

The temporal dynamics of familiar face recognition: Event-related brain potentials reveal the efficient activation of facial identity representations

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ABSTRACT

While it is widely known that humans are typically highly accurate at recognizing familiar faces, it is less clear how efficiently recognition is achieved. In a series of three experiments, we used event-related brain potentials (ERP) in a repetition priming paradigm to examine the efficiency of familiar face recognition. Specifically, we varied the presentation time of the prime stimulus between 500 ms and 33 ms (Experiments 1 and 2), and additionally used backward masks (Experiment 3) to prevent the potential occurrence of visual aftereffects. Crucially, to test for the recognition of facial identity rather than a specific picture, we used different images of the same facial identities in repetition conditions. We observed clear ERP repetition priming effects between 300 and 500 ms after target onset at all prime durations, which suggests that the prime stimulus was sufficiently well processed to allow for facilitated recognition of the target in all conditions. This finding held true even in severely restricted viewing conditions including very brief prime durations and backward masks. We conclude that the facial recognition system is both highly effective and efficient, thus allowing for our impressive ability to recognise the faces that we know.

1. Introduction

Humans are highly accurate at recognizing the faces of the people they know (e.g. [Burton et al., 1999b](#); [Young and Burton, 2017](#)). This ability is remarkable, given that we know many different faces (on average approximately 5000; see [Jenkins et al., 2018](#)), and that the same face can look surprisingly different in changing viewing conditions ([Bruce et al., 1999](#); [Jenkins et al., 2011](#); [White et al., 2014](#)). However, for face recognition to be highly functional, it not only needs to be accurate (or effective) but also efficient. Our daily-life experience seems to suggest fast and effortless recognition in most cases, and it only takes the brain approximately 200 ms to recognise a face as familiar in relatively unrestricted viewing conditions (e.g. [Wiese et al., 2019b](#)). The present study further tested the efficiency of familiar face recognition by restricting exposure to a face, and thus the duration during which facial information can be extracted from the stimulus. Specifically, using event-related brain potentials (ERPs), we aimed to determine (i) the minimum exposure duration sufficient for image-independent familiar face recognition and (ii) whether increasing availability of the stimulus would result in stronger familiarity signals.

Cognitive models (e.g. [Bruce and Young, 1986](#)) typically assume that a face perceived in the visual field first undergoes a perceptual process known as structural encoding. This generates an internal code of the stimulus, which is then compared to stored representations of known faces (Face Recognition Units, FRUs; [Bruce and Young, 1986](#); [Burton et al., 1999a](#); [Burton et al., 1990](#); [Schweinberger and Neumann, 2016](#)). Accessing familiar face representations is modelled as a change in the respective FRU activation levels, with higher similarity between the stimulus representation and an FRU resulting in higher activation ([Burton et al., 1999a](#)). If a critical threshold is met, the face is perceived as familiar (see [Burton et al., 1990](#)). Importantly, FRUs need to be abstract, rather than coding for a specific instance (or picture) of a face, as we recognise familiar faces under highly variable circumstances, e.g. from images we have never seen before. Accordingly, familiar face representations need to be conceptualised in a way that allows for their activation from highly variable stimuli ([Kramer et al., 2018](#); [Young and Burton, 2017](#)).

While this activation process of image-invariant representations arguably reflects the critical step for familiar face recognition, its characteristics are largely unclear. In particular, it is not known how

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efficiently image-invariant representations become activated after perceiving a face. To answer this question, the present experiments manipulated presentation times, assuming that shorter exposure would feed less activation into the face recognition system. Moreover, we measured the activation of familiar face representations using event-related brain potentials (ERPs). ERPs are derived from scalp-recorded EEG and reflect summed post-synaptic potentials (Jackson and Bolger, 2014), which are time-locked to “events” such as the presentation of a visual stimulus. The resulting waveforms consist of positive and negative deflections, or components, which are associated with specific cognitive processing steps (e.g. Luck and Kappenman, 2012).

The first ERP component sensitive to face stimuli is the N170, a negative deflection at occipito-temporal channels peaking between 140 and 180 ms after stimulus onset (e.g. Bentin et al., 1996; Eimer, 2011). While this component is substantially more negative for faces relative to other visual stimuli (e.g. Itier and Taylor, 2004; Rossion and Jacques, 2008), most researchers agree that it does not differentiate between familiar and unfamiliar faces (Andrews et al., 2017; Bentin and Deouell, 2000; Eimer, 2011; Schweinberger and Burton, 2003; Tanaka et al., 2006) (but see Caharel and Rossion, 2021). In line with hierarchical cognitive models outlined above, reliable ERP differences between familiar and unfamiliar faces are typically detected at subsequent processing stages, between 200 and 250 ms after stimulus onset at occipito-temporal channels (Andrews et al., 2017; Bentin and Deouell, 2000; Gosling and Eimer, 2011; Olivares et al., 2015; Saavedra et al., 2010; Tanaka et al., 2006; Wiese et al., 2019b). This N250 familiarity effect presumably reflects the activation of long-term visual representations, as such representations are available for familiar but not unfamiliar faces. Of note, however, the direct comparison of familiar and unfamiliar faces can be confounded by systematic differences between stimulus categories other than familiarity. For instance, when images of celebrities are compared with unfamiliar faces, potential familiarity effects could at least partly reflect differences in attractiveness, distinctiveness, or image characteristics resulting from the use of professional make-up (e.g. Wiese et al., 2022). While some experimental designs allow the counterbalancing of stimuli across familiarity conditions (e.g. Wiese et al., 2019b), it is generally desirable to measure neural responses to identical stimuli in all experimental conditions. This becomes possible with immediate repetition priming.

In each trial of immediate repetition priming experiments, two faces are presented in rapid succession. The second, or target face, is directly preceded by a prime face that can depict either the same (repetition condition) or a different person (non-repetition condition). While in the repetition condition the target representation will have already been activated when the prime was presented, this is not the case in the non-repetition condition. This pre-activation then results in higher activation levels of the target representation at target onset in the repetition condition, which in turn facilitates recognition (e.g. Burton et al., 1990). In ERPs, this facilitation is reflected in more negative amplitudes for repetitions relative to non-repetitions at occipito-temporal electrodes, starting 200 to 220 ms after target onset (Begleiter et al., 1995; Schweinberger et al., 1995). This N250r effect (r for repetition) occurs for repeated upright, but not for inverted faces (Schweinberger et al., 2004), which rules out a potential explanation on the basis of low-level visual characteristics. It has further been shown to be domain-specific, as it occurs for face-face prime/target pairs, but combinations of written names and faces do not elicit the effect (Pickering and Schweinberger, 2003; Wiese et al., 2017). This is in line with the assumption that the N250r has its locus at the level of visual face representations, as written names should not pre-activate domain-sensitive face units and vice versa. Of note, and again in line with hierarchical models of face processing, the neural sources underlying the N170 and the N250r are spatially separable (Schweinberger et al., 2002).

Of relevance to the question of how efficiently familiar face representations can become activated, previous studies have observed N250r effects with very short prime presentation times (i.e. 50 ms; Martens

et al., 2006; Trenner et al., 2004). At first sight, one might conclude from these findings that 50 ms of seeing a face are sufficient for the activation of the corresponding familiar face representation. However, these results were obtained using same image priming, meaning that the same picture of a familiar face was presented as prime and target in the repetition condition. Critically, this experimental procedure substantially restricts any conclusions about the image-invariant nature of face recognition. As discussed above, familiar faces are recognised from a wide range of highly variable images, and the underlying representations should be activated by a wide range of pictures of the respective face. Therefore, to measure how efficiently *facial* rather than *pictorial* representations become activated, it is critically important to present different images of the same person as primes and targets.

Previous research has demonstrated that an N250r effect can be observed using different images of the same person as primes and targets (Bindemann et al., 2008; Wiese et al., 2019a), but that it is reduced in magnitude relative to same-image priming (Schweinberger et al., 2002). This suggests that the N250r as measured in same-image priming consists of an image-dependent and an image-independent part, with the former likely reflecting the activation of short-term pictorial representations and only the latter reflecting access to long-term familiar face representations/FRUs. In line with this interpretation, the N250r from same-image priming is larger for familiar faces but is nevertheless also observed for unfamiliar faces (Schweinberger et al., 1995). At the same time, an N250r using different-image priming has not been observed for completely unfamiliar faces (Zimmermann and Eimer, 2013).

Accordingly, it seems unclear to what extent the observed N250r priming effects from same-image priming with brief prime durations reflect pictorial priming, facial identity priming, or a combination of both. All studies to date using different-image priming have used considerably longer prime presentation times, demonstrating N250r effects with 500 ms (Bindemann et al., 2008; Schweinberger et al., 2002; Wiese et al., 2019a) or 200 ms primes (Zimmermann and Eimer, 2013). Whether an image-independent effect can be elicited with shorter prime durations, and whether image-invariant representations can be activated with such reduced exposure, has not yet been tested. Moreover, it is not known whether the image-independent N250r becomes larger with increasing prime duration. Previous research has shown that higher levels of familiarity with a given identity result in larger ERP familiarity effects (Andrews et al., 2017; Popova and Wiese, 2022; Wiese et al., 2022). However, it is not known whether gradual activation of the same face representation can be demonstrated at a given level of familiarity, or whether representations become active in a dichotomous, all-or-nothing fashion.

The present series of experiments was designed to examine the question of how efficiently image-invariant face representations become activated. For that purpose, we adopted different-image immediate repetition priming and measured the N250r with varying prime durations (see Fig. 1). In Experiment 1, we examined three different prime presentation times (100 ms, 200 ms, and 500 ms) to test whether an N250r would be observed in the shortest condition and whether the effect increased with longer prime durations. As an N250r was observed in the shortest condition, prime duration was further reduced in Experiment 2 (to 33 ms, 67 ms, and 100 ms). Clear N250r effects were again observed in all conditions. Finally, to test whether priming would still be observed in conditions largely excluding effects of visual persistence, we added a backward mask between prime and target stimuli in our final Experiment 3. Here, we observed a substantially reduced N250r relative to the two previous experiments, but nevertheless clear ERP priming effects in a subsequent time window, even for very short prime durations.

2. Experiment 1: different-image priming with varying prime durations

Experiment 1 used different-image priming with prime durations of

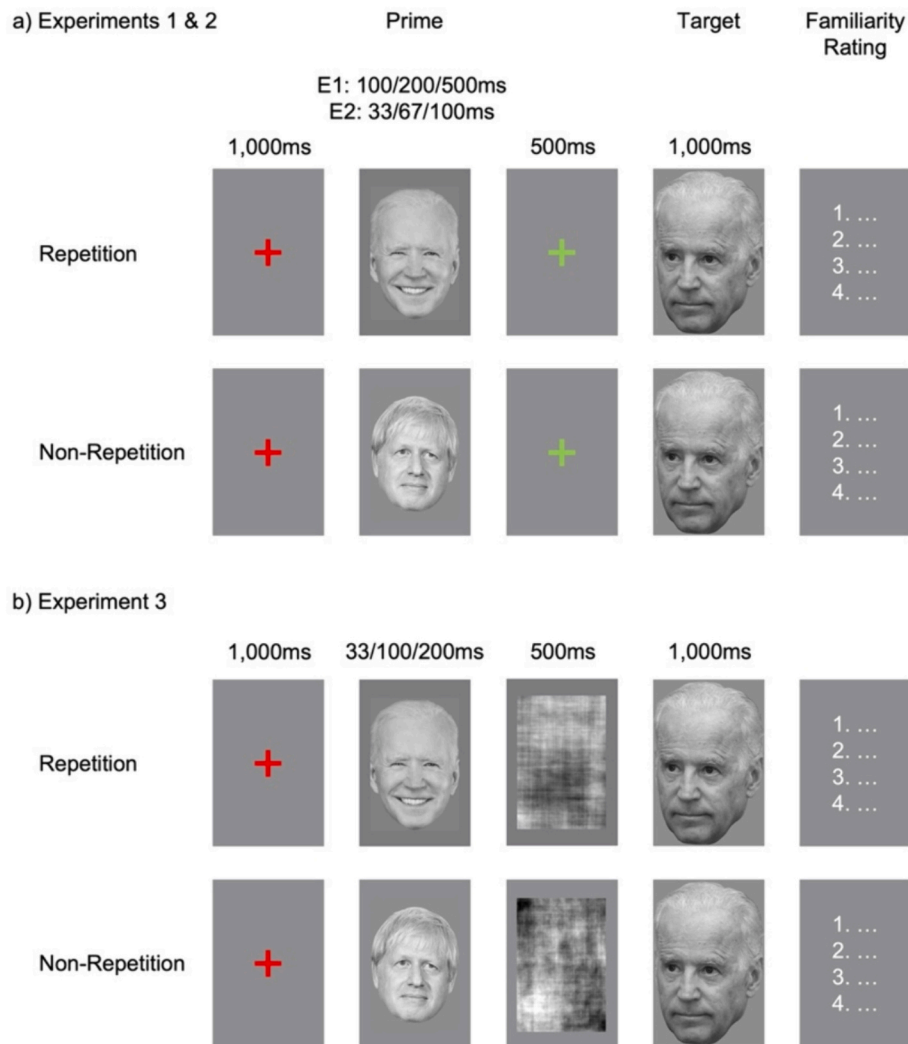


Fig. 1. Example stimuli and trial structure of the experiments. Target stimuli were rated for familiarity on a four-point scale. Images of the celebrities are reproduced here under creative commons licence. Joe Biden, Source: <https://www.flickr.com/photos/58993040@N07/13978713242>, Attribution: U.S. Embassy Kyiv, Ukraine, public domain mark. Joe Biden 2 (Prime) Source www.whitehouse.gov/administration/president-biden/. Official portrait of President Joe Biden, public domain mark. Boris Johnson Source: <https://www.flickr.com/photos/148748355@N05/48790940708>, Attribution: Trump White House Archived, public domain mark.

