# When a stranger becomes a friend: Measuring the neural correlates of real-world face familiarisation

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# When a stranger becomes a friend: Measuring the neural correlates of real-world face familiarisation

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**ABSTRACT**
Humans can readily and effortlessly learn new faces encountered in the social environment. As a face transitions from unfamiliar to familiar, the ability to generalize across different images of the same person increases substantially. Fast periodic visual stimulation and EEG (FPVS-EEG) was used to isolate identity-specific responses that generalize across different images of the same person from low-level visual processing and face-general processes that aren't identity-specific. We observed these signals emerge and increase in magnitude as a group of strangers became lab mates ($N$=9). The neural response to an unfamiliar identity that remained unfamiliar did not change. Comparison of the response to the newly familiarised face to a highly overlearned face (the own-face) showed that this identity-specific signal was modulated by level of familiarity. The study presents the first examination of identity-specific processing changes as they occur *in situ* from normal, everyday face experience.

Faces are ubiquitous to the human visual experience. A recent visual diary study found that we spend 20% of the day looking at faces and encounter about 255 different individuals each day (Oruc et al., 2019), while the total number of faces that a person will know has been estimated to be 5000 on average (Jenkins et al., 2018). This extensive experience has been said to give rise to a visual expertise for faces (Carey, 1992; Diamond & Carey, 1986) that supports the constant demand for discriminating and individuating all those faces in our day-to-day environment and for recognizing the identities of the faces we know. This is consistent with studies showing robust recognition of well-known faces from almost any image, even when they are degraded (Burton et al., 1999; Lander et al., 2001), distorted (Bindemann et al., 2008; Hole et al., 2002), or partially occluded (Brunas et al., 1990; Johnston et al., 1996). By contrast, an unfamiliar face is more difficult to recognize as the same person across different photos (Bruce et al., 2001; Burton et al., 2010), where within-person variability (i.e., changes in appearance) is often confused for between-person variability (i.e., different identities; Adini et al., 1997; Jenkins et al., 2011). This

discrepancy between the highly efficient recognition of familiar faces and the fallibility of unfamiliar face recognition has led some to claim that we are only experts for recognizing faces we know, and not for the generic recognition of any face identity (Young & Burton, 2018).

An alternative view is that our expertise for face recognition is not for the perception of identity *per se*, but in the ability to readily learn a new face so that unfamiliar faces quickly and easily become familiar (Rossion, 2014). In daily life, faces are usually learned without explicit efforts to encode the faces of new acquaintances. Subsequent recognition requires the ability to overcome within-person variability of the appearance of an individual face due to changes to the environment or to the face itself (Burton, 2013; Jenkins et al., 2011). Face learning is therefore especially impressive given that individual faces have been found to vary along idiosyncratic dimensions (Burton et al., 2016), meaning that learning to tolerate the variability of one identity does not transfer to other identities (Dowsett et al., 2016). Instead, recognizing a familiar face is thought to depend on an image-invariant representation that is

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identity-specific and that is robust to within-person variability (Bruce & Young, 1986; Burton et al., 2011; Kramer et al., 2018), and that invariance is acquired through experience with an identity's variability (Baker et al., 2017; Burton et al., 2016; Dowsett et al., 2016; Murphy et al., 2015; Ritchie & Burton, 2017).

If familiar face recognition is mediated by accessing a stable face representation, this activation should be measurable by comparing the neural processing of an unfamiliar face as it transitions to familiar. The goal of the experiment was to measure the neural changes that occur during everyday, real-world experience by tracking the face representations that emerged when a group of strangers became lab mates. Whereas many studies have examined changes in neural processing for experimentally learned faces (e.g., Pierce et al., 2011; Verosky et al., 2020; Zimmermann & Eimer, 2013), there is currently no research that examines how face recognition changes as a result of learning a new face "in the wild" through normal social interaction and under naturalistic viewing conditions (but see Ambrus et al., 2021 where participants interacted with confederates). Here we had a unique opportunity to measure neural responses amongst personally familiar lab mates, first before familiarisation (i.e., before meeting) and again after 2 months of real-world familiarisation in an actual social setting. This ecological factor may have substantial consequences for face identity processing, since the recognition of personally familiar faces can involve increased perceptual, semantic, affective, and lexical processing compared to faces that are only visually familiar, famous, or experimentally learned (Ramon & Gobbini, 2018). Most importantly, it captures our natural "expertise" for acquiring highly stable face representations without any deliberate encoding effort.

We used fast periodic visual stimulation (FPVS) to parse identity-specific processing signals from signals related to general face processing, face individuation, and low-level visual processes (Campbell et al., 2020; Yan et al., 2020; Zimmermann et al., 2019). Familiarised faces were presented at a predetermined presentation frequency (i.e., 0.86 Hz) to evoke brain responses at the exact frequency of presentation and associated harmonics. The major advantage of this approach is that the familiarised face response can be decomposed into two separate frequencies to isolate the identity-specific response. By presenting images of a familiarised face within a stream of other faces that are matched on all dimensions except the one of interest (e.g., identity), the neurophysiological responses elicited by these other dimensions are siphoned into this higher face presentation frequency (e.g., 6 Hz); what remains at the slower presentation frequency of the familiarised face images (e.g., 0.86 Hz) is the response related to the identity of the familiarised face.

Previously, we found that the magnitude of identity-specific responses to personally familiar faces may index the relative familiarity of pre-familiarised faces (Campbell et al., 2020). Responses related to identity processing of the face of a well-known friend were stronger than an unfamiliar face, but identity-specific responses elicited by the own-face was, on average, 2.5 times greater than those elicited by the friend's face. Own-face recognition is often faster compared to less familiar faces, and own-face processing advantages have been attributed to the extreme familiarity with one's own face (Bortolon & Raffard, 2018; Devue et al., 2009; Devue & Brédart, 2008). The response magnitude associated with identity processing may therefore provide an index of face familiarity.

Here, we tracked the effect of personal familiarity on changes in the magnitude of an identity-specific response. Changes in face processing were measured by comparing identity-specific responses to images of an assigned lab partner pre-familiarisation and at two months post-familiarisation. The key prediction was that real-world face learning would cause changes to identity-specific processing that would not be observed for a novel face that remained unfamiliar at both test times. We also contrasted the response to a newly learned face against a highly overlearned face by comparing it to the response obtained for the participant's own face. We therefore predicted that the own-face response would remain stronger than the response to the newly familiarised face.

## Methods

### Participants

Participants were ten undergraduate students from the University of Victoria who were recruited as research assistants to join the lab as part of an undergraduate research course. Each participant was

partnered with another student (their "new friend") whom they had not met and whom was unfamiliar to them. EEG data from one participant was not included due to a technical recording issue but who remained partnered with another participant. The remaining nine participants (8 female) had a mean age of 21.4 years ($SD = 1.5$ years). The experiment and consenting procedures were approved by the human research ethics committee of the University of Victoria.

## Power analysis

FPVS provides a very high signal-to-noise ratio (SNR) compared to normal ERP techniques because presenting the visual stimuli at a specific frequency leads to the response to be concentrated within narrow frequency bins of the EEG bandwidth (Regan, 1989; Rossion, 2014). Responses of interest are therefore relatively immune to artifacts because they are isolated from broadband EEG noise. This sensitivity makes FPVS especially well-suited for measuring effects in single patient cases (Liu-Shuang et al., 2016), individual participants (Xu et al., 2017; Yan & Rossion, 2020) and from small samples of special populations (Dwyer et al., 2018; Hagen & Tanaka, 2019). Because the main goal of the study was to examine face learning in an ecologically-relevant social setting, the size of our sample was constrained by the number of new student researcher assistants who join our research lab each year. Using this group as our naturalistic sample also ensured that the quality, duration and frequency of social interactions between our participants were roughly the same.

To ensure that we had adequate power to detect familiarisation effects, a power analysis was conducted based on previously reported effect sizes. The appropriate sample size for a given level of power depends on the size of the effect, and previous work has shown that familiarity effects on FPVS face-identity responses are very strong (Campbell et al., 2020; Zimmermann et al., 2019). We used effect sizes reported for responses to the own-face and a personally familiar face relative to an unfamiliar face (Campbell et al., 2020) to determine the statistical power (1 – β) of the planned sample ($n = 9$) using a dependent $t$-test. Effect sizes were adjusted to account for publication bias and uncertainty using the correction procedure designed by Anderson et al. (2017) and implemented

in the R BUCSS package (Anderson & Kelley, 2020). This procedure uses the previously reported $t$-statistic and sample size to adjust the noncentrality parameter. The adjusted noncentrality parameter (based on a $t$-value of 6.82, $n = 12$, $d = 1.97$ reported by Campbell et al., 2020) used to determine statistical power to detect responses to a personally familiar face using a dependent $t$-test was 3.796. The adjusted noncentrality parameter (based on a $t$-value of 10.18, $n = 12$, $d = 2.94$ reported by Campbell et al., 2020) used to determine statistical power to detect responses to the own-face using a dependent $t$-test was 6.175. To correct for publication bias, we specified a prior alpha-level of .05 (i.e., the assumed statistical significance necessary for publishing in the field). To correct for uncertainty, we specified an assurance level of 0.95 (i.e., the proportion of times that power will be at or above the desired level, if the experiment were to be reproduced many times). The alpha-level for the planned study was set at .05. Using this conservative approach, our power analysis showed that we had 80% power to detect personally familiar face effects and 99% power to detect own-face effects with an $n = 9$.

