimulus repetitions. Additionally, effects of expectation might also explain differences between priming and adaptation in general. In the present study, nonadapted and adapted trials were presented in separate blocks (FOU and FEM), while primed and unprimed trials were intermixed within one block (AND-S and AND-D trials of AND). This difference can influence the accuracy of predictions for the S2 and can possibly explain the observed effects. Indeed, such effects of stimulus probability and predictions on the magnitude of fMRIa have been recently described (Kovács et al. 2012; Larsson and Smith 2012; Summerfield et al. 2008) at least for face stimuli (Kaliukhovich and Vogels 2011; Kovács et al. 2013). As for the present experiments, while the S1 would always lead to adaptation of the signal in the FEM blocks, only one-half of the trials (the AND-S trials) would lead to priming in the AND blocks. It has to be noted, however, that the S2 stimuli contained the features of the identity presented as S1 in the FEM blocks as well (see MATERIALS AND METHODS). Thus participants saw stimulus pairs of related identities in one-half of the trials and of different identities in the other one-half during the FEM blocks. This limits prediction differences between adapted and primed trials. Nonetheless, the dependence of priming and adaptation effects on top-down effects, such as prediction or expectation, is an interesting topic for future studies that are specifically designed to orthogonally manipulate expectations and the degree of priming and adaptation.

One limitation of the present study is that, due to the low number of subjects in whom we could reliably localize every ROI in each hemisphere ( $n = 7$  for all six ROIs,  $n = 10$  for OFA and FFA; see MATERIALS AND METHODS for details), we were unable to directly compare the adaptation and priming effects across the different areas of the occipito-temporal cortex within a single analysis. The separate analysis of different ROIs is a common practice in the current neuroimaging literature (for similar approaches, see Ewbank et al. 2011; Gorlin et al. 2012; Larsson and Smith 2012). As a consequence of this type of analysis, it might be argued that the observed differences are related to different noise levels in the analyzed ROIs. We believe that the specific pattern of our results clearly speaks against this potential concern for two reasons. First, the right- and left-hemispheric homologues of the ROIs show a great correspondence in their activation patterns. If the effects were due to noise only, such a large similarity between the two hemispheres would not be expected. Second, and more importantly, one could argue that there might be different noise levels present in the posterior and anterior ROIs, which could explain the different results of FFA and OFA. In this case, the same pattern of results would be expected for both regions, but with a weaker magnitude for the higher-noise region. However, our data clearly show a different pattern of effects for each region: while we observed a sex-specific adaptation effect in OFA, such an effect was absent in FFA. By contrast, priming and adaptation effects were dissociated in FFA, but not in OFA. This specific pattern of findings cannot be explained by different noise levels in the various ROIs in a straightforward manner.

Altogether, our results show that it is possible to dissociate priming and adaptation related neural activity, using the same paradigm within the same subjects. While generic, category-level adaptation effects are visible in most object and face

selective regions, repetition priming effects are only present in the face selective areas. In addition, sex-specific adaptation effects are specifically observed in OFA. The observation that different regions of the visual cortex are sensitive to either priming or adaptation suggests that the two processes rely on different neural mechanisms.

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## DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

## AUTHOR CONTRIBUTIONS

Author contributions: D.K., C.W., S.R.S., and G.K. conception and design of research; D.K. and G.K. performed experiments; D.K. and G.K. analyzed data; D.K., C.W., and G.K. interpreted results of experiments; D.K. and G.K. prepared figures; D.K., C.W., and G.K. drafted manuscript; D.K., C.W., S.R.S., and G.K. edited and revised manuscript; D.K., C.W., S.R.S., and G.K. approved final version of manuscript.

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