100 ms, 200 ms, or 500 ms. Assuming efficient activations of familiar face representations (Burton et al., 1999a; Wiese et al., 2019b), we predicted clear ERP priming effects, i.e. more negative ERP amplitudes for repeated versus non-repeated identities, in all conditions. We were further interested to establish whether priming effects were exhibited dichotomously or continuously - i.e. whether the size of the priming effect varied with prime presentation time.

2.1. Methods

2.1.1. Participants

The required sample size was estimated on the basis of the N250r effect size obtained in Experiment 2 of Wiese et al. (2019; contrast positive condition) using G*Power (Faul et al., 2007). Calculation of N for a repeated-measures *t*-test for the difference between the repetition and non-repetition condition, assuming half the effect size of our previous experiment ($d_z = 0.41$, power = 0.80, two-tailed alpha = 0.05), revealed a sample size of 48. For Experiment 1, we tested 52 participants, four of whom were excluded due to insufficient familiarity with the stimuli, i.e. with less than 20 trials in any of the experimental conditions (see below). The final sample consisted of 48 Durham University undergraduate students (32 female, 16 male; mean age = 21.0 years

+/- 2.5 SD). Four participants were left- and 44 right-handed according to a modified version of the Edinburgh Handedness Inventory. All participants reported normal or corrected-to-normal vision, and did not take central acting medication. All gave written informed consent and were compensated with course credit or a monetary reward of £8/h. The study was approved by the ethics committee of Durham University's Psychology Department.

2.1.2. Stimuli

We used six different images of 40 celebrities (musicians, actors, politicians etc.; 240 images in total) collected from various internet sources (identical to those used in Wiese et al., 2019a, 2019b). Faces were cropped from the original background, copied to a uniform grey background, converted to greyscale and standardised to 190 × 285 pixels (corresponding to 2.9° x 4.3° visual angle at 100 cm viewing distance) for prime stimuli and to 228 × 342 pixels (corresponding to 3.4° x 5.2° visual angle) for targets using GIMP (version 2.8.14; www.gimp.org).

2.1.3. Procedure

Participants were seated in a sound-attenuated and electrically shielded chamber, with their heads in a chin rest positioned at a distance

of 100 cm from an LCD monitor. Stimuli were combined to prime/target pairs such that prime and target could either show different images of the same identity (repetition condition) or two different identities (non-repetition condition; see Fig. 1). Each trial started with a red fixation cross (1000 ms), followed by the prime (100 ms, 200 ms, or 500 ms), a green fixation cross (500 ms), and the target face (1000 ms). Finally, a response screen (presented until the participants made a response) was shown which asked participants to rate the familiarity of the target (1 = definitely unfamiliar, 2 = probably unfamiliar, 3 = probably familiar, 4 = definitely familiar; see Fig. 1). Participants were asked to withhold their response until this screen was presented and then to respond via a keypad. Key assignment was presented on the screen. Participants were explicitly instructed to pay close attention to the monitor at all times, but to respond only to the target faces.

Forty trials per condition were presented randomly intermixed, with each of the forty identities occurring in all six conditions, such that no target image was repeated. Assignment of the six different target images per identity to experimental conditions was counterbalanced across participants. A practice block consisting of twelve trials using stimuli from additional celebrities preceded the main experiment to familiarise participants with the task.

2.1.4. EEG recording and data analysis

During the experiment, 64-channel EEG was recorded from sintered Ag/AgCl electrodes mounted in a textile cap using an ANT EEGo amp (ANT Neuro, Hengelo, The Netherlands). The sampling rate was set to 1024 Hz, allowing for accurate measurement from DC to 266 Hz (see http://www.ant-neuro.com/products/eego_mylab/specs). An electrode on the forehead (AFz) served as ground, and CPz was used as the recording reference. Blink artefacts were corrected offline using the algorithm implemented in BESA 6.3. Trials were segmented from –200 to 1000 ms relative to target onset, with the first 200 ms as baseline. An amplitude criterion of 100 μ V and a gradient criterion of 75 μ V were used for artefact rejection. Only trials in which participants indicated to probably or definitely recognise the face (response options 3 and 4) were analysed. Remaining trials were re-referenced to the common average reference and averaged for each experimental condition separately. Average trial numbers were 34.4 (\pm 4.5 SD, min = 24) for 100 ms/repetition, 34.5 (\pm 4.7 SD, min = 23) for 100 ms/non-repetition, 34.7 (\pm 4.1 SD, min = 26) for 200 ms/repetition, 34.4 (\pm 4.7 SD, min = 23) for 200 ms/non-repetition, 34.8 (\pm 4.2 SD, min = 24) for 500 ms/repetition, and 34.4 (\pm 4.6 SD, min = 23) for 500 ms/non-repetition conditions.

Similar to previous work (Wiese et al., 2019a), repetition effects were analysed as the mean amplitude between 200 and 300 ms, as well as between 300 and 400 ms, at occipito-temporal channels P9/P10 and TP9/TP10. As the repetition effect was observed to last until approximately 500 ms, a subsequent time window (400–500 ms) was additionally analysed. In the following, we will refer to the earliest 200–300 ms time window as the N250r, while we will use the term ERP repetition effects for the two later time windows. Moreover, the peak latency of the repetition effect at electrode TP10 was determined for each participant by identifying the time point of the non-repetition minus repetition difference wave maximum. While previous ERP studies on repetition priming have also analysed performance (and particularly response times), such measures are not meaningful for the present experimental procedure due to the delayed option to respond which did not allow to emphasise response speed in the task instructions. We report the proportion of the responses for all experimental conditions for the sake of completeness but refrain from any further analysis.

Statistical analyses on ERP measures were carried out using repeated-measures Analyses of Variance (ANOVA), with degrees of freedom corrected using the Huyn-Feldt procedure when appropriate. Moreover, a priori hypotheses (see above) were tested using repeated-measures *t*-tests as well as Bayesian tests to examine our predictions of priming in all condition and of no difference between the effects. In line

with a “new statistics” approach (Cumming, 2012), confidence intervals (CIs) and effect size measures are reported for all ERP priming effects (non-repetition minus repetition conditions) using bias-corrected Cohen's *d* (d_{unb}) with the average standard deviation as the denominator. CIs for d_{unb} were calculated using ESCI (Cumming, 2012; Cumming and Calin-Jageman, 2017), CIs for partial eta squared (η_p^2) were calculated using scripts provided by M.J. Smithson (<http://www.michaelsmithson.online/stats/Cistuff/CI.html>).

2.1.5. Transparency and open science

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. Study data and analysis code is available via a publicly accessible repository (https://osf.io/32y9m/?view_only=6eee82a3ed524b1790173da85149ac34). The conditions of our ethical approval do not permit the public archiving of the photos of facial identities used in this study and images cannot be shared with anyone outside the author team. Images of selected individuals are used as examples in Fig. 1. This study's design and its analysis were not pre-registered.

2.2. Results

2.2.1. Performance

Rating data is reported in Table 1.

2.2.2. Event-related potentials

ERP results are depicted in Fig. 2. A repeated-measures ANOVA in the 200–300 ms time window revealed significant main effects of repetition, $F(1, 47) = 31.957, p < .001, \eta_p^2 = 0.405, 90\% \text{ CI } [0.221, 0.536]$, and prime duration, $F(2, 94) = 38.821, p < .001, \eta_p^2 = 0.452, 90\% \text{ CI } [0.321, 0.541]$,¹ but no significant interaction, $F(2, 94) = 0.195, p = .823, \eta_p^2 = 0.004, 90\% \text{ CI } [0.0, 0.028]$. Planned comparisons testing for repetition effects at different levels of prime duration yielded significant effects in the 100 ms, $M_{\text{diff}} = 0.611 \mu\text{V}, 95\% \text{ CI } [0.286, 0.935], t(47) = 3.782, p < .001, d_{\text{unb}} = 0.262, 95\% \text{ CI } [0.117, 0.414]$, 200 ms, $M_{\text{diff}} = 0.523 \mu\text{V}, 95\% \text{ CI } [0.176, 0.871], t(47) = 3.028, p = .004, d_{\text{unb}} = 0.207, 95\% \text{ CI } [0.067, 0.352]$, and 500 ms condition, $M_{\text{diff}} = 0.669 \mu\text{V}, 95\% \text{ CI } [0.302, 1.036], t(47) = 3.663, p = .001, d_{\text{unb}} = 0.239, 95\% \text{ CI } [0.103, 0.380]$. To test for the absence of an influence of prime duration on the N250r, we ran additional Bayes paired-sample *t*-tests, which revealed moderate evidence for the null hypothesis when comparing the 100 ms versus 200 ms condition, $BF_{01} = 6.361, \text{ \% error} = 0.065$, 100 ms versus 500 ms condition, $BF_{01} = 5.827, \text{ \% error} = 0.063$, and the 200 ms versus 500 ms condition, $BF_{01} = 5.558, \text{ \% error} = 0.061$.

A corresponding ANOVA in the 300–400 ms time window again yielded significant main effects of repetition, $F(1, 47) = 99.233, p < .001, \eta_p^2 = 0.679, 90\% \text{ CI } [0.539, 0.755]$, and prime duration, $F(2, 94) = 33.465, p < .001, \eta_p^2 = 0.416, 90\% \text{ CI } [0.282, 0.509]$, but no significant interaction, $F(2, 94) = 0.460, p = .633, \eta_p^2 = 0.010, 90\% \text{ CI } [0.0, 0.049]$. Planned *t*-tests revealed significant repetition effects in the 100 ms, $M_{\text{diff}} = 0.909 \mu\text{V}, 95\% \text{ CI } [0.602, 1.216], t(47) = 5.956, p < .001, d_{\text{unb}} = 0.373, 95\% \text{ CI } [0.232, 0.525]$, 200 ms, $M_{\text{diff}} = 0.896 \mu\text{V}, 95\% \text{ CI } [0.559, 1.234], t(47) = 5.341, p < .001, d_{\text{unb}} = 0.349, 95\% \text{ CI } [0.205, 0.502]$, and 500 ms conditions, $M_{\text{diff}} = 1.090 \mu\text{V}, 95\% \text{ CI } [0.752, 1.423], t(47) = 6.482, p < .001, d_{\text{unb}} = 0.386, 95\% \text{ CI } [0.248, 0.533]$. Bayes tests again revealed moderate evidence for the null hypothesis when

¹ Here and in the following, we refrain from interpreting main effects of prime duration. As can be seen in Fig. 2, the gradient in the baseline changes with prime duration, presumably as a function of overlap with the waveform elicited by the prime. As a consequence, target ERPs already start at different levels depending on prime duration, which explains the main effects observed in the present experiments. Crucially, this does not affect ERP priming effects (as, for the critical comparisons, prime duration is identical in repetition and non-repetition trials).