## Stimuli

Prior to the experimental test session, an experimenter conducted brief interviews with each participant individually that were video-recorded using a Canon EOS Rebel DSLR camera mounted on a tripod. The camera was repositioned throughout the interview to capture video of the seated participant from the front, the right angle, and the left angles. Stimuli were created this way to obtain images that varied in viewing angle and to capture natural rather than posed expressions.

All interviewees sat on the same chair during video recording.[1] Still frame images (6 frontal, 3/4 right, 3/4 left) were randomly selected from the video frames to serve as the image set for each identity (12 images per identity). Using Adobe Lightroom, images were cropped so that the face occupied roughly 80% of the image with the nose just below centre and then resized to $350 \times 350$ pixels.

## Stranger faces

The same procedure was used to obtain images of 10 individuals (12 images per identity) who were not participants in the study or the research lab. Each

participant was assigned a "stranger" that was matched to their "new friend" in gender and general description (e.g., hair colour, skin colour) and served as a control identity that remained unfamiliar at both testing times. Consequently, 1 male and 8 female identities used to match the gender of participant faces used in the new friend and own-face condition.

### Unfamiliar base faces

The same procedure was used to obtain images of 12 individuals (12 images per identity) who were not participants in the study or the research lab. The images of these identities were used for the unfamiliar base face stimuli (6 identities in each set, all female[2]). One set was used for the unfamiliar base faces in the pre-familiarisation test and the other set was used for the unfamiliar base faces in the post-familiarisation test. This was done to ensure that the base faces at the second testing time were completely unfamiliar to participants. The set used for pre- and post-familiarisation was counterbalanced across participants.

The same set of images (own, new friend, stranger) were used at both testing times.

### Procedure

Each participant was partnered with another incoming student in the research lab. Each week, students met for a two hour lab meeting and a two hour research meeting to work on a joint lab research project with their assigned partner (the "new friend"). In the first "pre-familiarisation" test time, participants were tested before meeting their assigned partner, and in the second "post-familiarisation" test time, participants were tested after ~8 weeks of working with the partner in the lab. In both test sessions, participants were seated at a table in front of a keyboard and LCD monitor.

As shown in Figure 1, visual stimulation consisted of four 70 s image sequences for each condition (own, new friend, stranger) and was presented using a custom MATLAB script (SinStim; Jacques et al., 2016). In each sequence, images were presented at a constant rate of 6 Hz ($F1$ = the base-stimulation frequency). The image sequence was structured so that, depending on the condition, every 7th image was the participant's own face (own-face condition), the face
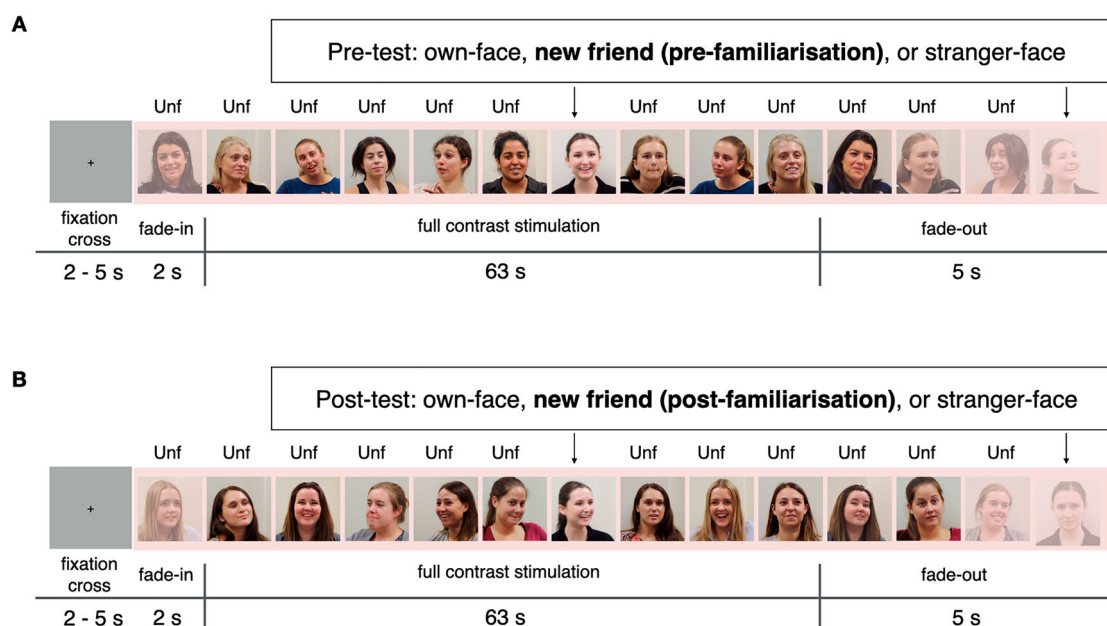
of their assigned partner (new friend condition), or an unfamiliar stranger face (stranger condition), and were drawn randomly from the images of the relevant identity. All other images were randomly selected from the set of unfamiliar base faces. Identity therefore varied at every image cycle, but the face of the own/new friend/stranger appeared with a periodicity of $F1/7 \approx 0.86$ Hz ($F2$ = the identity-specific frequency).

The presentation of each stimulation sequence was as follows:

1) 2–5 s black fixation cross appeared on a grey background;
2) 2 s image sequence fade-in;
3) 63 s image sequence presentation;
4) 5 s image sequence fade-out;
5) 2 s black fixation cross on grey background (Figure 1).

The fixation cross remained on the screen for the entire duration of the stimulation sequence and was positioned to appear over the centre of the image. Across all face images, this roughly corresponded to the area just above the nose. Displayed on a monitor from a distance of 0.7 m, the stimuli subtended an angle of approximately 7 degrees of visual angle. To maintain a steady point of fixation and attention during visual stimulation, participants were asked to engage in a fixation colour change detection task during each sequence presentation (e.g., Liu-Shuang et al., 2016). At eight random time points in the sequence, the colour of the fixation cross changed briefly (200 ms) to red. Participants were told that face images would be presented rapidly on the screen with a black fixation cross in the middle of the screen and that their primary task was to press the spacebar on the computer keyboard every time they detected the colour of the cross changed from black to red.

The visual stimulation sequences at the pre-familiarisation (A) and post-familiarisation (B) test sessions consisted of face images contrast modulated at a rate of 6 Hz (each image cycle had a duration of ~167 ms). Depending on the condition, every 7th image presented was either the participant's own face, the face of the to-be-familiarised new friend, or the face of an unfamiliar stranger (another subject who was unfamiliar to the participant). The own, new friend,

**A**

Pre-test: own-face, **new friend (pre-familiarisation)**, or stranger-face

| Unf | Unf | Unf | Unf | Unf | Unf | ↓ | Unf | Unf | Unf | Unf | Unf | Unf | ↓ |

| fixation cross | fade-in | full contrast stimulation | fade-out |
| 2 - 5 s | 2 s | 63 s | 5 s |

**B**

Post-test: own-face, **new friend (post-familiarisation)**, or stranger-face

| Unf | Unf | Unf | Unf | Unf | Unf | ↓ | Unf | Unf | Unf | Unf | Unf | Unf | ↓ |

| fixation cross | fade-in | full contrast stimulation | fade-out |
| 2 - 5 s | 2 s | 63 s | 5 s |

**Figure 1.** The visual stimulation sequences at the pre-familiarisation (A) and post-familiarisation (B) test sessions consisted of face images contrast modulated at a rate of 6 Hz (each image cycle had a duration of ∼167ms). Depending on the condition, every 7th image presented was either the participant's own face, the face of the to-be-familiarised new friend, or the face of an unfamiliar stranger (another subject who was unfamiliar to the participant). The own, new friend, or stranger-face therefore appeared at a rate of 6 Hz/7 = 0.86 Hz. All other images were selected randomly from a set of faces that were unfamiliar to all participants. Identities used for the base face stimuli at post-familiarisation were novel to ensure unfamiliarity; the set of base face identities used for pre-familiarisation and post-familiarisation were counterbalanced across participants. During visual stimulation, participants engaged in a fixation cross colour change detection task (not shown) that required them to press the spacebar every time that a fixation cross superimposed in the middle of the screen changed from black to red. Fixation cross changes occurred 8 times at random intervals. Face images are shown here with permission from the participants/models.

or stranger-face therefore appeared at a rate of 6 Hz/7 = 0.86 Hz. All other images were selected randomly from a set of faces that were unfamiliar to all participants. Identities used for the base face stimuli at post-familiarisation were novel to ensure unfamiliarity; the set of base face identities used for pre-familiarisation and post-familiarisation were counterbalanced across participants. During visual stimulation, participants engaged in a fixation cross colour change detection task (not shown) that required them to press the spacebar every time that a fixation cross superimposed in the middle of the screen changed from black to red. Fixation cross changes occurred 8 times at random intervals. Face images are shown here with permission from the participants/models.

During each stimulation sequence, the electroencephalogram (EEG) was recorded using a montage of 42 electrode sites in accordance with the extended international 10–20 system (Jasper, 1958). Signals were acquired using Ag/AgCl ring electrodes mounted in a nylon electrode cap with an abrasive, conductive gel (EASYCAP GmbH, Herrsching-Breitbrunn, Germany). Signals were amplified by low-noise electrode differential amplifiers with a frequency response of DC 0.017–67.5 Hz (90 dB–octave roll off) and digitized at a rate of 250 samples per second. Digitized signals were recorded to disk using Brain Vision Recorder Software (Brainproducts, Munich, Germany). Impedances were kept below 20 kΩ. The EEG was recorded using the average reference.

Breaks of about one minute were provided between each stimulation sequence, and the condition order was pseudorandomized for each participant. The testing time for each test session was approximately 25 min.

### EEG analysis

All EEG processing steps were carried out using the free software Letswave 6 (https://github.com/NOCIONS/letswave6) running on MATLAB

(MathWorks). A Butterworth filter with cut-off values of 0.1-100 Hz and a slope of 24 dB/octave was applied to the data. Data of participants who blinked more than 10 times during any of the stimulation sequences within a recording session were corrected by applying ICA to the data from each stimulation sequence and removing a single component accounting for blink artifacts (mean number of blinks across participants and recording sessions = 9.5, $SD$ = 6.8). ANOVA of the number of blinks showed no significant difference between identity conditions, $p$ = .080 (mean number of blinks within the own-face condition = 8.9, $SD$ = 7.2; mean number of blinks within the new friend condition = 9.5, $SD$ = 7.0; mean number of blinks within the stranger condition = 10.0, $SD$ = 6.5).

Channels which were artifact-prone across multiple trials (less than 1% of channels on average) were re-estimated using linear interpolation of the two nearest channels. All EEG segments were re-referenced to a common average reference.

The EEG for each sequence was re-segmented, beginning from sequence onset until approximately 64 s (including stimulus fade-in but before stimulus fade-out), to contain an integer number of 0.86 Hz cycles (55 cycles, 16035 time bins in total ≈ 64 s). For every participant during the pre- and post-familiarisation testing sessions, the four segmented sequences within the own, new friend, and stranger face conditions were averaged in the time-domain to reduce EEG activity that is not phase-locked to the stimulus. A Fast Fourier Transform (FFT) was then applied to the averaged segments to represent the data of each channel as a normalized amplitude spectrum (μV) in the frequency domain with a frequency resolution of 0.0156 Hz (i.e., 1/64.14 s).

As responses are expected to be observed across multiple harmonics of the stimulation frequencies, we assessed harmonics of each stimulation frequency (i.e., $F1$, $F2$) based on $z$-scores. The procedure was as follows:

1) Within each condition and test session, individual amplitude spectra were averaged across participants and all channels;
2) At each harmonic, $z$-scores were computed as the difference between the amplitude at the frequency of interest and the mean amplitude of the local baseline divided by the standard deviation of local baseline (local baseline = 20 surrounding frequency bins, excluding the immediately adjacent bins and the bins containing the minimum and maximum response);
3) Using the $z$-scores as a stopping rule, the range of harmonics was constrained to the highest number of consecutively significant harmonics observed in any one condition (e.g., 1$F2$, 2$F2$, 3$F2$, etc., where each $z \geqq 3.1$, $p$ < .001, 1-tailed, i.e., signal > noise).

Responses were significant up to the 6th harmonic for the 6 Hz base-simulation response (i.e., 6$F1$ = 36 Hz), and up to the 12th harmonics for the 0.86 Hz identity-specific response (i.e., 12$F2$ = 10.29 Hz, but excluding the 6 Hz harmonic that overlapped with the base-stimulation frequency). For each stimulation frequency *(F1, F2)*, the same number of harmonics were used for quantifying responses in each identity condition.

A baseline-subtraction correction was applied to the amplitude spectra using the same local baseline definition used for the $z$-score. For each stimulation frequency, responses were quantified as the sum of the baseline-corrected amplitudes across significant harmonics.

### Base-stimulation response (6 hz)
The 6 Hz response was quantified as the average summed-harmonic response in the channels of maximum response: Oz, POz, PO8 and the left hemisphere homologue PO7. These defined a *medial-occipital* (MO) region.

Given that we did not have predictions for effects in the base-stimulation responses (6 Hz), response differences across identity conditions and time were tested using repeated-measures ANOVA with condition (own, new friend, stranger) and time (pre- and post-familiarisation) as within-subject factors. Effects of condition and time were also assessed by computing the Bayes factor favouring either a model that included the effect of interest or a model that excluded that effect. All Bayes factors were generated using the R BayesFactor package (Morey & Rouder, 2018) using default priors. We interpreted Bayes factors (*BF*) according to the modified guidelines of Jeffreys (1961), whereby a *BF* of 3 is taken as positive support for an outcome (Lee & Wagenmakers, 2013; Raftery, 1995).

### Identity-specific response (0.86 hz)

The 0.86 Hz identity-specific response was quantified as the average summed-harmonic response in the channels of maximum response (averaged across all identity conditions): P10, PO10, PO8 and the left hemisphere homologues P9, PO9, and PO7. These defined an *occipito-temporal* (OT) region; the same region-of-interest was used for quantifying the identity-specific specific response for all conditions.

Because it was our goal to observe face familiarisation that occurs spontaneously in the real-world, the sample size was determined by the actual group size in a real-world social setting: a psychology research lab. However, the trade-off of this ecological validity is statistical power. Although increasing the number of participants would increase statistical power, it would disturb the critical element of a real-word social setting for capturing face familiarisation *in situ*.

To maximize power, our main analysis relied on three planned comparisons:

1) response to the stranger face would not change between sessions;
2) response to the new friend face, which transitions from unfamiliar to familiar between test sessions, would show a significant increase in response;
3) response to the own-face would not change between sessions.

Uncorrected paired-samples *t*-tests were used to test for a significant increase in the response to the face of the assigned lab partner ("new friend"), the stranger face, and the own-face across test sessions. To increase the credibility of our findings, Bayesian tests were conducted to quantify the evidence for and against the hypothesis that an effect was present, and responses were examined at the individual level to corroborate the group-level effects.

We then determined the significance of the 0.86 Hz identity-specific responses for individual participants. This was done for each condition and test time by summing the raw amplitude spectra containing the relevant 0.86 Hz harmonics and their local baselines (i.e., 20 surrounding frequency bins) and calculating *z*-scores to quantify the response relative to EEG noise in surrounding frequency bins.

Statistical significance of each participant's response change to the familiarised new friend face was assessed using single case *t*-tests with one-tailed significance

thresholds (Crawford et al., 2010; see Liu-Shuang et al., 2016). Here, each participant was treated as a single case, and their difference score (of summed-harmonic responses) for the familiarised new friend face was compared against difference scores in the control group, which in this case was the differences scores of all participants for the unfamiliarised stranger face. The procedure was repeated to evaluate any changes to the own-face response (two-tailed).

To examine differences between identity conditions, multiple comparisons (Bonferroni–Holm corrected) were conducted to compare response magnitudes across identity conditions in each test session.

### Between- and within-session reliability

We examined the test-retest reliability and the split-half reliability (i.e., internal consistency) of the 6 Hz base-stimulation and 0.86 Hz identity-specific responses using the intraclass correlation coefficient (ICC). This provides a measure of the absolute agreement between measurements. Since the ICC is defined by the proportion of the total variance due to between-subject variance, values can range between 0 and 1, with higher values indicating more consistency within-subjects (Koo & Li, 2016; Shrout & Fleiss, 1979). For each identity condition, split-half reliability was assessed by comparing the mean responses evoked in the first (first two stimulation sequences) and second halves (third and fourth stimulation sequences) of a test session.