Table 1

Proportion of targets in Experiment 1 rated as “definitely unfamiliar” (1), “probably unfamiliar” (2), “probably familiar” (3), or “definitely familiar” (4). M = Mean, SD = standard deviation.

| | | 100 ms Prime Duration | | | | 200 ms Prime Duration | | | | 500 ms Prime Duration | | | |
|----------------|----|-----------------------|------|------|------|-----------------------|------|------|------|-----------------------|------|------|------|
| | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Repetition | M | 0.06 | 0.06 | 0.08 | 0.81 | 0.06 | 0.05 | 0.07 | 0.82 | 0.06 | 0.04 | 0.07 | 0.82 |
| | SD | 0.09 | 0.07 | 0.06 | 0.15 | 0.10 | 0.06 | 0.06 | 0.15 | 0.10 | 0.05 | 0.06 | 0.14 |
| Non-Repetition | M | 0.06 | 0.06 | 0.08 | 0.80 | 0.06 | 0.05 | 0.09 | 0.80 | 0.06 | 0.06 | 0.09 | 0.80 |
| | SD | 0.08 | 0.06 | 0.07 | 0.15 | 0.08 | 0.06 | 0.07 | 0.16 | 0.08 | 0.05 | 0.07 | 0.16 |

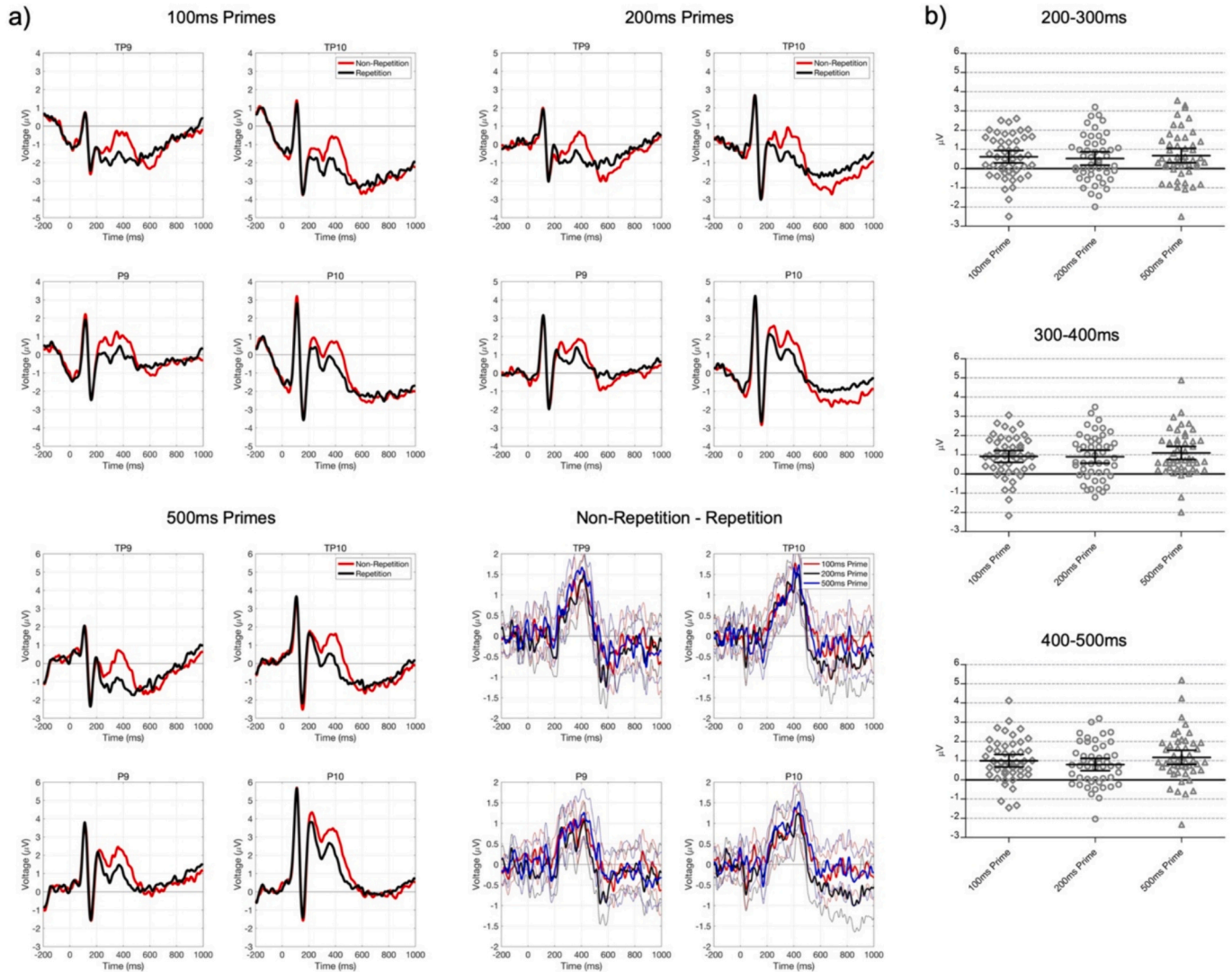


Fig. 2. ERP results for Experiment 1. a) Grand average event-related brain potentials for repetition and non-repetition trials at left- (TP9, P9) and right-hemispheric (TP10, P10) occipito-temporal electrodes in the different prime duration conditions, as well as mean (+/− 95 % CIs) difference curves (non-repetition – repetition). b) Mean and individual repetition effects, averaged across the four electrodes of interest, for each of the three analysis time windows separately. Error bars depict 95 % confidence intervals.

comparing the 100 ms with the 200 ms condition, $BF_{01} = 6.355$, % error = 0.065, the 100 ms with the 500 ms condition, $BF_{01} = 5.827$, % error = 0.063, and the 200 ms with the 500 ms condition, $BF_{01} = 5.969$, % error = 0.063.

Finally, analysis of the 400–500 ms time window revealed significant main effects of repetition, $F(1, 47) = 78.056$, $p < .001$, $\eta_p^2 = 0.624$, 90 % CI [0.469, 0.713], and prime duration, $F(2, 94) = 20.987$, $p < .001$, $\eta_p^2 = 0.309$, 90 % CI [0.176, 0.410], but no significant interaction, $F(2, 94) = 1.496$, $p = .229$, $\eta_p^2 = 0.031$, 90 % CI [0.0, 0.094]. Planned t-tests showed significant repetition effects in all condition, 100 ms: $M_{diff} = 0.993$ μV,

95 % CI [0.671, 1.315], $t(47) = 6.211$, $p < .001$, $d_{unb} = 0.531$, 95 % CI [0.336, 0.740], 200 ms: $M_{diff} = 0.794$ μV, 95 % CI [0.474, 1.113], $t(47) = 4.998$, $p < .001$, $d_{unb} = 0.374$, 95 % CI [0.211, 0.546], 500 ms: $M_{diff} = 1.169$ μV, 95 % CI [0.800, 1.539], $t(47) = 6.362$, $p < .001$, $d_{unb} = 0.437$, 95 % CI [0.279, 0.606]. Bayes paired-sample t-tests revealed moderate evidence for the null hypothesis when comparing the 100 ms versus 200 ms condition, $BF_{01} = 3.868$, % error = 0.051, and 100 ms versus 500 ms condition, $BF_{01} = 4.379$, % error = 0.054, as well as anecdotal evidence for the null when comparing the 200 ms versus 500 ms condition, $BF_{01} = 2.339$, % error = 0.039.

Finally, Bayesian paired-sample t-tests on repetition effect peak latencies revealed moderate evidence for the null hypothesis of no difference between conditions for the 100 ms ($M = 376.2$ ms, $SD = 78.9$, 95 % CI [353.3, 399.2]) versus 200 ms prime duration comparison ($M = 357.5$ ms, $SD = 76.6$, 95 % CI [335.3, 379.8]), $BF_{01} = 3.383$, error % = 0.048, and for the 100 ms versus 500 ms prime duration comparison ($M = 375.5$ ms, $SD = 80.2$, 95 % CI [352.2, 398.8]), $BF_{01} = 6.370$, error % = 0.065. Anecdotal evidence for the null hypothesis was found for the 200 ms versus 500 ms prime duration comparison, $BF_{01} = 2.955$, error % = 0.044.

2.3. Discussion

Experiment 1 was designed to investigate the efficiency of activating image-invariant face representations. For that purpose, we examined whether different-image priming with a shorter presentation time than previously tested (100 ms) would result in ERP repetition priming effects (including the N250r), and whether the magnitude of the effect would increase with longer prime durations. We observed a clear repetition priming in all conditions, including the shortest prime duration, and found no evidence for an increasing effect with longer prime duration. This latter observation is based on the highly similar effect sizes and largely overlapping confidence intervals in the 100, 200, and 500 ms conditions, as well as Bayes statistics, directly testing for evidence for the null.

As a clear ERP repetition priming was observed in the 100 ms condition, even briefer presentations of the prime might be sufficient to elicit the effect. We examined this question in Experiment 2.

3. Experiment 2: very short prime durations

Experiment 2 further reduced prime durations relative to our first experiment to 33 ms, 67 ms, or 100 ms. Assuming highly efficient activation of familiar face representations, we again predicted priming in all three conditions and no difference between them.

3.1. Methods

3.1.1. Participants

We tested a total of 52 participants, four of whom were excluded due to insufficient familiarity with the stimuli (see above). The final sample consisted of 43 right- and 5 left-handed Durham University undergraduate students (43 female, 5 male; mean age = 18.7 years \pm 3.0 SD). Reimbursement and inclusion/exclusion criteria were identical to Experiment 1. None of the participants had taken part in Experiment 1. All participants gave written informed consent, and the experiment was approved by the ethics committee at Durham University's Psychology Department.

3.1.2. Stimuli, procedure, and EEG recording

Stimuli and procedures were identical to Experiment 1, except that primes were presented for either 33 ms, 67 ms, or 100 ms. Average trial numbers were 33.8 (\pm 4.7 SD, min = 21) for 33 ms/repetition, 33.9 (\pm 4.9 SD, min = 20) for 33 ms/non-repetition, 34.6 (\pm 4.7 SD, min = 20) for 67 ms/repetition, 34.2 (\pm 5.0 SD, min = 20) for 67 ms/

non-repetition, 33.9 (\pm 4.9 SD, min = 23) for 100 ms/repetition, and 33.7 (\pm 5.2 SD, min = 20) for 100 ms/non-repetition conditions.

3.2. Results

3.2.1. Performance

Familiarity rating data for Experiment 2 is reported in Table 2.

3.2.2. Event-related potentials

ERP results are depicted in Fig. 3. A repeated-measures ANOVA in the 200–300 ms time window yielded significant main effects of repetition, $F(1, 47) = 41.319$, $p < .001$, $\eta_p^2 = 0.468$, 90 % CI [0.286, 0.589], and prime duration, $F(2, 94) = 15.219$, $p < .001$, $\eta_p^2 = 0.245$, 90 % CI [0.119, 0.348], but no significant interaction, $F(2, 94) = 0.096$, $p = .909$, $\eta_p^2 = 0.002$, 90 % CI [0.0, 0.023]. Planned comparisons revealed significant repetition effects in the 33 ms, $M_{diff} = 0.709$ μ V, 95 % CI [0.380, 1.038], $t(47) = 4.334$, $p < .001$, $d_{unb} = 0.353$, 95 % CI [0.180, 0.535], 67 ms, $M_{diff} = 0.785$ μ V, 95 % CI [0.505, 1.064], $t(47) = 5.649$, $p < .001$, $d_{unb} = 0.392$, 95 % CI [0.237, 0.557], and 100 ms prime duration conditions, $M_{diff} = 0.710$ μ V, 95 % CI [0.348, 1.072], $t(47) = 4.026$, $p < .001$, $d_{unb} = 0.317$, 95 % CI [0.148, 0.493]. Additional Bayes tests yielded moderate evidence for the null hypothesis when comparing the 33 ms versus 67 ms conditions, $BF_{01} = 5.847$, error % = 0.063, the 33 ms versus the 100 ms conditions, $BF_{01} = 6.377$, error % = 0.065, and the 67 ms versus the 100 ms conditions, $BF_{01} = 5.981$, error % = 0.064.