ICC estimates and their 95% confidence intervals were calculated for both the 6 and 0.86 Hz responses for each identity condition and ROI using the R psych package (Revelle, 2019) based on an absolute agreement, one-way model. As there are no definitive standards for acceptable reliability using ICC (Koo & Li, 2016), we interpreted ICC using the same conservative guidelines recently used to evaluate the FPVS face individuation response (Dzhelyova et al., 2019): Within-subject reliability was interpreted as poor (ICC < 0.40), moderate (ICC 0.41-0.59), good (ICC 0.60-0.74), or excellent (ICC > 0.75).

## Results

### Behavioural data

Accuracy for the colour change detection task was close to ceiling across all three conditions and test

times ($M = 96.6\%$, $SD = 5.9\%$), and a repeated measures ANOVA found no effects of identity (own, new friend, stranger; $F(2, 16) = 1.41$, $p = .27$, $\eta^2_p = .15$), or time (pre- and post-familiarisation; $F(1, 8) = 0.31$, $p = .59$, $\eta^2_p = .04$), and no interaction, $F(2, 16) = 1.23$, $p = .32$, $\eta^2_p = .13$.

Response times (RT; $M = 439$ ms, $SD = 70$ ms) were calculated relative to the onset of fixation cross colour change and for responses recorded within 1500 ms of the colour change. A repeated measures ANOVA found no effects of identity (own, new friend, stranger; $F(2, 16) = 1.00$, $p = .39$, $\eta^2_p = .11$), or time (pre- and post-familiarisation; $F(1, 8) < .01$, $p = .99$, $\eta^2_p < .01$), or interaction, $F(2, 16) = 1.23$, $p = .32$, $\eta^2_p = .13$.

### EEG data

Distinct peaks were observed in the frequency domain at the exact stimulation frequencies and their associated harmonics. Figure 2 shows the grand-averaged EEG amplitude spectra (baseline-corrected using a signal-to-noise subtraction) during visual stimulation pooled across all channels. Scalp topography of the group-averaged and individual response changes (post minus pre) for each identity condition and stimulation frequency is shown in Figures 3 and 4, respectively. Figure 5 shows the average 6 and 0.86 Hz summed-harmonic responses for each identity and test time in the relevant ROIs. Figure 6 shows the 6 and 0.86 Hz summed-harmonic responses for individual participants, with post-familiarisation responses plotted against the pre-familiarisation response.

(A) Grand-averaged EEG amplitudes across the frequency spectrum, averaged across channels and test time. Clear responses were observed at the base-stimulation frequency (6 Hz and its harmonics) and the identity-specific frequency (0.86 Hz and its harmonics). Own-face, newly familiarised face, and unfamiliar stranger face responses are shown in blue, red, and black, respectively. (B) Scalp topographies of significant harmonics for each stimulation frequency, averaged across identity conditions and test times. Responses at the 6 Hz frequency were significant up to the 6th harmonic (36 Hz; only the first four harmonics are shown in the spectrum). Responses at the 0.86 Hz frequency were significant up to the 12th harmonic (the 7th harmonic that overlaps with the 6 Hz

component was excluded). For each stimulation frequency, responses were quantified as the sum of the baseline-corrected amplitudes across significant harmonics.
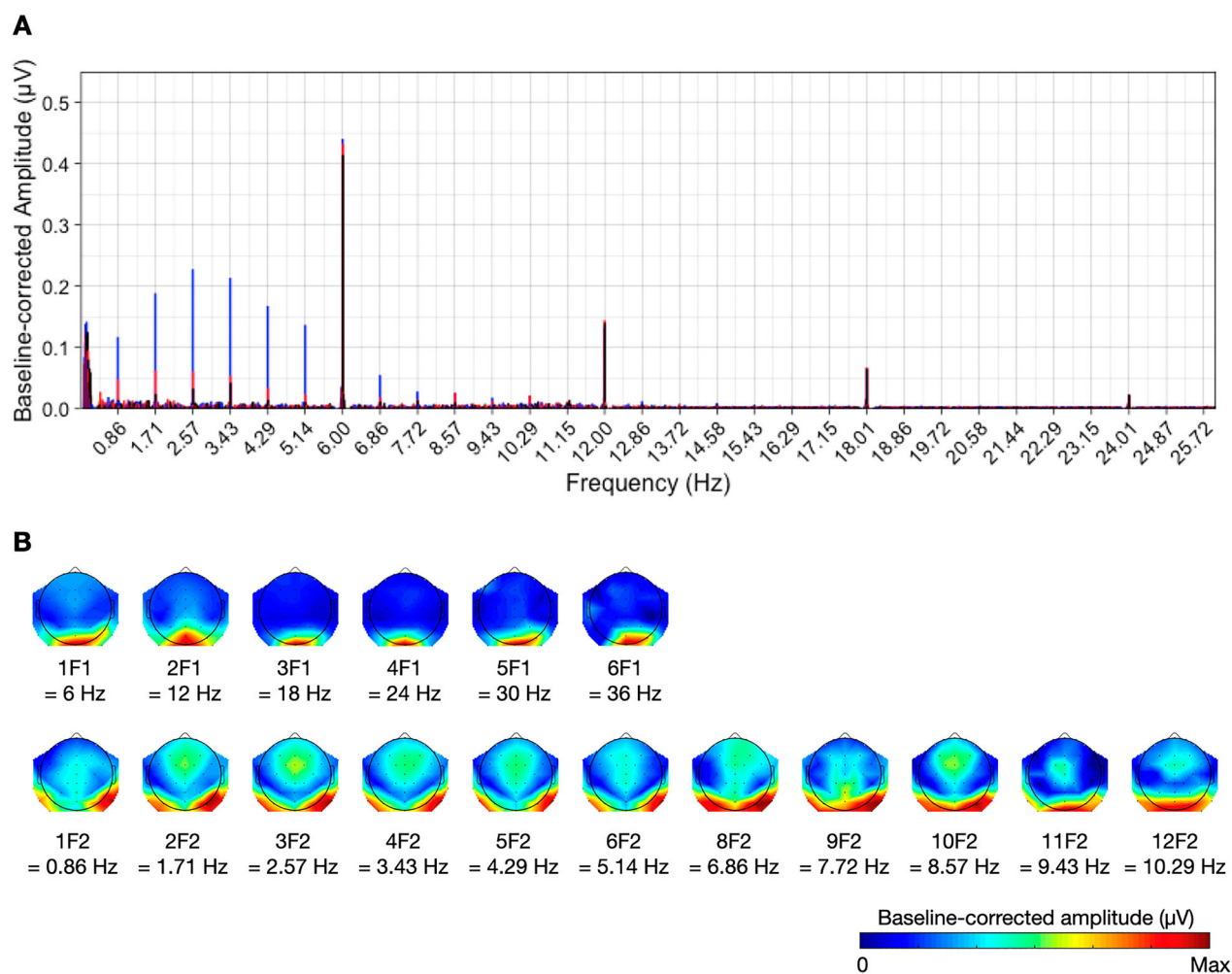
### Base-stimulation responses

At the 6 Hz base-stimulation frequency, ANOVA of the summed-harmonic response in the medial occipital region (MO: Oz, POz, PO8/PO7) showed no effects of identity, $F(2, 16) = 0.36$, $p = .706$, $\eta^2_p = .04$, or time, $F(1, 8) = 0.95$, $p = .357$, $\eta^2_p = .11$, and no interaction, $F(2, 16) = 0.31$, $p = .739$, $\eta^2_p = .04$. A Bayesian analysis with identity and time as within-subjects factors showed no effect of condition ($BF = 5.3$ in favour of the null hypothesis), time ($BF = 1.3$ in favour of the null hypothesis), or interaction ($BF = 4.6$ in favour of the null hypothesis).

### Identity-specific responses: Pre- vs. post-familiarisation

At the 0.86 Hz identity-specific frequency, planned comparison of responses to the face of the assigned lab partner ("new friend") showed a significant increase in the response post-familiarisation compared to pre-familiarisation (pre $M$: 0.63 μV, $SD = 0.67$ μV; post $M$: 0.91 μV, $SD = 0.67$ μV; $t(8) = 2.21$, $p = .029$, $d = 0.74$, 95% CI [−0.03, 1.55], one-tailed). Bayesian analysis indicated moderate evidence against the null hypothesis: specifically, $BF_{+0} = 3.1$, meaning that the data are approximately 3.1 times more likely to occur under the alternative hypothesis (i.e., post > pre) than under the null hypothesis (i.e., post not greater than pre).

When the response to the new friend was examined in the right (P10, PO10, PO8) and left (P9, PO9, PO7) channels separately, the response increase was significant in the right hemisphere (pre $M$: 0.66 μV, $SD = 0.63$ μV; post $M$: 0.99 μV, $SD = 0.64$ μV; $t(8) = 2.85$, $p = .012$, $d = 0.94$, 95% CI [−0.13, 1.81], one-tailed) and Bayesian analysis showed moderate evidence in favour of an effect ($BF_{+0} = 6.5$). The response increase was not significant in the left hemisphere (pre $M$: 0.60 μV, $SD = 0.72$ μV; post $M$: 0.83 μV, $SD = 0.74$ μV; $t(8) = 1.46$, $p = .091$, $d = 0.49$, 95% CI [−0.23, 1.24], one-tailed), although the corresponding Bayes factor indicated anecdotal evidence in favour of an effect ($BF_{+0} = 1.3$).

Planned comparison of the identity-specific responses to the stranger face showed no change in

**A**



**B**



**Figure 2.** (A) Grand-averaged EEG amplitudes across the frequency spectrum, averaged across channels and test time. Clear responses were observed at the base-stimulation frequency (6 Hz and its harmonics) and the identity-specific frequency (0.86 Hz and its harmonics). Own-face, newly familiarised face, and unfamiliar stranger face responses are shown in blue, red, and black, respectively. (B) Scalp topographies of significant harmonics for each stimulation frequency, averaged across identity conditions and test times. Responses at the 6 Hz frequency were significant up to the 6th harmonic (36 Hz; only the first four harmonics are shown in the spectrum). Responses at the 0.86 Hz frequency were significant up to the 12th harmonic (the 7th harmonic that overlaps with the 6 Hz component was excluded). For each stimulation frequency, responses were quantified as the sum of the baseline-corrected amplitudes across significant harmonics.

response between test times, (pre $M$: 0.28 μV, $SD =$ 0.21 μV; post $M$: 0.30 μV, $SD = 0.26$ μV; $t(8) = 0.41$, $p = .670$, $d = 0.14$, 95% CI [−0.55, 0.84], two-tailed). The corresponding Bayes factor ($BF_{01} = 2.9$) indicated anecdotal evidence in favour of the null hypothesis. Comparison of responses in the right hemisphere were consistent with the null hypothesis (pre $M$: 0.30 μV, $SD = 0.23$ μV; post $M$: 0.34 μV, $SD = 0.35$ μV; $t(8) = 0.59$, $p = .571$, $d = 0.20$, 95% CI [−0.50, 0.90], two-tailed; $BF_{01} = 2.7$), as were those in the left hemisphere (pre $M$: 0.27 μV, $SD = 0.22$ μV; post $M$: 0.27 μV, $SD = 0.21$ μV; $t(8) = 0.13$, $p = .900$, $d = −0.04$, 95% CI [−0.74, 0.65], two-tailed; $BF_{01} = 3.1$).

Planned comparison of the identity-specific responses to the own-face showed no change in response between test times, (pre $M$: 2.38 μV, $SD =$ 0.80 μV; post $M$: 2.23 μV, $SD = 1.00$ μV; $t(8) = 0.80$, $p = .445$, $d = −0.27$, 95% CI [−0.98, 0.43], two-tailed; $BF_{01} = 2.4$). Comparison of responses in the right hemisphere were consistent with the null hypothesis (pre $M$: 2.68 μV, $SD = 0.85$ μV; post $M$: 2.44 μV, $SD = 1.15$ μV; $t(8) = 0.93$, $p = .381$, $d = −0.31$, 95% CI [−1.03, 0.39], two-tailed; $BF_{01} = 2.2$), as were those in the left hemisphere (pre $M$: 2.09 μV, $SD = 0.94$ μV; post $M$: 2.02 μV, $SD = 1.07$ μV; $t(8) = 0.43$, $p = .673$, $d = −0.31$, 95% CI [−1.03, 0.39], two-tailed, $BF_{01} = 2.9$).
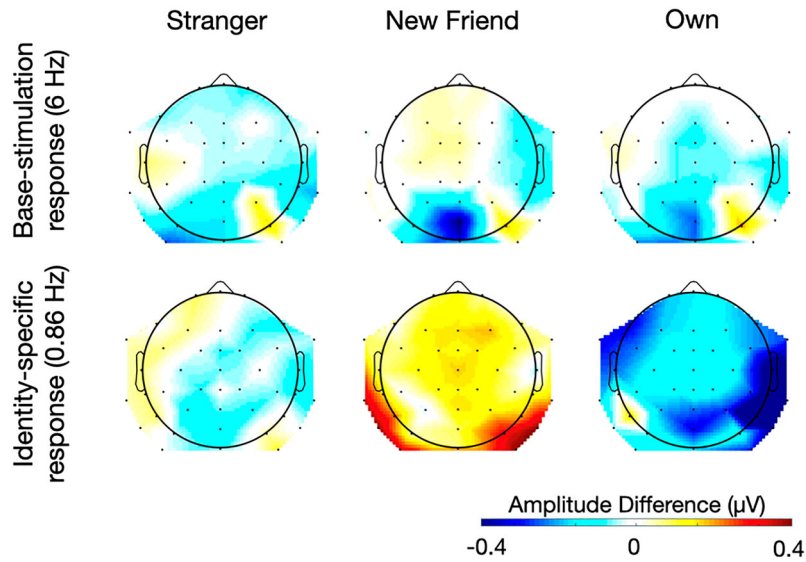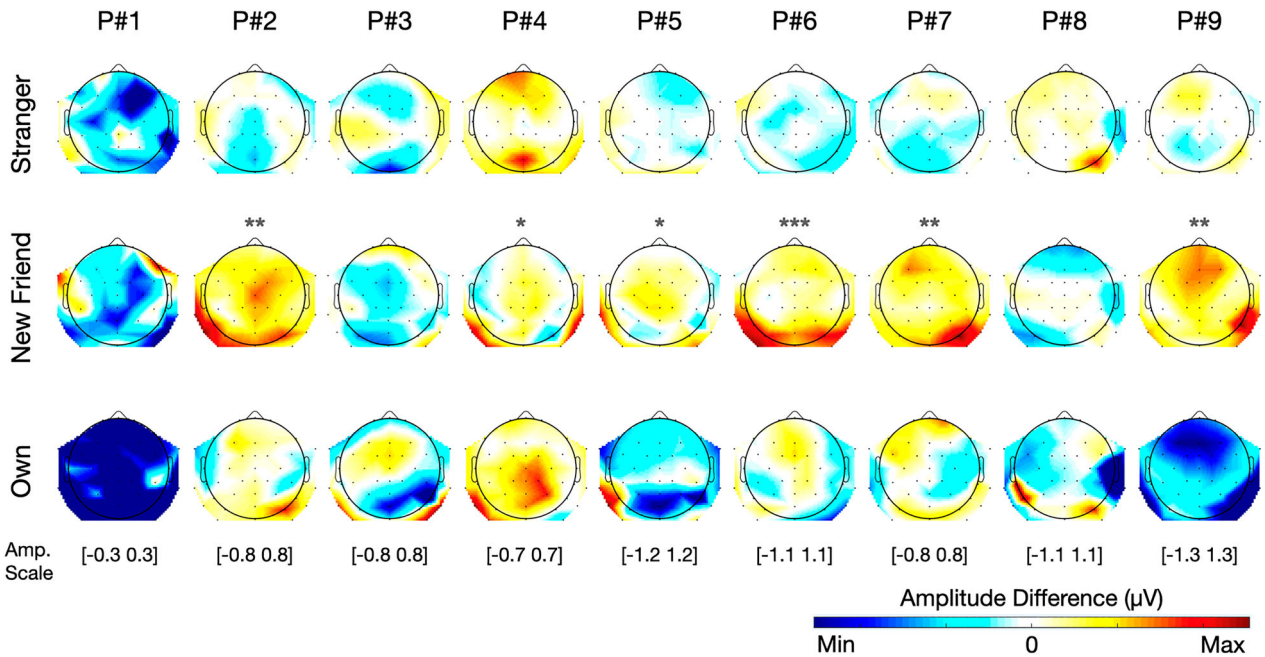
**Figure 3.** Scalp distribution of the group-averaged change in response (post minus pre) of the summed-harmonic responses at base-stimulation and identity-specific frequency. Scale is based on maximum response increase independent of condition.

Scalp distribution of the group-averaged change in response (post minus pre) of the summed-harmonic responses at base-stimulation and identity-specific frequency. Scale is based on maximum response increase independent of condition.