A corresponding analysis in the 300–400 ms time window revealed significant main effects of repetition, $F(1, 47) = 35.808$, $p < .001$, $\eta_p^2 = 0.432$, 90 % CI [0.249, 0.559], and prime duration, $F(2, 94) = 11.014$, $p < .001$, $\eta_p^2 = 0.190$, 90 % CI [0.075, 0.292], but no interaction, $F(2, 94) = 0.055$, $p = .946$, $\eta_p^2 = 0.001$, 90 % CI [0.0, 0.018]. Planned comparisons yielded significant repetition effects for the 33 ms, $M_{diff} = 0.770$ μ V, 95 % CI [0.423, 1.117], $t(47) = 4.463$, $p < .001$, $d_{unb} = 0.361$, 95 % CI [0.188, 0.542], the 67 ms, $M_{diff} = 0.842$ μ V, 95 % CI [0.502, 1.183], $t(47) = 4.975$, $p < .001$, $d_{unb} = 0.393$, 95 % CI [0.221, 0.575], and the 100 ms prime duration conditions, $M_{diff} = 0.819$ μ V, 95 % CI [0.386, 1.252], $t(47) = 3.802$, $p < .001$, $d_{unb} = 0.331$, 95 % CI [0.149, 0.521]. Again, Bayes tests revealed moderate evidence for the null hypothesis when comparing the 33 ms with the 67 ms condition, $BF_{01} = 5.938$, error % = 0.063, the 33 ms with the 100 ms condition, $BF_{01} = 6.242$, error % = 0.065, as well as the 67 ms with the 100 ms condition, $BF_{01} = 6.352$, error % = 0.065.

Finally, analysis of the 400–500 ms time window yielded significant main effects of repetition, $F(1, 47) = 6.401$, $p = .015$, $\eta_p^2 = 0.120$, 90 % CI [0.013, 0.266], and prime duration, $F(2, 94) = 10.396$, $p < .001$, $\eta_p^2 = 0.181$, 90 % CI [0.068, 0.283], but no interaction, $F(2, 94) = 0.659$, $p = .520$, $\eta_p^2 = 0.014$, 90 % CI [0.0, 0.060]. Planned comparisons revealed no significant repetition effect for the 33 ms condition, $M_{diff} = 0.211$ μ V, 95 % CI [−0.208, 0.631], $t(47) = 1.014$, $p = .316$, $d_{unb} = 0.092$, 95 % CI [−0.089, 0.276], but significant effects for both the 67 ms, $M_{diff} = 0.464$ μ V, 95 % CI [0.106, 0.822], $t(47) = 2.609$, $p = .012$, $d_{unb} = 0.222$, 95 % CI [0.049, 0.400], and the 100 ms prime duration conditions, $M_{diff} = 0.425$ μ V, 95 % CI [0.005, 1.845], $t(47) = 2.034$, $p = .048$, $d_{unb} = 0.176$, 95 % CI [0.002, 0.354]. Bayes tests revealed moderate evidence for the null hypothesis when comparing the 33 ms with the 67 ms condition, $BF_{01} = 3.655$, error % = 0.050, the 33 ms with the 100 ms condition,

Table 2

Proportion of targets in Experiment 2 rated as “definitely unfamiliar” (1), “probably unfamiliar” (2), “probably familiar” (3), or “definitely familiar” (4). M = Mean, SD = standard deviation.

| | | 33 ms Prime Duration | | | | 67 ms Prime Duration | | | | 100 ms Prime Duration | | | |
|----------------|----|----------------------|------|------|------|----------------------|------|------|------|-----------------------|------|------|------|
| | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Repetition | M | 0.06 | 0.06 | 0.10 | 0.78 | 0.05 | 0.06 | 0.11 | 0.78 | 0.05 | 0.07 | 0.09 | 0.79 |
| | SD | 0.06 | 0.08 | 0.09 | 0.17 | 0.06 | 0.08 | 0.09 | 0.17 | 0.06 | 0.08 | 0.08 | 0.18 |
| Non-Repetition | M | 0.06 | 0.06 | 0.11 | 0.77 | 0.05 | 0.07 | 0.11 | 0.77 | 0.06 | 0.07 | 0.11 | 0.77 |
| | SD | 0.07 | 0.07 | 0.10 | 0.18 | 0.07 | 0.09 | 0.10 | 0.19 | 0.07 | 0.09 | 0.09 | 0.18 |

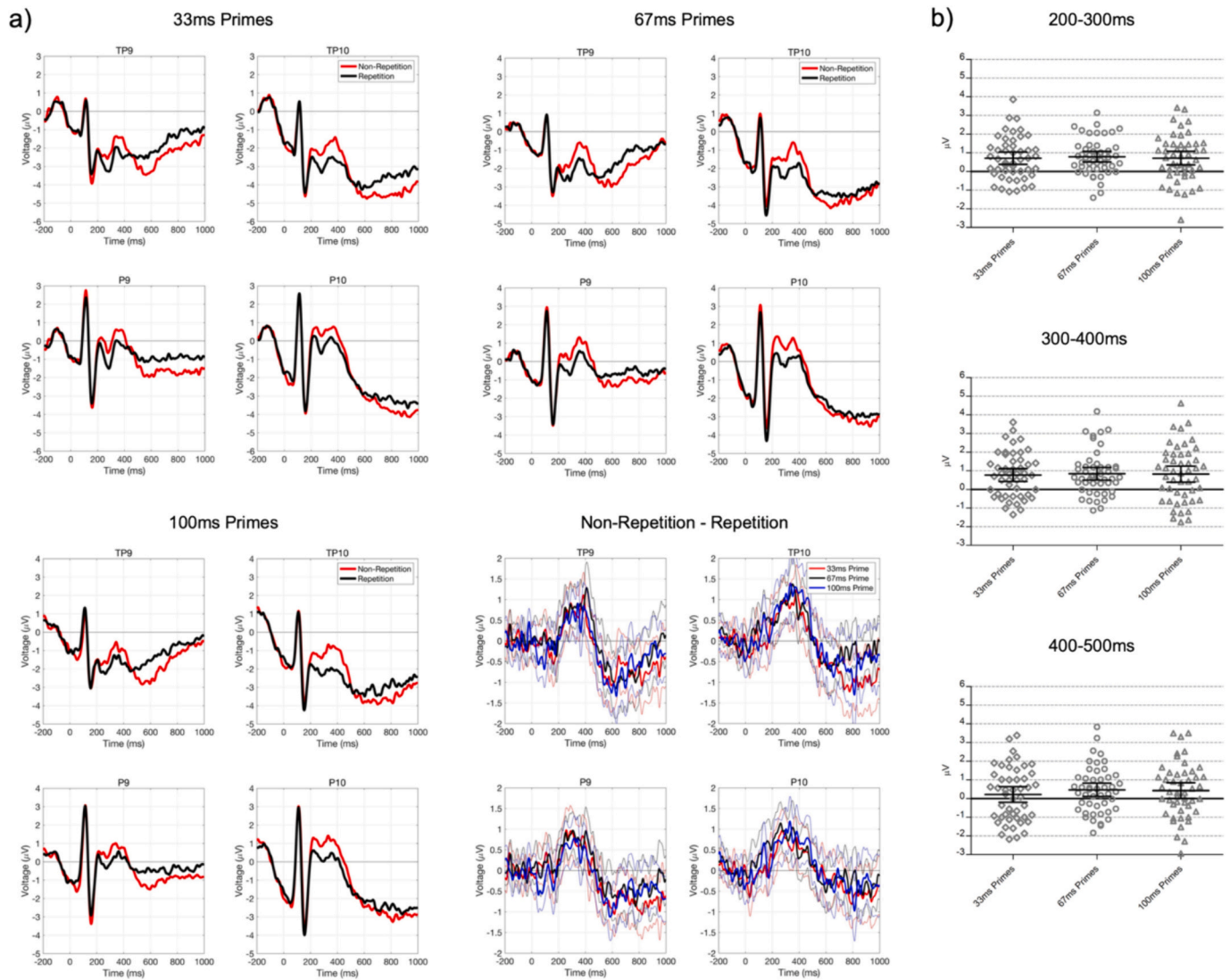


Fig. 3. ERP results for Experiment 2. a) Grand average event-related brain potentials for repetition and non-repetition trials at left- (TP9, P9) and right-hemispheric (TP10, P10) occipito-temporal electrodes in the different prime duration conditions, as well as mean (\pm 95 % CIs) difference curves (non-repetition – repetition). b) Mean and individual repetition effects (non-repetition – repetition conditions), averaged across the four electrodes of interest, for the three analysis time windows separately. Error bars depict 95 % confidence intervals.

$BF_{01} = 4.341$, error % = 0.054, as well as the 67 ms with the 100 ms condition, $BF_{01} = 6.294$, error % = 0.065.

Bayesian paired-sample t -tests on repetition effect peak latencies revealed moderate evidence for the null hypothesis for all comparisons: 33 ms ($M = 347.5$ ms, $SD = 94.4$, 95 % CI [320.1, 374.9]) versus 67 ms ($M = 357.2$ ms, $SD = 83.8$, 95 % CI [332.9, 391.5]), $BF_{01} = 5.381$, error % = 0.060; 33 ms versus 100 ms prime duration ($M = 353.6$ ms, $SD = 76.9$, 95 % CI [331.3, 376.0]), $BF_{01} = 5.951$, error % = 0.063; 67 ms versus 100 ms prime duration, $BF_{01} = 6.185$, error % = 0.065.

3.3. Discussion

In Experiment 2, we again observed clear ERP repetition effects in all conditions, including the shortest prime duration of 33 ms. Although this latter effect was not significant in the latest (400–500 ms) time window, and therefore somewhat less long-lasting in comparison to the 67 ms and 100 ms conditions, our findings overall indicate that very brief presentations of a familiar face are sufficient to activate the corresponding long-term representations, reflecting the high efficiency of facial identity processing. Moreover, similar to Experiment 1, we did not find any evidence for stronger priming effects with increased prime

durations.

As a potential limitation, we note that we did not use visual masks in Experiments 1 and 2, and accordingly visual afterimages of the primes might have been available to the participants after stimulus offset. Studies on iconic memory have shown that the duration of such afterimages, or visible persistence, is negatively related to stimulus duration (Di Lollo and Dixon, 1988). Accordingly, afterimages should be stronger with shorter prime durations. On the one hand, similar ERP repetition effects across presentation times could potentially be based on such effects, particularly in the shorter conditions. On the other hand, it seems questionable whether afterimages generated from small grey-scale stimuli as used in the present study against a grey background are detailed enough to allow for the extraction of identity information. Moreover, visual afterimages reflect the original luminance information with reversed contrast, and negative contrast faces are hard to recognise even from physically available, fully detailed pictures (e.g. Galper, 1970; Kemp et al., 1996; Russell et al., 2006). However, to further investigate this issue we used visual masks after the presentation of the prime stimulus in Experiment 3 (see also Dörr et al., 2011).

4. Experiment 3: priming with backward masking

In the final experiment reported here, we used phase-randomized face images to backward-mask prime stimuli which were presented with durations of 33 ms, 100 ms, or 200 ms. If visual aftereffects were not responsible for the effects observed in the previous experiments, we would expect clear priming for all conditions, and no relevant differences between them.

4.1. Methods

4.1.1. Participants

The required sample size for finding a significant difference between repeated and non-repeated conditions was calculated on the basis of the smallest effect within the first 400 ms in Experiment 2 (two-tailed repeated-measures *t*-test, $d_z = 0.55$, $1-\beta = 0.8$), which revealed $N = 28$. For reasons of counterbalancing, we rounded this number up to 30. Moreover, we improved power by substantially increasing the number of trials per condition (see below), which has been found to have a stronger influence on detecting true effects than increasing participant numbers in within-participant design ERP studies (Boudewyn et al., 2018).

We recorded data from 33 participants, three of whom were excluded due to not being sufficiently familiar with the used celebrities (see above; two participants) or technical problems during data acquisition (one participant). The final sample consisted of 30 Durham University students, 25 female/five male, one left-/29 right-handed, with a mean age of 21.7 years ($SD = 3.0$). Exclusion criteria and compensation were analogue to Experiments 1 and 2. None of the participants had taken part in Experiments 1 or 2. The study was approved by the ethics committee of Durham University's Psychology Department.