Scalp distribution of each subject's change in identity-specific response (post minus pre) to an unfamiliar stranger face (top row), the new friend's face (middle row), and their own face (bottom row). Scale is based on maximum response increase for each participant independent of condition and is reported at the bottom of each subject's column. Asterisks indicate a significant increase in the 0.86 Hz response to the new friend face in the



**Figure 4.** Scalp distribution of each subject's change in identity-specific response (post minus pre) to an unfamiliar stranger face (top row), the new friend's face (middle row), and their own face (bottom row). Scale is based on maximum response increase for each participant independent of condition and is reported at the bottom of each subject's column. Asterisks indicate a significant increase in the 0.86 Hz response to the new friend face in the occipito-temporal ROI (P10/P9, PO10/PO9, PO8/PO7). * $p < .05$, ** $p < .01$, *** $p < .001$.
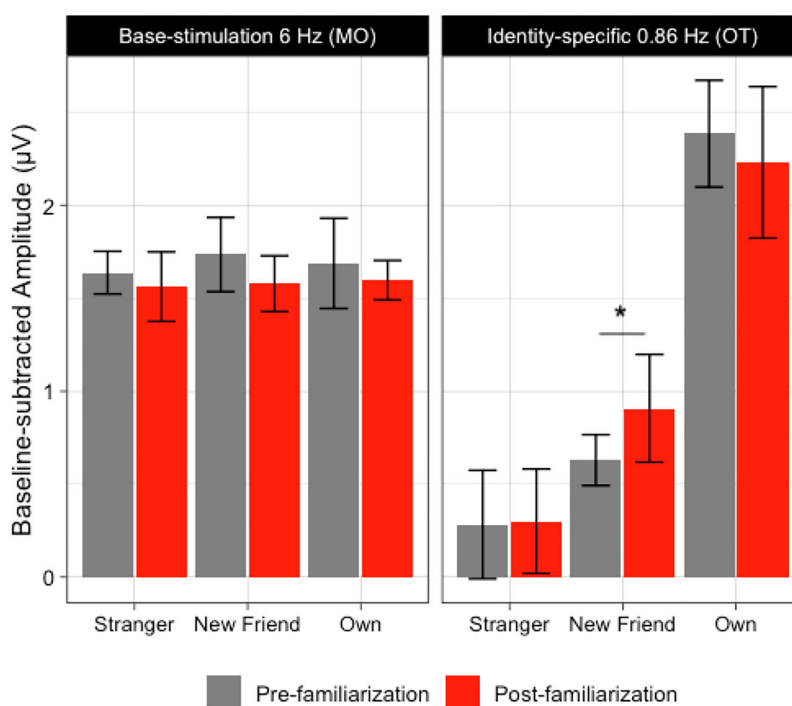
**Figure 5.** Group-averaged summed-harmonic responses for the base-stimulation responses (6 Hz) and identity-specific responses (0.86 Hz) for each face category and test time. Error bars represent 95% within-subject confidence intervals (Cousineau, 2005). *$p$ < .05, one-tailed.

occipito-temporal ROI (P10/P9, PO10/PO9, PO8/PO7). * $p$ < .05, ** $p$ < .01, *** $p$ < .001.

Group-averaged summed-harmonic responses for the base-stimulation responses (6 Hz) and identity-specific responses (0.86 Hz) for each face category and test time. Error bars represent 95% within-subject confidence intervals (Cousineau, 2005). *$p$ < .05, one-tailed.

Post-familiarisation responses are plotted against the pre-familiarisation responses for each participant, identity condition, and response frequency. Each point represents a participant's summed-harmonic response for the particular frequency, with points above the diagonal line representing participants whose response at the second test time was larger than the response observed at the first test time.

As shown in Figure 7, presentation of the own-face generated clear identity-specific responses in all participants: in both test sessions, the occipito-temporal 0.86 Hz response was significant for all 9 participants ($z$ > 3.1, $p$ < .001, one-tailed). Pre-familiarisation, the assigned partner face elicited a significant response in 5 participants (P1, P2, P3, P5, P8); after familiarisation, all but one participant (P2, P3, P4, P5, P6, P7, P8) showed a significant response to the new friend face. By comparison, the unfamiliar stranger face

elicited significant responses in the same 3 (P3, P5, P8) participants in the first and second test session, respectively.

Single-case $t$-tests (one-tailed) showed that the response difference between pre- and post-familiarisation for the new friend significantly exceeded that observed for the stranger faces in 6 participants: P2, $t(8) = 3.08$, $p = .008$; P4, $t(8) = 2.02$, $p = .039$; P5, $t(8) = 2.70$, $p = .014$; P6, $t(8) = 6.13$, $p < .001$; P7, $t(8) = 3.20$, $p = .006$; and P9, $t(8) = 3.96$, $p = .002$. Three participants failed to show an increased response to the new friend: P1, $t(8) = 2.16$, $p = .97$; P3, $t(8) = 0.10$, $p = .538$; and P8, $t(8) = 1.84$, $p = .948$. Statistically significant response increases are indicated in Figure 7. For responses to the own-face, single-case t-tests (two-tailed) showed a change in response in 3 participants: P1, $t(8) = 4.95$, $p = .001$, and P9, $t(8) = 10.68$, $p < .001$, showed a decrease in response; P3, $t(8) = 2.83$, $p = .022$, showed an increase in response.

### Identity-specific responses: Comparing own, newly-familiarised, and stranger faces

Comparison of identity-specific responses across identity conditions at each test time was conducted using two-tailed paired-sample $t$-tests (Bonferroni–Holm corrected). Pre-familiarisation, the difference
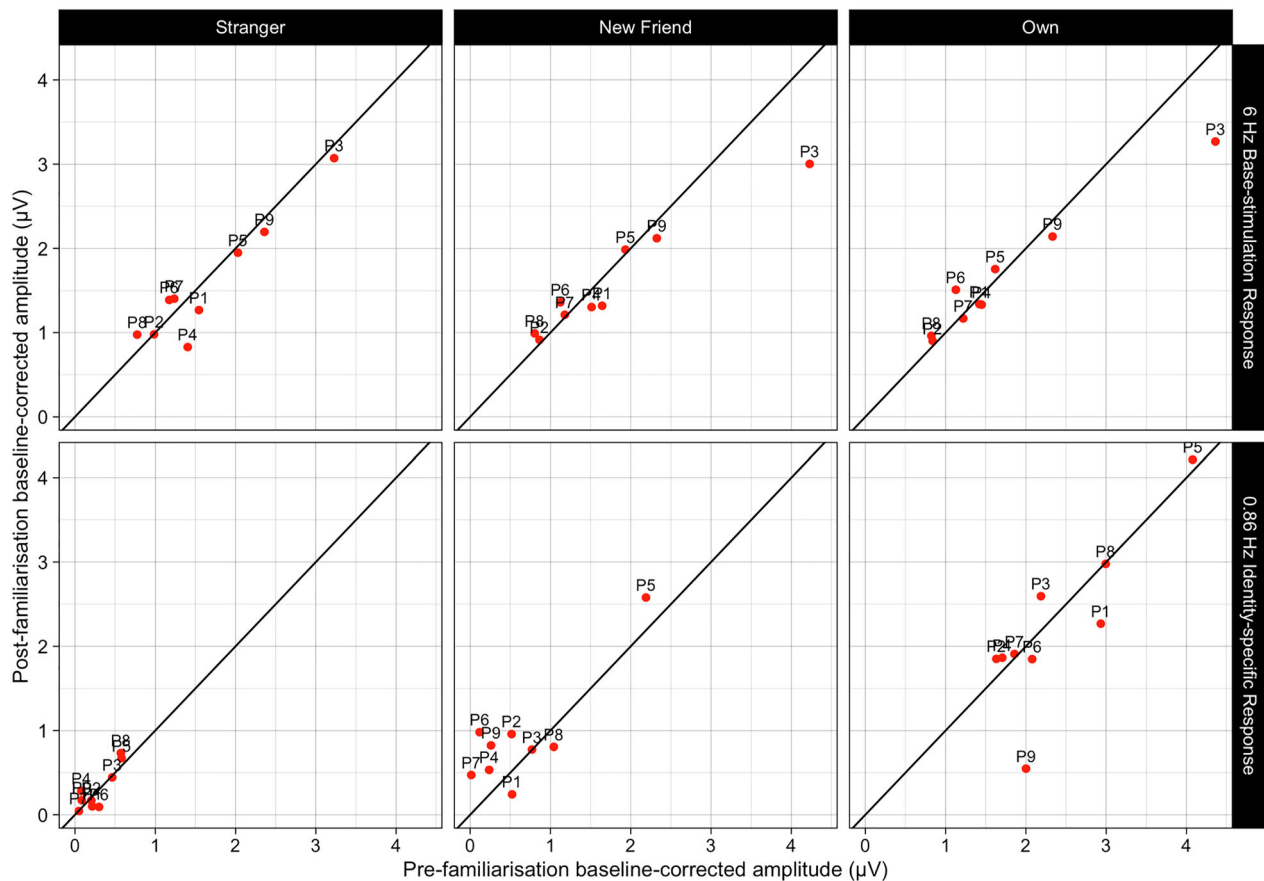
**Figure 6.** Post-familiarisation responses are plotted against the pre-familiarisation responses for each participant, identity condition, and response frequency. Each point represents a participant's summed-harmonic response for the particular frequency, with points above the diagonal line representing participants whose response at the second test time was larger than the response observed at the first test time.

between the stranger face and the unfamiliarised new friend face was not significant, $t(8) = 2.03$, $p = .077$, $d = 0.68$, 95% CI [−0.07, 1.47], $BF_{01} = 0.75$, however the own-face response was greater than both the unfamiliarised new friend face, $t(8) = 13.94$, $p < .001$, $d = 4.65$, 95% CI [2.46, 7.38], $BF_{10} = 20159$, and the stranger face, $t(8) = 9.57$, $p < .001$, $d = 3.19$, 95% CI [1.60, 5.13], $BF_{10} = 1728$. Post-familiarisation, the response to the newly familiarised friend face was significantly greater than the stranger face, $t(8) = 3.23$, $p = .012$, $d = 1.08$, 95% CI [0.24, 2.01], $BF_{10} = 5.5$, yet the response to the own-face remained stronger than both the familiarised new friend face, $t(8) = 5.28$, $p < .001$, $d = 1.76$, 95% CI [0.71, 2.98], $BF_{10} = 52$, and the stranger face, $t(8) = 7.02$, $p < .001$, $d = 2.34$, 95% CI [1.09, 3.84], $BF_{10} = 258$.

### Between- and within-session reliability

Test-retest reliability indices are shown in Table 1. The 6 Hz base-stimulation response had excellent overall within-subject reliability (ICC values ranged from .87-.94, $p$'s < .001). The reliability of the 0.86 Hz response was also excellent across all three identity conditions, with subject scores being the most consistent in the stranger face condition (ICC = .86, $p$ < .001, 95% CI = [0.60, 0.96]), followed by the own-face (ICC = .80, $p = .002$, 95% CI = [0.48, 0.94]), and the the new friend (ICC = .78, $p = .003$, 95% CI = [0.43, 0.93]). The split-half reliability was also excellent. Across test sessions and identity conditions, split-half reliability showed nearly perfect internal consistency for both the 6 Hz base-stimulus response (ICC = .98, $p < .001$, 95% CI = [.97 .99]) and the 0.86 Hz identity-specific response (ICC = .96, $p < .001$, 95% CI = [.93 .97]).

Bar graphs of the identity-specific response observed for each participant and condition. Bars represent the summed amplitudes of the relevant 0.86 Hz harmonics and their surrounding frequency bins, averaged over all channels in the left and right
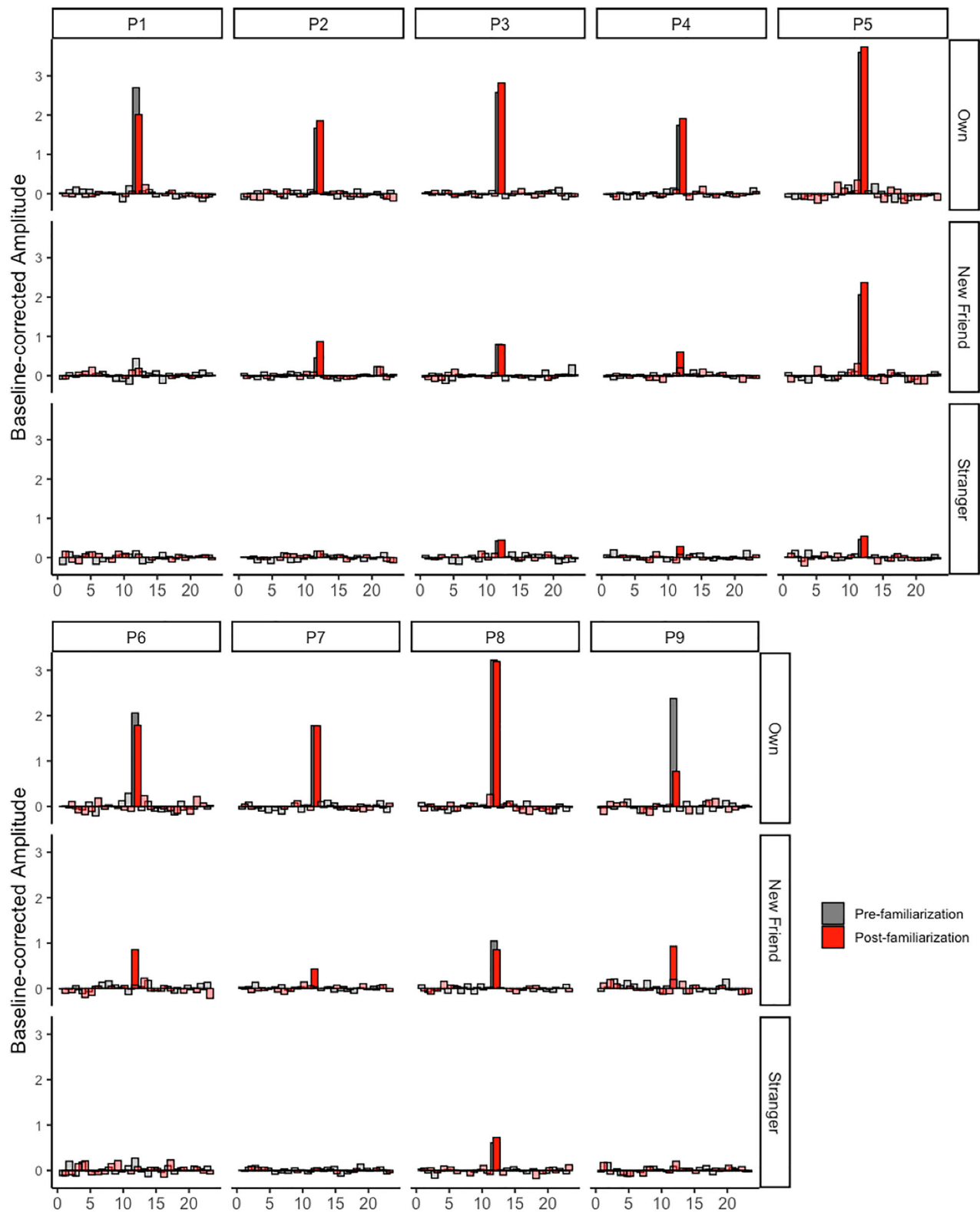
**Figure 7.** Bar graphs of the identity-specific response observed for each participant and condition. Bars represent the summed amplitudes of the relevant 0.86 Hz harmonics and their surrounding frequency bins, averaged over all channels in the left and right OT ROIs. Each subplot shows 21 frequency bins, with the bin containing the summed 0.86 Hz harmonics in the middle and their 10 neighbouring frequency bins on each side. The unit of the x-axis is arbitrary. Pre-familiarisation responses are shown in grey bars and post-familiarisation responses are shown in red. Overlapping bars have been jittered for visibility. Significant responses (z > 3.1, *p* < .001, one-tailed) are shown as solid bars. Significant increases in the response to the friend face (post > pre, one-tailed single case *t*-tests) are marked with asterisks: * *p* < .05, ** *p* < .01, *** *p* < .001.

**Table 1.** Intraclass correlation coefficients (ICC) for assessing test-retest reliability of base-stimulation and identity-specific responses.

| | Base-stimulation response (6 Hz) | | Identity-specific response (0.86 Hz) | |
|---|---|---|---|---|
| | ROI | ICC | ROI | ICC |
| Stranger | MO | 0.94 [0.83, 0.98] *** | OT | 0.86 [0.60, 0.96] *** |
| New Friend | MO | 0.87 [0.64, 0.96] *** | OT | 0.78 [0.37, 0.93] ** |
| Own | MO | 0.91 [0.73, 0.97] *** | OT | 0.80 [0.48, 0.94] ** |

Note. 95% confidence intervals in parentheses. MO = medial occipital region (Oz, POz, PO8, PO7). OT = occipito-temporal region (P10/P9, PO10/PO9, PO8/PO7). Within-subject reliability was interpreted as poor (ICC < 0.40), moderate (ICC 0.41-0.59), good (ICC 0.60-0.74), or excellent (ICC > 0.75). *$p < .05$, **$p < .01$, ***$p < .001$

OT ROIs. Each subplot shows 21 frequency bins, with the bin containing the summed 0.86 Hz harmonics in the middle and their 10 neighbouring frequency bins on each side. The unit of the x-axis is arbitrary. Pre-familiarisation responses are shown in grey bars and post-familiarisation responses are shown in red. Overlapping bars have been jittered for visibility. Significant responses ($z > 3.1$, $p < .001$, one-tailed) are shown as solid bars. Significant increases in the response to the friend face (post > pre, one-tailed single case $t$-tests) are marked with asterisks: * $p < .05$, ** $p < .01$, *** $p < .001$.