4.1.2. Stimuli

The stimuli consisted of six images of each of 50 celebrities. Data for Experiments 1 and 2 were recorded over a long time interval (between 2018 and 2022). We therefore changed the stimulus set relative to the first two experiments as some of the celebrities would not be as familiar to our participants anymore. A pilot study was carried out, in which 20 Durham under- and postgraduate students indicated for each of 200 celebrity names how likely they would recognise the person in a photo (from 1 = definitely no, 2 = probably no, 3 = don't know, 4 = probably yes, 5 = definitely yes). Based on average familiarity ratings, we chose the 50 highest-rated celebrities from this list. The lowest-rated celebrity accepted for the stimulus set had an average familiarity rating of 4.5 ($SD = 1.05$), with 15 out of 20 participants rating the celebrity with "definitely yes". In case of an overlap with the stimulus set of Experiments 1 and 2, the same images were used. Images for celebrities not used in the previous experiments were obtained via google image search. Image editing was analogous to the procedure described for Experiment 1.

A visual mask was created from each face stimulus by phase randomizing images by 360° using FourierImage (Risto Nasanen, personal communication; downloaded from www.nasanen.com/FourierImage2017.app.zip). This manipulation rendered the images completely unrecognisable while at the time keeping the amplitude spectrum, and accordingly brightness and contrast, unaltered (see Fig. 1b).

4.1.3. Procedure

As in the previous experiments, stimuli were combined to different image repetition and non-repetition prime/target pairs. Each trial started with a red fixation cross (1000 ms), followed by the prime (33 ms, 100 ms, or 200 ms), which was replaced by the visual mask created from the prime stimulus (500 ms), the target face (1000 ms), and finally the response screen (presented until the participants made a response; see Fig. 1b). Instructions were identical to the previous experiments.

100 trials per condition were presented randomly intermixed. Each

of the 300 pictures occurred four times, twice as a prime and twice as a target, and each of the fifty identities occurred twice as targets in each of the six conditions. Assignment of the six different target images per identity to experimental conditions was counterbalanced across participants. A practice block consisting of twelve trials using additional stimuli preceded the main experiment.

4.2. Results

4.2.1. Performance

Rating results are reported in Table 3.

4.2.2. Event-related potentials

ERP results are depicted in Fig. 4. A repeated-measures ANOVA in the 200–300 ms time window yielded significant main effects of repetition, $F(1, 29) = 7.976$, $p = .008$, $\eta_p^2 = 0.216$, 90 % CI [0.034, 0.401], and prime duration, $F(2, 58) = 32.559$, $p < .001$, $\eta_p^2 = 0.529$, 90 % CI [0.364, 0.623], but no significant interaction, $F(2, 58) = 0.877$, $p = .422$, $\eta_p^2 = 0.029$, 90 % CI [0.0, 0.107]. Planned comparisons revealed no significant repetition effects in the 33 ms condition, $M_{diff} = 0.309 \mu V$, 95 % CI [-0.020, 0.638], $t(29) = 1.923$, $p = .064$, $d_{unb} = 0.16$, 95 % CI [-0.01, 0.33], or in the 200 ms condition, $M_{diff} = 0.122 \mu V$, 95 % CI [-0.070, 0.312], $t(29) = 1.304$, $p = .202$, $d_{unb} = 0.05$, 95 % CI [-0.03, 0.13]. However, significant priming was detected in the 100 ms prime duration condition, $M_{diff} = 0.348 \mu V$, 95 % CI [0.029, 0.667], $t(29) = 2.234$, $p = .033$, $d_{unb} = 0.16$, 95 % CI [0.01, 0.31]. Additional Bayes tests yielded moderate evidence for the null hypothesis when comparing the 33 ms versus 100 ms conditions, $BF_{01} = 5.053$, error % = 0.034, the 33 ms versus the 200 ms conditions, $BF_{01} = 3.113$, error % = 0.032, but only anecdotal evidence for the null when comparing the 100 ms and 200 ms conditions, $BF_{01} = 2.326$, error % = 0.030.

A corresponding ANOVA in the 300–400 ms time window again revealed significant main effects of repetition, $F(1, 29) = 44.341$, $p < .001$, $\eta_p^2 = 0.605$, 90 % CI [0.388, 0.714], and prime duration, $F(2, 58) = 23.182$, $p < .001$, $\eta_p^2 = 0.444$, 90 % CI [0.270, 0.552], but no significant interaction, $F(2, 58) = 1.328$, $p = .273$, $\eta_p^2 = 0.044$, 90 % CI [0.0, 0.133]. Planned comparisons yielded significant priming in all conditions: 33 ms prime duration - $M_{diff} = 0.549 \mu V$, 95 % CI [0.241, 0.856], $t(29) = 3.652$, $p = .001$, $d_{unb} = 0.269$, 95 % CI [0.110, 0.439]; 100 ms - $M_{diff} = 0.813 \mu V$, 95 % CI [0.487, 1.139], $t(29) = 5.103$, $p < .001$, $d_{unb} = 0.364$, 95 % CI [0.199, 0.544]; 200 ms - $M_{diff} = 0.821 \mu V$, 95 % CI [0.502, 1.140], $t(29) = 5.271$, $p < .001$, $d_{unb} = 0.327$, 95 % CI [0.182, 0.486]. Bayes tests yielded only anecdotal evidence for the null hypothesis when comparing the 33 ms versus 100 ms conditions, $BF_{01} = 2.370$, error % = 0.031, and the 33 ms versus the 200 ms conditions, $BF_{01} = 2.116$, error % = 0.030, but moderate evidence for the null when comparing the 100 ms and 200 ms conditions, $BF_{01} = 5.140$, error % = 0.034.

Finally, a repeated-measures ANOVA in the 400–500 ms time window again revealed significant main effects of repetition, $F(1, 29) = 26.961$, $p < .001$, $\eta_p^2 = 0.552$, 90 % CI [0.317, 0.672], and prime duration, $F(2, 58) = 20.588$, $p < .001$, $\eta_p^2 = 0.415$, 90 % CI [0.239, 0.527], but no significant interaction, $F(2, 58) = 1.445$, $p = .244$, $\eta_p^2 = 0.047$, 90 % CI [0.0, 0.139]. Planned comparisons again yielded significant repetition effects in all conditions: 33 ms prime duration - $M_{diff} = 0.533 \mu V$, 95 % CI [0.186, 0.880], $t(29) = 3.137$, $p = .004$, $d_{unb} = 0.279$, 95 % CI [0.091, 0.478]; 100 ms - $M_{diff} = 0.731 \mu V$, 95 % CI [0.354, 1.108], $t(29) = 3.966$, $p < .001$, $d_{unb} = 0.344$, 95 % CI [0.154, 0.547]; 200 ms - $M_{diff} = 0.857 \mu V$, 95 % CI [0.505, 1.207], $t(29) = 4.989$, $p < .001$, $d_{unb} = 0.384$, 95 % CI [0.207, 0.576]. Bayes tests yielded moderate evidence for the null hypothesis when comparing the 33 ms versus 100 ms conditions, $BF_{01} = 3.462$, error % = 0.033, and the 100 ms versus the 200 ms conditions, $BF_{01} = 4.195$, error % = 0.034, but only anecdotal evidence for the null when comparing the 33 ms and 200 ms conditions, $BF_{01} = 1.104$, error % = 0.024.

Bayesian paired-sample *t*-tests on repetition effect peak latencies revealed moderate evidence for the null hypothesis of no difference for

Table 3

Proportion of targets in Experiment 3 rated as “definitely unfamiliar” (1), “probably unfamiliar” (2), “probably familiar” (3), or “definitely familiar” (4). M = Mean, SD = standard deviation.

| | | 33 ms Prime Duration | | | | 100 ms Prime Duration | | | | 200 ms Prime Duration | | | |
|----------------|----|----------------------|------|------|------|-----------------------|------|------|------|-----------------------|------|------|------|
| | | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Repetition | M | 0.03 | 0.03 | 0.05 | 0.89 | 0.03 | 0.03 | 0.05 | 0.89 | 0.03 | 0.03 | 0.05 | 0.89 |
| | SD | 0.08 | 0.07 | 0.06 | 0.16 | 0.07 | 0.06 | 0.06 | 0.15 | 0.07 | 0.07 | 0.05 | 0.16 |
| Non-Repetition | M | 0.03 | 0.03 | 0.05 | 0.89 | 0.03 | 0.03 | 0.05 | 0.88 | 0.03 | 0.03 | 0.05 | 0.88 |
| | SD | 0.08 | 0.08 | 0.05 | 0.16 | 0.07 | 0.06 | 0.06 | 0.16 | 0.07 | 0.07 | 0.06 | 0.16 |

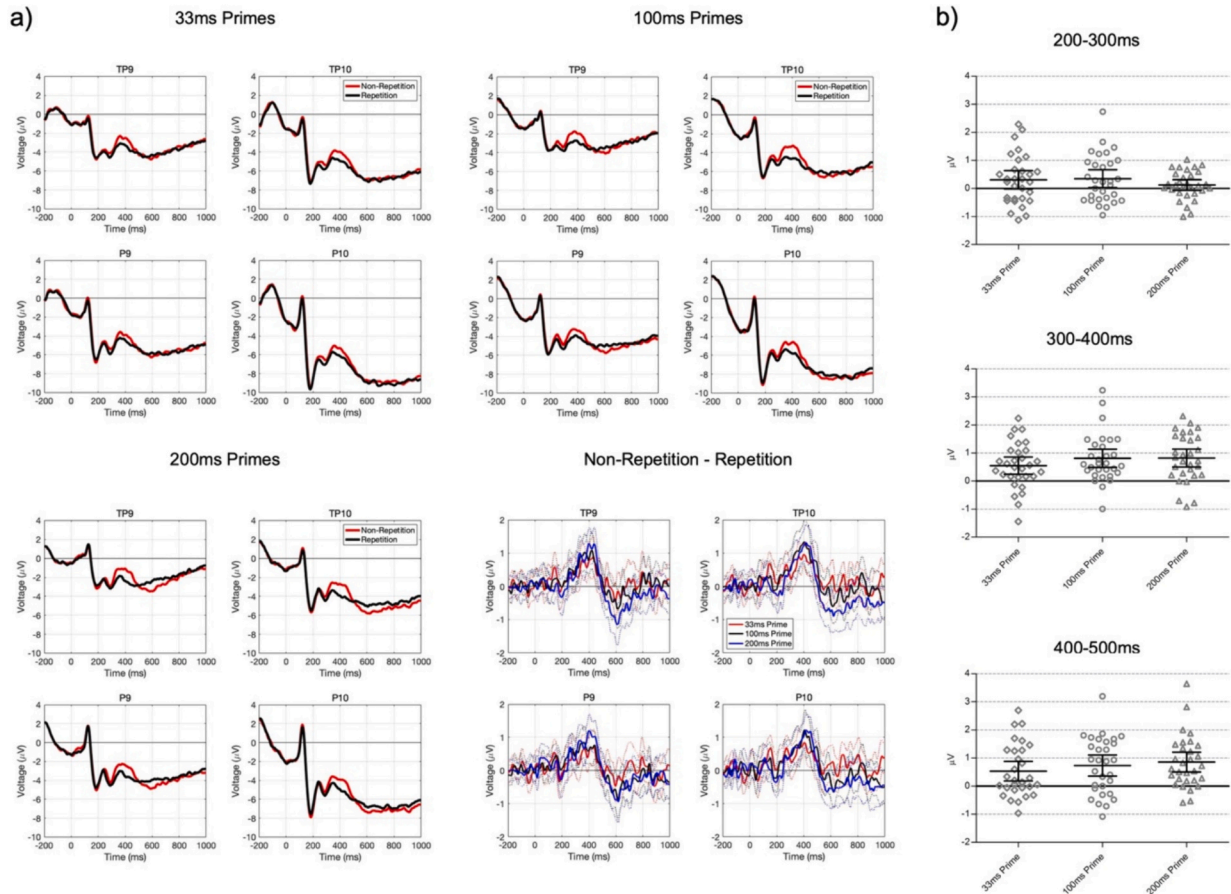


Fig. 4. ERP results for Experiment 3. a) Grand average event-related brain potentials for repetition and non-repetition trials at left- (TP9, P9) and right-hemispheric (TP10, P10) occipito-temporal electrodes in the different prime duration conditions, as well as mean (+/- 95 % CIs) difference curves (non-repetition - repetition). b) Mean and individual repetition effects (non-repetition - repetition conditions), averaged across the four electrodes of interest, for the three analysis time windows separately. Error bars depict 95 % confidence intervals.

all comparisons: 33. ms ($M = 360.6$ ms, $SD = 80.8$, 95 % CI [330.4, 390.8]) versus 100 ms ($M = 373.8$ ms, $SD = 82.4$, 95 % CI [343.0, 404.6]), $BF_{01} = 4.111$, error % = 0.034; 33 ms versus 200 ms prime duration ($M = 379.4$ ms, $SD = 74.9$, 95 % CI [351.4, 407.4]), $BF_{01} = 3.494$, error % = 0.033; 100 ms versus 200 ms prime duration, $BF_{01} = 4.878$, error % = 0.034.

4.3. Discussion

Adding backward masks did not eliminate ERP repetition effects. Accordingly, ERP effects observed in previous experiments, including those with short prime durations, cannot be fully explained by visual persistence. At the same time, while clear effects were observed for all prime durations in the two later time windows (300–400 ms, 400–500 ms), only the 100 ms prime duration condition yielded significant priming in the N250r/200–300 ms window. This contrasts with the

result of Experiment 2, in which priming was observed in all conditions. Even in the 100 ms condition, which elicited priming in both experiments, the N250r was about half the size in Experiment 3 relative to Experiment 2. Together, these results suggest that backward masking generally (and substantially) affected the N250r - while varying unmasked prime duration within the limits tested in Experiments 1 and 2 did not. It therefore appears that the early effect depends on visual persistence when tested with short prime durations. While some previous studies have used even shorter prime durations than the present study (Campbell and Tanaka, 2024; Trenner et al., 2004), it seems unlikely to us that using such shorter durations would change this general conclusion.

At the same time, as noted above, very short prime durations were sufficient to elicit later repetition effects. All conditions, including the shortest one, yielded significant effects from 300 ms onwards. Given that such repetition effects reflect the facilitated activation of visual face

representations (see General Discussion below), this process is highly efficient and reliably triggered even with very restricted visual input.

5. General discussion

The present series of experiments analysed ERP repetition priming effects to investigate the efficiency of familiar face recognition. Specifically, we tested whether brief presentation times, and therefore limited exposure to a face, are sufficient to activate image-independent facial identity representations. Across three experiments, we consistently observed clear ERP repetition priming effects with 100 ms prime durations and found additional evidence for corresponding effects with 67 ms and even 33 ms when primes were presented without backward masks. The application of such masks clearly reduced the N250r and delayed reliable priming effects to a time window from approximately 300 ms onwards. In this later time window, however, priming was observed even with prime durations of 33 ms. Moreover, in all three experiments, ERP priming effects were comparable in magnitude for the different prime durations. These findings suggest that image-independent long-term representations of familiar faces are activated highly efficiently, after very limited exposure to a face. Moreover, familiar face representations do not seem to respond in a gradual fashion but rather become activated in a dichotomous way.

Our results clearly indicate that faces presented for 100 ms can be processed highly effectively by the visual system, such that the visual stimulus can be categorised as a face (relative to a different visual object), recognised as a familiar (rather than unfamiliar) face, and identified as a specific person (Bruce and Young, 1986; Schweinberger and Neumann, 2016; Young and Bruce, 2024). The N250 familiarity effect and particularly the N250r presumably reflect the second step in this cascade during which a visual long-term representation of a familiar face is activated. As noted above, reliable ERP priming effects were also observed for substantially shorter presentation times (33 ms) in the subsequent 300–400 ms time window. Accordingly, our findings extend previous results which have demonstrated ERP repetition priming effects with unmasked prime presentation times as short as 50 ms (Martens et al., 2006; Trenner et al., 2004). These previous results, however, were obtained using same-image priming, and it remained unclear to what extent they reflected the activation of short-term picture-based rather than facial identity representations. The present experimental procedures rule out explanations in terms of picture-based priming, and we therefore conclude that activations of image-independent long-term representations form the basis for the effects observed here.

Moreover, as the N250r did not become notably larger with increasing prime presentation times in Experiments 1 and 2, it seems to more closely follow a dichotomous rather than gradual response function. Accordingly, once the underlying representation has reached its threshold, a signal is generated that depends on the degree of familiarity with the specific identity, in the sense that more familiar faces will generate stronger signals (Andrews et al., 2017; Popova and Wiese, 2022; Wiese et al., 2022). However, the size of the N250r does not seem to depend on the time a face is available. As long as exposure is sufficient to drive activation levels above the threshold, the underlying representation becomes activated and a signal of a fixed magnitude is generated. It thus appears that different individual identities generate familiarity responses of varying sizes, with more familiar faces generating stronger responses, while at the same time the magnitude of the familiarity signal for each individual identity is fixed, at least at a given point in time such as an experimental session. Over longer time intervals, particularly for less familiar faces, additional learning may take place, which would then increase the respective familiarity signal (Popova and Wiese, 2022, 2023).

At first sight, this line of argument might be seen as contradicting previous findings of covert recognition in prosopagnosia. For instance, Young and colleagues (Young et al., 1988) demonstrated facilitated

responses to the presentation of (overtly recognised) written celebrity names in a prosopagnosic participant when these name targets were preceded by (unrecognised) face primes of highly associated celebrities (e.g. the written name “Kamala Harris” preceded by the face of Joe Biden). This cross-domain associative priming effect was explained by sub-threshold (and therefore non-conscious) activation of face representations, which still allowed to prime identity-specific person representations of highly related people (Burton et al., 1991). Of relevance for the present study, this account suggests a graded activation of face representations, which can be activated either above or below a threshold necessary for overt recognition. We note that this account is not contradictory to our interpretation of the present findings. In the present study, participants likely overtly recognised the large majority of the prime stimuli, even in the (100 ms and 200 ms prime duration) backward-masked conditions of Experiment 3 (also see discussion below), and accordingly activation levels were clearly above the threshold for overt recognition. While we do suggest that no further increase above this threshold will arise with longer exposure, it remains plausible that activation below this threshold occurs in cases of covert recognition.

As noted above, although a significant main effect was detected in the omnibus ANOVA, N250r priming effects (200–300 ms) were substantially smaller in Experiment 3 relative to the previous experiments, and not significant for two out of three experimental conditions. While the most obvious explanation lies in the application of the backward mask, it may also appear plausible that Experiment 3 was generally less sensitive to detect priming in comparison to the other two because we tested fewer participants. However, we substantially increased the number of trials in Experiment 3, and trial numbers have been shown to have a stronger influence than sample size on the detection of a true effect in within-subjects ERP designs (Boudewyn et al., 2018). To check whether Experiment 3 (with increased trial numbers) was similarly informative as Experiment 2 (with larger N), we calculated the margin of error (MoE) for the overlapping conditions in the early N250r time window in both experiments. The margin of error is half the width of the confidence interval around the mean effect and can be interpreted as the precision of measurement (e.g. Cumming, 2012). While the MoE for priming in the 33 ms condition was 0.33 μ V in both experiments, it was 0.36 μ V in the 100 ms condition in Experiment 2 and 0.32 μ V in Experiment 3. Accordingly, precision was highly similar, and if anything even slightly better in Experiment 3. It therefore appears unlikely that the smaller N in Experiment 3 can explain the weaker priming effects in the early time window, and we conclude that backward masking, and consequently the prevention of visual aftereffects, clearly reduces priming with short prime durations in the N250r.

Of note, previous studies have examined the N250r with masked prime stimuli before. Most similar to the present study, Dörr and colleagues (Dörr et al., 2011) used an unfamiliar face as a backward mask and observed clear repetition effects with 500 ms prime durations. Using a sandwich masking procedure with very short prime durations of 17 ms, Trenner and colleagues (Trenner et al., 2004) did not observe any ERP priming effects. Similarly, Martens and colleagues did not find a masked N250r (Martens et al., 2006), again using a sandwich masking procedure with prime durations of 34 ms. Similar to the study of Dörr cited above, the purpose of masking in the present Experiment 3 was not to prevent the conscious recognition of the prime, but to avoid visual aftereffects. Accordingly, no forward masking was used, which likely explains the varying results from the studies using sandwich masking.

A recent study (Campbell and Tanaka, 2024) presented face stimuli in combination with backward masks either left or right of fixation at various presentation times (8 ms, 50 ms, 400 ms). The authors report that 8 ms were sufficient to elicit accurate saccadic responses towards the faces, even though participants were not subjectively aware of the stimuli. In the condition most similar to our shortest prime duration in Experiment 3 (50 ms presentation time), Campbell and Tanaka's (2024) participants reported a “brief glimpse” in about 60 % and an “almost

clear image” in about 40 % of the trials when asked for their subjective experience of the masked stimuli. This may suggest that participants in the 33 ms condition of the present Experiment 3 were not able to consciously recognise the prime identity in the majority of the trials. Interestingly, we observed ERP priming effects from 300 ms onwards, but not in the earlier time window, and accordingly one might be tempted to interpret this finding as suggesting that the image-independent N250r (in the 200–300 ms time window) depends on conscious recognition. According to this interpretation, a small number of consciously identified primes in the 33 ms condition would only elicit a small and non-significant effect, while longer prime durations would make prime identification much more likely and would accordingly result in significant priming. We note, however, that this interpretation is not easy to integrate with the absence of an N250r in the 200 ms condition, and it seems more likely that backward masking more generally reduced priming. Consequently, particularly the earlier, somewhat weaker effect would be more difficult to observe.

Overall, our results suggest that variation of prime duration does not affect the N250r, as long as the prime is not backward-masked. Masking, however, clearly reduces the N250r (200–300 ms), and this reduction seems to be largely independent of prime duration, at least between 33 ms and 200 ms. While these conclusions seem convincing to us, we note that prime durations below 33 ms may eliminate the effect, even when unmasked primes are presented. Therefore, a full exploration of the disruptive effects of prime duration as compared to masking (and their potential interaction) should further probe the lower bounds of the image-independent N250r.

As noted above, all previous studies on masked ERP repetition priming discussed above have used same-image priming. Importantly, the issue of same- versus different image priming is not a question of minor experimental detail, but – to the contrary – of major theoretical relevance. As discussed in the introduction, familiar faces are recognised from a wide range of highly variable images (Burton et al., 1999b; Jenkins et al., 2011), and accordingly the underlying familiar face representations are activated by highly variable pictures. Recognizing that different images show the same unfamiliar person can be very difficult (Bruce et al., 1999; Hancock et al., 2000), because we do not have image-independent representations for unfamiliar faces (Young and Burton, 2018). Recognition of a previously seen picture of an unfamiliar face, however, is considerably easier (Bruce, 1983), as it can be achieved using a presumably temporary pictorial representation. How is this related to ERP priming effects? An N250r-like ERP effect for unfamiliar faces can be observed if the same image is used as prime and target (Schweinberger et al., 1995; Zimmermann and Eimer, 2013), and this effect is presumably based on pictorial short-term representations. However, when using same image priming with familiar faces, the N250r will partly reflect the activation of pictorial short-term and partly of image-independent long-term representations. As a consequence, any results from same-image priming will likely reflect a mixture of the two, and the specific contributions of each underlying representation are unclear. At the same time, the N250r as measured with *different* image priming may reflect a purer measure of facial identity processing and therefore of the activation of long-term image-independent representations, which form the basis for familiar face recognition. In contrast to previous studies, the present results unambiguously demonstrate that such representations are activated highly efficiently.

A further question concerns the specific interpretation of the observed ERP priming effects. As discussed above, the N250r, as measured between approximately 200 and 300 ms, is traditionally interpreted as reflecting the facilitated activation of facial, i.e. visual, representations. At the same time, ERP effects in subsequent time windows have also been shown in studies of semantic priming. Such effects typically show their maxima at centro-parietal channels, with reversed polarity relative the occipito-temporal ERP effects discussed here, and are usually interpreted as reflecting N400-like effects (Schweinberger, 1996; Wiese and Schweinberger, 2011, 2015). Given the common

average reference used in this study, the 300–400 ms effects measured at occipito-temporal channels may reflect the opposite end of the same dipole underlying such N400 effects. Consequently, these priming effects might not purely reflect visual priming but might at least partly represent post-perceptual processes. One could argue that in the repetition condition not only is the same facial identity activated by prime and target, but also the corresponding semantic information. Accordingly, priming in the 300–400 ms might not be seen as evidence for the pre-activation of visual facial representations.