## Discussion

Results confirmed the predictions and indicated that learning a new face "in the wild" was associated with an increased identity-specific response. By contrast, there was no change in the response elicited by a stranger face that remained unfamiliar to participants at both test times. Individually, 6 of 9 participants showed a significant increase in the magnitude of the identity-specific response to the new friend face after familiarisation. This suggests that the real-world face learning that occurred in the 2 months between test sessions caused a neural change, such that brief (∼166 ms) presentations of the same face images that were once unfamiliar to the participants evoked stronger neural responses after real-world familiarisation. Importantly, this response was elicited automatically, since face identity was task irrelevant and attention was directed to another target (the fixation cross) superimposed on the face stimulus. Post-hoc analysis of this response increase suggests that increased magnitude is more prominent in the right hemisphere, and future studies with larger samples would be helpful for

replicating this effect and understanding whether this reflects a group-level effect or individual differences in hemispheric specialization.

We also found that the identity-specific responses might index the relative familiarity of a face. Although newly familiarised faces evoked stronger responses than unfamiliar faces, the own-face response was still 2.5 times larger on average than the newly learned face. Both the N170 and the N250 ERP components have been shown to respond differentially to familiar faces relative to unfamiliar faces (for recent discussion, see Caharel & Rossion, 2021; Campbell et al., 2020). However, neither of these components discriminate between highly familiar faces and less familiar faces, such as a newly learned face (Andrews et al., 2017; Pierce et al., 2011; Tanaka et al., 2006). The only ERP component that has been shown to be sensitive to the degree of face familiarity emerges about 400 ms post-stimulus (Andrews et al., 2017; Wiese et al., 2019) and is therefore too late to account for perceptual processes underlying the fast recognition of familiar faces.

These results provide the first demonstration of transformations in the neural response to face identity as a result of real-world familiarization in a real-world social context. Participants were told that they were participating in a study about face recognition as part of their research experience but were not aware of the research question or that their familiarisation with their assigned lab partner was the key "manipulation" until after the study. These results extend previous studies of identity-specific processing of famous (Yan et al., 2020; Zimmermann et al., 2019) and personally familiar faces (Campbell et al., 2020). Notably, we replicate the finding that implicit recognition of the a friend's face is associated with a stronger occipito-temporal response than an unfamiliar face and that the response to the own-face is at least twice as great in amplitude than the response elicited by another personally familiar face (Campbell et al., 2020).

Our findings conflict with those from a recent study by Ambrus et al. (2021) that examined how representations of face familiarity and identity changed as a result of perceptual, media, or personal familiarisation. Using representational similarity analysis, they found that both media and personal familiarisation led to clear representations of face familiarity, but the identity representations remained the same

even after personal familiarisation. One explanation for this difference might be due to the limited familiarity for even the personally familiar faces in their experiment, since familiarisation consisted of three 1-hour conversations with a research assistant. By comparison, the identity representations we tracked in both the current and previous study reflect identities that are also socially-relevant, since they share either a personal (Campbell et al., 2020) or a working relationship. Experimental work on face learning has shown that socially-relevant, conceptual information can be even more important than perceptual information (Schwartz & Yovel, 2016; Schwartz & Yovel, 2019), so future studies might investigate the role of social information during personal familiarisation. The identity representations measured here also reflect extensive familiarisation that would expose participants to the familiarised faces on different days and in different environments (in and outside the lab). Previous research on face learning has shown that increasing the within-person variability of a face during learning leads to much more robust identity recognition (Ritchie & Burton, 2017), so it is also possible that the limited variability in a single in-person encounter was not strong enough to induce detectable changes to the identity representations. Finally, our ability to observe post-familiarisation changes to an identity-specific response might be due to the increased sensitivity obtained by using a frequency-tagging approach to isolate the activation of an identity representation. By periodically presenting the familiarised faces within a stream of other faces identities, the neurophysiological response associated with general face processing, face individuation, and low-level processing are siphoned off at the base-stimulation frequency, leaving responses that are uniquely elicited by the familiarised face identities observable at their presentation frequency (Yan et al., 2020; Zimmermann et al., 2019). The former are reflected in the scalp distribution of the 6 Hz response, where response was highest over medial-occipital regions and did not vary according to the identity category of the face inserted at the 0.86 Hz frequency. The response that remained at the 0.86 Hz frequency at which the stranger, new friend, or own-face was presented should reflect the population of neurons that are specifically responsive to that face identity and that support the ability to generalize across different images of that face.

Unfamiliar face individuation measured using FPVS has already been shown to have high test-retest reliability for both amplitude and spatial distribution (Dzhelyova et al., 2019), and our study provides evidence that this stability extends to individual face recognition responses. Given that we expect measurement consistency for the same subject under the same conditions, responses to the stranger and own-face are the most relevant because their familiarity status did not change between test sessions. The 0.86 Hz response to the stranger face had the highest intraclass correlation, but, because it is unfamiliar to participants, this response likely reflects low-level image and face features and not identity recognition. More importantly, responses to the own-face also had excellent within-subject stability in the identity-specific responses evoked 2 months apart. Additionally, unlike many ERP components which have been found to be sensitive to image repetition (Caharel et al., 2009, 2014; Kaufmann et al., 2009; Wiese et al., 2019), the split-half reliability was near perfect within test sessions for both the 6 Hz base-stimulation response and the 0.86 Hz identity-specific response. This suggests that responses evoked in a FPVS paradigm may be better protected from image repetition effects and learning during tests.

A limitation of the current paradigm is that it remains unknown to what extent the element of social interaction contributed to the development and magnitude of the observed identity recognition responses. The condition of the unfamiliar stranger face served as a control comparison for stimulus exposure effects and test time to ensure that increases in the identity recognition responses post-familiarisation were not likely to be spontaneous or a result of prior exposure to the test stimuli. Future studies could attempt to determine the relevant contribution of visual exposure and social interaction by including another set of identities that are viewed with the same temporal regularity but with whom the participants have no interactions.

Second, although we were able to examine neural response changes arising from faces learned in the real-world and with all their natural variability (at least within 2 months time), we had less control over the exact quality and quantity of exposure

during the "familiarisation" phase. Exposure among partners all exceeded a certain threshold based on weekly meetings and in-lab work, but it is not possible to know to what extent exposure differences account for variability in the post-familiarisation response (e.g., whether students spent time together socially outside of the lab). There is also a question as to whether behavioural differences measured in a standardized face recognition test could account for the variability in the post-familiarisation response. Previous studies have found a modest correlation between standardised behavioural measures of face recognition and the neural responses measured using FPVS with a face discrimination paradigm (Xu et al., 2017). However, future research should examine whether variability in behavioural measures of face learning and memory correspond to neural response changes to face identity after familiarisation.

Third, it is unknown what proportion of the identity-specific responses measured here reflect a general familiarity signal. Recently, a common familiarity response was shown to be evoked by different identities, indicating that familiar faces share a common neural network that is not identity-specific (Yan & Rossion, 2020). This could be tested in subsequent experiments by embedding a familiar identity within a stream of other familiar faces, so that the general dimension of face familiarity is also siphoned into the higher base-stimulation frequency.

Finally, photos of each identity were obtained on the same day and therefore had less within-person variability compared to social media images or personal photo collections (e.g., Jenkins et al., 2011). However, personal photos and selfies are often highly posed and can be a biased representation (White et al., 2016). Our stimuli captured a range of spontaneous and idiosyncratic facial expressions as they appeared during a real-life interaction, and therefore may more closely match how they are represented in memory (Redfern & Benton, 2019). However, future studies would benefit from increasing the within-person variability across images to provide a stronger test of the generalisability of the identity-specific response over highly variable images.

In conclusion, the human brain readily and effortlessly learns new faces that are regularly encountered in the social environment. Here, we documented changes in identity processing as a face transitions from being an unfamiliar person to a familiar person in the real-world. Critically, this biological marker shows that normal, everyday experiences and social interactions transform the neural network to increase perceptual sensitivity and responsiveness to a familiar face identity.

## Notes

1. We did observe a small but significant difference in the image luminance between the participant faces compared to the stranger and base faces. This difference was due to slight lighting variations that were unexpected. However, since these stimulus qualities were present at both pre- and post-test, they would not contribute to any change in response between test times.
2. We used female base faces because all but one participant was female. In test conditions where a male face was presented at 0.85 Hz, it is possible that the 0.85 Hz response also reflects a gender discrimination response (Rekow et al., 2020). However, this gender discrimination response would be present in both pre- and post-test measurements, so could not account for an increase between test sessions. Also, since the stranger faces were matched by gender, any influence of a gender discrimination response would be present in all three identity conditions and would not bias any one identity response condition.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

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