We note, however, that the precise interpretation of these priming effects is not of critical importance for our overall conclusions. Semantic priming effects can be observed independent of stimulus domain, e.g. with combinations of written name and face stimuli as primes and targets (Schweinberger, 1996; Wiese and Schweinberger, 2011; Young et al., 1988), which rules out domain-selective representations as the locus of the N400 effect. In the present study, however, we presented only faces, and the corresponding visual representations are activated prior to semantic information (e.g. Bruce and Young, 1986; Schweinberger and Neumann, 2016). In other words, in the present experiments, access to identity-specific semantic information would have only been possible after the corresponding facial representation had been sufficiently activated. This means that even in Experiment 3, which revealed no significant priming in the N250r time window for the shortest prime duration while a corresponding effect was observed between 300 and 400 ms, this latter effect could only possibly arise if the prime stimulus had activated the corresponding facial representation. Accordingly, independent of what type of information is represented by the 300–400 ms effect, it could not possibly occur without the (pre-)activation of a facial representation by the prime.

Building on a long tradition of cognitive models in face recognition research (Bruce and Young, 1986; Burton et al., 1990), the discussion so far has assumed that facial familiarity and facial identity signals stem from the activation of one person-specific facial representation (such as an FRU). Interestingly, however, a recent EEG study using time-resolved representational similarity analysis concluded that familiarity and identity representations are not identical and emerge independently (Ambrus et al., 2021; see also Dobs et al., 2019). In other words, the authors suggested that a general feeling of having seen a face before (which they assumed as reflecting familiarity) is separate from recognizing a face as an individual identity, and that the two processes are based on separate neural representations. Image-independent identity-specific representations are further suggested to become active from approximately 400 ms onwards (Ambrus et al., 2019).

We note that these conclusions seem hard to integrate with the present and previous results on the N250r. The image-independent N250r is based on identity-specific representations, and the familiarity signal that is generated by its activation, therefore, does not reflect a general feeling of familiarity but is specific to an individual identity. In the present experiments, both the prime and target stimulus were typically familiar, both in the repeated and the non-repeated condition (see Fig. 1 as an example). Accordingly, a general familiarity signal should be generated by all stimuli and should therefore be similar in the two conditions, given that all images were used as both primes and targets and were balanced across conditions. Critically, however, as the image-independent N250r does consistently emerge as the difference between repeated and non-repeated conditions (the present experiments, but also Bindemann et al., 2008; Quinn and Wiese, 2023; Schweinberger et al., 2002; Wiese et al., 2019a), this effect provides a strong argument for the activation of identity-specific representations. We know what the individual faces we are familiar with look like, and this specific information is stored in the representations of each facial identity (Burton et al., 2005; Burton et al., 2016). The image-independent N250r provides clear evidence that we access this information from approximately 200 ms onwards after seeing a face.

Moreover, several recent studies have used Fast Periodic Visual Presentation (FPVS) to examine familiar face recognition (Campbell

et al., 2020; Yan and Rossion, 2020; Yan et al., 2020; Zimmermann et al., 2019). Generally in line with our results, these studies have detected familiarity responses to individual identities with very short presentation times. Faces in these studies were presented at a rate of 6 Hz, or more precisely faded in and out within 167 ms. This change in contrast over the presentation interval makes it difficult to unequivocally determine for how long the face stimuli were recognisable to the participants. Yan and Rossion (2020) estimated that the “true” stimulus onset was delayed by 41.7 ms. Subtracting this number from both ends of the 167 ms period results in an estimated recognisable presentation time of 83.6 ms. The present findings suggest that even shorter presentation times may be sufficient to activate familiar face representations. We further note that FPVS experiments will pick up any physical difference between stimuli presented at the target and base frequencies, and that particular care is necessary to ensure that the neural response at the target frequency exclusively reflects the characteristic of interest (i. e. facial identity in the present case). At the same time, as noted in the introduction, experiments using the N250r can present physically identical target stimuli in the repetition and non-repetition conditions, which effectively rules out any influence of physical stimulus differences.

As outlined above, our interpretation of the present results assumes a basically hierarchical architecture for face processing. Potentially challenging this assumption, recent fMRI work has investigated face repetition, face “perception” (i.e. differences between face and non-face stimuli), and face recognition (differences between familiar and unfamiliar faces) using Direct Causal Modelling (DCM; Lee et al., 2022). The authors report that face perception included modulation of direct connections from Early Visual Cortex (EVC) to the Fusiform Face Area (FFA), without needing modulation from the Occipital Face Area (OFA) to FFA, which does not support a hierarchical organisation of the “core” face network in the posterior ventral stream (as suggested by e.g. Haxby et al., 2000). While this finding might at first sight be interpreted as evidence against the idea of a hierarchical organisation of the face processing system more generally, the authors also explicitly state that effective connectivity associated with face recognition remains unclear in this study (particularly because regions that are known to contribute were not modelled). Accordingly, the results reported by Lee and colleagues do not directly speak to the suggestion of separate processing stages for face detection, structural encoding, and face recognition, and therefore do not seem to challenge the theoretical assumptions relevant to the present study.

Finally, we note that the present series of experiments leaves important research questions unanswered (as no given series of experiments can possibly answer all questions relevant to a broader research topic). For instance, it is unclear at present to what extent image-independent ERP priming effects result from facilitated processing of the target due to identity repetition, as compared to inhibition of the target representations by the different facial identity in the non-repeated condition. This could be tested in an experiment that uses an additional unfamiliar prime condition. If the image-independent N250r was a facilitation-dominant effect, then the difference between the ID repetition and non-repetition conditions should be similar for a non-repeated familiar prime as compared to an unfamiliar/neutral prime (which does not activate any long-term representation and can therefore not elicit inhibitory effects). Alternatively, if the N250r had an inhibitory component, its magnitude should be larger when comparing the repetition condition to a non-repeated familiar prime relative to an unfamiliar prime condition. Work on the same-image N250r has used both unfamiliar and different familiar identities as primes, and has shown similar ERP repetition effects (Begleiter et al., 1995; Schweinberger et al., 1995; Schweinberger et al., 2002), which may suggest facilitation as the underlying mechanism. However, we are unaware of any previous study that has directly compared facilitation and inhibition for image-independent repetition priming within the same experiment, and it will be important to test these competing accounts of the image-

independent N250r.

In conclusion, the present series of experiments demonstrates the activation of image-independent familiar face representations from severely limited visual input. Our ERP results show clear priming effects for very short (up to 33 ms) stimulus presentation times, even when visual aftereffects are effectively ruled out to support recognition. Moreover, longer presentation times do not result in stronger priming, suggesting that – once a threshold of overt recognition is reached – the underlying representations respond in a dichotomous rather than gradual fashion. These results are suggestive of a facial recognition system that is highly effective and efficient, thus allowing for our impressive abilities to recognise the faces that we know.

CRedit authorship contribution statement

Holger Wiese: Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Tsvetomila Popova:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation. **Linda H. Lidborg:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Data curation. **A. Mike Burton:** Writing – review & editing, Writing – original draft, Funding acquisition.

Data availability

All data will be deposited in a publicly accessible repository at the time of publication

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References

- Ambrus, G.G., Kaiser, D., Cichy, R.M., Kovacs, G., 2019. The neural dynamics of familiar face recognition. *Cereb. Cortex* 29 (11), 4775–4784. <https://doi.org/10.1093/cercor/bhz010>.
- Ambrus, G.G., Eick, C.M., Kaiser, D., Kovacs, G., 2021. Getting to know you: emerging neural representations during face familiarization. *J. Neurosci.* 41 (26), 5687–5698. <https://doi.org/10.1523/JNEUROSCI.2466-20.2021>.
- Andrews, S., Burton, A.M., Schweinberger, S.R., Wiese, H., 2017. Event-related potentials reveal the development of stable face representations from natural variability. *Q. J. Exp. Psychol.* 70 (8), 1620–1632. <https://doi.org/10.1080/17470218.2016.1195851>.
- Begleiter, H., Porjesz, B., Wang, W., 1995. Event-related brain potentials differentiate priming and recognition to familiar and unfamiliar faces. *Electroencephalogr. Clin. Neurophysiol.* 94 (1), 41–49. [https://doi.org/10.1016/0013-4694\(94\)00240-I](https://doi.org/10.1016/0013-4694(94)00240-I).
- Bentin, S., Deouell, L.Y., 2000. Structural encoding and identification in face processing: ERP evidence for separate mechanisms. *Cogn. Neuropsychol.* 17 (1), 35–55. <https://doi.org/10.1080/026432900380472>.
- Bentin, S., Allison, T., Puce, A., Perez, E., McCarthy, G., 1996. Electrophysiological studies of face perception in humans. *J. Cogn. Neurosci.* 8 (6), 551–565. <https://doi.org/10.1162/jocn.1996.8.6.551>.
- Bindemann, M., Burton, A.M., Leuthold, H., Schweinberger, S.R., 2008. Brain potential correlates of face recognition: geometric distortions and the N250r brain response to stimulus repetitions. *Psychophysiology* 45 (4), 535–544. <https://doi.org/10.1111/j.1469-8986.2008.00663.x>.
- Boudewyn, M.A., Luck, S.J., Farrens, J.L., Kappenman, E.S., 2018. How many trials does it take to get a significant ERP effect? It depends. *Psychophysiology* 55 (6), e13049. <https://doi.org/10.1111/psyp.13049>.
- Bruce, V., 1983. Recognizing faces. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* 302 (1110), 423–436. <https://doi.org/10.1098/rstb.1983.0065>.
- Bruce, V., Young, A., 1986. Understanding face recognition. *Br. J. Psychol.* 77 (Pt 3), 305–327. <https://doi.org/10.1111/j.2044-8295.1986.tb02199.x>.
- Bruce, V., Henderson, Z., Greenwood, K., Hancock, P.J.B., Burton, A.M., Miller, P., 1999. Verification of face identities from images captured on video. *Journal of Experimental Psychology-Applied* 5 (4), 339–360. <https://doi.org/10.1037/1076-898x.5.4.339>.

- Burton, A.M., Bruce, V., Johnston, R.A., 1990. Understanding face recognition with an interactive activation model. *Br. J. Psychol.* 81 (Pt 3), 361–380. <https://doi.org/10.1111/j.2044-8295.1990.tb02367.x>.
- Burton, A.M., Young, A.W., Bruce, V., Johnston, R.A., Ellis, A.W., 1991. Understanding covert recognition. *Cognition* 39 (2), 129–166. [https://doi.org/10.1016/0010-0277\(91\)90041-2](https://doi.org/10.1016/0010-0277(91)90041-2).
- Burton, A.M., Bruce, V., Hancock, P.J.B., 1999a. From pixels to people: a model of familiar face recognition. *Cognit. Sci.* 23 (1), 1–31. Retrieved from WOS:000079939800001.
- Burton, A.M., Wilson, S., Cowan, M., Bruce, V., 1999b. Face recognition in poor-quality video: evidence from security surveillance. *Psychol. Sci.* 10 (3), 243–248. <https://doi.org/10.1111/1467-9280.00144>.
- Burton, A.M., Jenkins, R., Hancock, P.J., White, D., 2005. Robust representations for face recognition: the power of averages. *Cogn. Psychol.* 51 (3), 256–284. <https://doi.org/10.1016/j.cogpsych.2005.06.003>.
- Burton, A.M., Kramer, R.S., Ritchie, K.L., Jenkins, R., 2016. Identity from variation: representations of faces derived from multiple instances. *Cognit. Sci.* 40 (1), 202–223. <https://doi.org/10.1111/cogs.12231>.
- Caharel, S., Rossion, B., 2021. The N170 is sensitive to long-term (personal) familiarity of a face identity. *Neuroscience* 458, 244–255. <https://doi.org/10.1016/j.neuroscience.2020.12.036>.
- Campbell, A., Tanaka, J.W., 2024. Fast saccades to faces during the feedforward sweep. *J. Vis.* 24 (4), 16. <https://doi.org/10.1167/jov.24.4.16>.
- Campbell, A., Louw, R., Michniak, E., Tanaka, J.W., 2020. Identity-specific neural responses to three categories of face familiarity (own, friend, stranger) using fast periodic visual stimulation. *Neuropsychologia* 141, 107415. <https://doi.org/10.1016/j.neuropsychologia.2020.107415>.
- Cumming, G., 2012. *Understanding the New Statistics*. Routledge, New York.
- Cumming, G., Calin-Jageman, R., 2017. *Introduction to the New Statistics: Estimation, Open Science, & beyond*. Routledge, New York.
- Di Lollo, V., Dixon, P., 1988. Two forms of persistence in visual information processing. *J. Exp. Psychol. Hum. Percept. Perform.* 14 (4), 671–681. <https://doi.org/10.1037/0096-1523.14.4.671>.
- Dobs, K., Isik, L., Pantazis, D., Kanwisher, N., 2019. How face perception unfolds over time. *Nat. Commun.* 10 (1), 1258. <https://doi.org/10.1038/s41467-019-09239-1>.
- Dörr, P., Herzmans, G., Sommer, W., 2011. Multiple contributions to priming effects for familiar faces: analyses with backward masking and event-related potentials. *Br. J. Psychol.* 102 (4), 765–782. <https://doi.org/10.1111/j.2044-8295.2011.02028.x>.
- Eimer, M., 2011. The face-sensitive N170 component of the event-related brain potential. In: Calder, A.J., Rhodes, G., Johnson, M.H., Haxby, J.V. (Eds.), *The Oxford Handbook of Face Perception*. Oxford University Press, Oxford.
- Faul, F., Erdfelder, E., Lang, A.G., Buchner, A., 2007. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39 (2), 175–191. <https://doi.org/10.3758/bf03193146>.
- Galper, R.E., 1970. Recognition of faces in photographic negative. *Psychon. Sci.* 19 (4), 207–208.
- Gosling, A., Eimer, M., 2011. An event-related brain potential study of explicit face recognition. *Neuropsychologia* 49 (9), 2736–2745. <https://doi.org/10.1016/j.neuropsychologia.2011.05.025>.
- Hancock, P.J.B., Bruce, V., Burton, A.M., 2000. Recognition of unfamiliar faces. *Trends Cogn. Sci.* 4 (9), 330–337. [https://doi.org/10.1016/s1364-6613\(00\)01519-9](https://doi.org/10.1016/s1364-6613(00)01519-9).
- Haxby, J.V., Hoffman, E.A., Gobbini, M.I., 2000. The distributed human neural system for face perception. *Trends Cogn. Sci.* 4 (6), 223–233. [https://doi.org/10.1016/s1364-6613\(00\)01482-0](https://doi.org/10.1016/s1364-6613(00)01482-0).
- Itier, R.J., Taylor, M.J., 2004. N170 or N1? Spatiotemporal differences between object and face processing using ERPs. *Cereb. Cortex* 14 (2), 132–142. <https://doi.org/10.1093/cercor/bhg111>.
- Jackson, A.F., Bolger, D.J., 2014. The neurophysiological bases of EEG and EEG measurement: a review for the rest of us. *Psychophysiology* 51 (11), 1061–1071. <https://doi.org/10.1111/psyp.12283>.
- Jenkins, R., White, D., Van Montfort, X., Burton, A.M., 2011. Variability in photos of the same face. *Cognition* 121 (3), 313–323. <https://doi.org/10.1016/j.cognition.2011.08.001>.
- Jenkins, R., Dowsett, A.J., Burton, A.M., 2018. How many faces do people know? *Proc. Biol. Sci.* 285 (1888). <https://doi.org/10.1098/rspb.2018.1319>.
- Kemp, R., Pike, G., White, P., Musselman, A., 1996. Perception and recognition of normal and negative faces: the role of shape from shading and pigmentation cues. *Perception* 25 (1), 37–52. <https://doi.org/10.1068/p250037>.
- Kramer, R.S.S., Young, A.W., Burton, A.M., 2018. Understanding face familiarity. *Cognition* 172, 46–58. <https://doi.org/10.1016/j.cognition.2017.12.005>.
- Lee, S.M., Tibon, R., Zeidman, P., Yadav, P.S., Henson, R., 2022. Effects of face repetition on ventral visual stream connectivity using dynamic causal modelling of fMRI data. *Neuroimage* 264, 119708. <https://doi.org/10.1016/j.neuroimage.2022.119708>.
- Luck, S.J., Kappenman, E.S., 2012. *The Oxford Handbook of Event-Related Potential Components*. Oxford University Press, Oxford.
- Martens, U., Schweinberger, S.R., Kiefer, M., Burton, A.M., 2006. Masked and unmasked electrophysiological repetition effects of famous faces. *Brain Res.* 1109 (1), 146–157. <https://doi.org/10.1016/j.brainres.2006.06.066>.
- Olivares, E.I., Iglesias, J., Saavedra, C., Trujillo-Barreto, N.J., Valdes-Sosa, M., 2015. Brain signals of face processing as revealed by event-related potentials. *Behav. Neurol.* 1–16. <https://doi.org/10.1155/2015/514361>.
- Pickering, E.C., Schweinberger, S.R., 2003. N200, N250r, and N400 event-related brain potentials reveal three loci of repetition priming for familiar names. *J. Exp. Psychol. Learn. Mem. Cogn.* 29 (6), 1298–1311. <https://doi.org/10.1037/0278-7393.29.6.1298>.
- Popova, T., Wiese, H., 2022. The time it takes to truly know someone: neurophysiological correlates of face and identity learning during the first two years. *Biol. Psychol.* 170, 108312. <https://doi.org/10.1016/j.biopsycho.2022.108312>.
- Popova, T., Wiese, H., 2023. Developing familiarity during the first eight months of knowing a person: a longitudinal EEG study on face and identity learning. *Cortex* 165, 26–37. <https://doi.org/10.1016/j.cortex.2023.04.008>.
- Quinn, B.P., Wiese, H., 2023. The role of the eye region for neural correlates of familiar face recognition: the N250r reveals no evidence for eye-centred face representations. *Vis. Cogn.* 31 (7), 501–519. <https://doi.org/10.1080/13506285.2024.2315787>.
- Rossion, B., Jacques, C., 2008. Does physical interstimulus variance account for early electrophysiological face sensitive responses in the human brain? Ten lessons on the N170. *Neuroimage* 39 (4), 1959–1979. <https://doi.org/10.1016/j.neuroimage.2007.10.011>.
- Russell, R., Sinha, P., Biederman, I., Nederhouser, M., 2006. Is pigmentation important for face recognition? Evidence from contrast negation. *Perception* 35 (6), 749–759. <https://doi.org/10.1068/p5490>.
- Saavedra, C., Iglesias, J., Olivares, E.I., 2010. Event-related potentials elicited by the explicit and implicit processing of familiarity in faces. *Clin. EEG Neurosci.* 41 (1), 24–31. <https://doi.org/10.1177/155005941004100107>.
- Schweinberger, S.R., 1996. How Gorbachev primed Yeltsin: analyses of associative priming in person recognition by means of reaction times and event-related brain potentials. *J. Exp. Psychol. Learn. Mem. Cogn.* 22 (6), 1383–1407.
- Schweinberger, S.R., Burton, A.M., 2003. Covert recognition and the neural system for face processing. *Cortex* 39 (1), 9–30. [https://doi.org/10.1016/s0010-9452\(08\)70071-6](https://doi.org/10.1016/s0010-9452(08)70071-6).
- Schweinberger, S.R., Neumann, M.F., 2016. Repetition effects in human ERPs to faces. *Cortex* 80, 141–153. <https://doi.org/10.1016/j.cortex.2015.11.001>.
- Schweinberger, S.R., Pfütz, E.M., Sommer, W., 1995. Repetition and associative priming of face recognition - evidence from event-related potentials. *Journal of Experimental Psychology-Learning Memory and Cognition* 21 (3), 722–736. <https://doi.org/10.1037/0278-7393.21.3.722>.
- Schweinberger, S.R., Pickering, E.C., Jentzsch, I., Burton, A.M., Kaufmann, J.M., 2002. Event-related brain potential evidence for a response of inferior temporal cortex to familiar face repetitions. *Brain Res. Cogn. Brain Res.* 14 (3), 398–409. [https://doi.org/10.1016/s0926-6410\(02\)00142-8](https://doi.org/10.1016/s0926-6410(02)00142-8).
- Schweinberger, S.R., Huddy, V., Burton, A.M., 2004. N250r: a face-selective brain response to stimulus repetitions. *Neuroreport* 15 (9), 1501–1505. <https://doi.org/10.1097/01.wnr.0000131675.00319.42>.
- Tanaka, J.W., Curran, T., Porterfield, A.L., Collins, D., 2006. Activation of preexisting and acquired face representations: the N250 event-related potential as an index of face familiarity. *J. Cogn. Neurosci.* 18 (9), 1488–1497. <https://doi.org/10.1162/jocn.2006.18.9.1488>.
- Trenner, M.U., Schweinberger, S.R., Jentzsch, I., Sommer, W., 2004. Face repetition effects in direct and indirect tasks: an event-related brain potentials study. *Brain Res. Cogn. Brain Res.* 21 (3), 388–400. <https://doi.org/10.1016/j.cogbrainres.2004.06.017>.
- White, D., Kemp, R.I., Jenkins, R., Matheson, M., Burton, A.M., 2014. Passport officers' errors in face matching. *PloS One* 9 (8), e103510. <https://doi.org/10.1371/journal.pone.0103510>.
- Wiese, H., Schweinberger, S.R., 2011. Accessing semantic person knowledge: temporal dynamics of nonstrategic categorical and associative priming. *J. Cogn. Neurosci.* 23 (2), 447–459. <https://doi.org/10.1162/jocn.2010.21432>.
- Wiese, H., Schweinberger, S.R., 2015. Getting connected: both associative and semantic links structure semantic memory for newly learned persons. *Q J Exp Psychol (Hove)* 68 (11), 2131–2148. <https://doi.org/10.1080/17470218.2015.1008526>.
- Wiese, H., Komes, J., Tüittenberg, S., Leiding, J., Schweinberger, S.R., 2017. Age-related differences in face recognition: neural correlates of repetition and semantic priming in young and older adults. *J. Exp. Psychol. Learn. Mem. Cogn.* 43 (8), 1254–1273. <https://doi.org/10.1037/xlm0000380>.
- Wiese, H., Chan, C.Y.X., Tüittenberg, S.C., 2019a. Properties of familiar face representations: only contrast positive faces contain all information necessary for efficient recognition. *J. Exp. Psychol. Learn. Mem. Cogn.* 45 (9), 1583–1598. <https://doi.org/10.1037/xlm0000665>.
- Wiese, H., Tüittenberg, S.C., Ingram, B.T., Chan, C.Y.X., Gurbuz, Z., Burton, A.M., Young, A.W., 2019b. A robust neural index of high face familiarity. *Psychol. Sci.* 30 (2), 261–272. <https://doi.org/10.1177/0956797618813572>.
- Wiese, H., Hobden, G., Siilbek, E., Martignac, V., Flack, T.R., Ritchie, K.L., Burton, A.M., 2022. Familiarity is familiarity: event-related brain potentials reveal qualitatively similar representations of personally familiar and famous faces. *J. Exp. Psychol. Learn. Mem. Cogn.* 48 (8), 1144–1164. <https://doi.org/10.1037/xlm0001063>.
- Yan, X., Rossion, B., 2020. A robust neural familiar face recognition response in a dynamic (periodic) stream of unfamiliar faces. *Cortex* 132, 281–295. <https://doi.org/10.1016/j.cortex.2020.08.016>.
- Yan, X., Zimmermann, F.G., Rossion, B., 2020. An implicit neural familiar face identity recognition response across widely variable natural views in the human brain. *Cogn. Neurosci.* 11 (3), 143–156. <https://doi.org/10.1080/17588928.2020.1712344>.
- Young, A.W., Bruce, V., 2024. *Face Perception (Second Edition ed.)*. Routledge, New York.
- Young, A.W., Burton, A.M., 2017. Recognizing Faces. *Curr. Dir. Psychol. Sci.* 26 (3), 212–217. <https://doi.org/10.1177/0963721416688114>.
- Young, A.W., Burton, A.M., 2018. Are we face experts? *Trends Cogn. Sci.* 22 (2), 100–110. <https://doi.org/10.1016/j.tics.2017.11.007>.

- Young, A.W., Hellawell, D., De Haan, E.H., 1988. Cross-domain semantic priming in normal subjects and a prosopagnosic patient. *Q J Exp Psychol A* 40 (3), 561–580. <https://doi.org/10.1080/02724988843000087>.
- Zimmermann, F.G., Eimer, M., 2013. Face learning and the emergence of view-independent face recognition: an event-related brain potential study. *Neuropsychologia* 51 (7), 1320–1329. <https://doi.org/10.1016/j.neuropsychologia.2013.03.028>.
- Zimmermann, F.G., Yan, X., Rossion, B., 2019. An objective, sensitive and ecologically valid neural measure of rapid human individual face recognition. *R. Soc. Open Sci.* 6 (6), 181904 <https://doi.org/10.1098/rsos.181904>.