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# An objective neural measure of the effect of wearing facemasks on single-glance human face identity recognition

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ABSTRACT

As highlighted during and since the COVID-19 pandemic, wearing facemasks significantly impacts human social interactions, notably by hindering facial recognition. Here we measured the reduction of single-glance facial identity recognition associated with wearing facemasks with an objective implicit approach. Electroencephalographic (EEG) recordings were conducted in a group of participants presented with the same unfamiliar face identity photograph at a 6 Hz frequency, interrupted by different face identities every 5 stimuli. For faces wearing a mask, the neural face identity recognition response at 1.2 Hz and harmonics was significantly reduced by about 40 % over the bilateral occipito-temporal cortex. This reduction was specific to upright faces, with the lower signal to inverted faces being unaffected by facemasks. Overall, these findings suggest a significant impact of mask-wearing on single-glance face identity recognition underpinned both by a direct alteration of diagnostic cues provided by the bottom half of the face and an indirect decreased diagnosticity of the top face half typically provided by holistic face perception.

## 1. Introduction

Faces occupy an essential place in our daily lives (Calder, 2011), particularly for our social interactions, conveying useful information regarding the identity, internal state, gender, age, or intentions of others (Fusar-Poli et al., 2009). During the COVID-19 pandemic, a large amount of the population has had to cover the lower part of their faces with masks in order to limit viral propagation, therefore impacting social interactions (Bylianto and Chan, 2022; Castelli et al., 2022; Wong and Estudillo, 2022). Beyond this recent pandemic, some people were already accustomed to wearing masks as it is still the case nowadays, such as in healthcare contexts (Bani et al., 2021, 2022; Knollman-Porter and Burshnic, 2020; Wong et al., 2013), forensic settings (Manley et al., 2019; Thorley et al., 2022), or in crowded places where there can be a risk of contamination from various diseases (Miyazaki and Kawahara, 2016). Moreover, challenges related to partly covering faces have been studied, not only with masks, but also with scarves, Islamic headdresses, caps, sunglasses, or hoods (Kret and De Gelder, 2012; Bennetts et al., 2022; Calbi et al., 2021; Carlaw et al., 2022).

The last few years have seen a growing number of experimental researches carried out on the impact of mask wearing on human face recognition. Overall, behavioral studies have found that wearing a mask impacts several aspects of face recognition, such as facial identity (Carragher and Hancock, 2020; Estudillo and Wong, 2024; Freud et al., 2020, 2022a; Guerra et al., 2022; Or et al., 2023), emotion (Carbon, 2020; Carbon et al., 2022; Grundmann et al., 2021; Grahlow et al., 2022; Kleiser et al., 2022; Thomas and Caharel, 2023; see also Pavlova and Sokolov, 2022 for a review), gender (Fitousi et al., 2021; Wong and Estudillo, 2022), social identity and ethnicity recognition (Cooper et al., 2022; Kahn and Money, 2022; Oldmeadow and Koch, 2021). Additionally, using simultaneous and delayed face matching as well as old/new memorization tasks with masked and unmasked unfamiliar faces, studies showed a negative impact of facemasks on face identity recognition (FIR), as evidenced by increased response times (RT) and decreased accuracy rates (Carragher and Hancock, 2020; Estudillo and Wong, 2024; Freud et al., 2020, 2022a; Guerra et al., 2022; Or et al., 2023).

A number of behavioral studies have proposed that by reducing available information in the lower part of the face, masks would reduce the impact of holistic face perception (i.e., the perception of facial parts and their configuration as a single integrated unit) (Estudillo and Wong, 2024; Freud et al., 2020, 2022a; Fitousi et al., 2021; Guerra et al., 2022;

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Or et al., 2023; Stajduhar et al., 2022). This has been shown essentially through the face inversion effect, a well-known marker of holistic perception of upright faces (Farah et al., 1998; Rossion, 2009), this effect being reduced for masked faces compared to their unmasked counterparts during both face matching tasks or face memory tasks (Estudillo and Wong, 2024; Freud et al., 2020, 2022a; Stajduhar et al., 2022; but see Fitousi et al., 2021 for opposite results).

Yet, despite these advances, the impact of facemasks on FIR remains unclear, with the effects ranging between around 3.5 % and 15 % performance drops across studies, depending on the tasks (Bennetts et al., 2022; Freud et al., 2020; Noyes et al., 2021; Wong and Estudillo, 2022). Moreover, explicit recognition tasks can lead response biases (Carragher and Hancock, 2020; Garcia-Marques et al., 2022; Kramer and Jones, 2022; Stajduhar et al., 2022) and effects that are generally spread onto two variables, i.e., accuracy rates and RT, sometimes to different extent across individuals tested (Bennetts et al., 2022; Carragher et al., 2022; Freud et al., 2022; Noyes et al., 2021). This makes it difficult to obtain a correct quantification of the effect of facemasks on human FIR. Finally, in most experiments, faces are presented for several hundreds of milliseconds (e.g., from 1000 to 4000 ms, Brunet, 2023; no time limit, with faces remaining on screen until response, Bennetts et al., 2022; Carragher and Hancock, 2020; Carragher et al., 2022; Estudillo and Wong, 2024; 2024; Noyes et al., 2021), allowing participants to scan various features differently with or without masks, potentially affecting performance and holistic perception.

Taking into account these issues, the goal of the present study is to assess, i.e., quantify, the effect of wearing face masks on rapid (i.e., single-glance) FIR. To do so, we rely on an objective compact measure of FIR as provided by Fast Periodic Visual Stimulation (FPVS) combined with electroencephalographic (EEG). This original approach, also called frequency-tagging, is based on the long-standing observation that the periodic presentation of a stimulus elicits a brain response exactly at the frequency at which the stimulus is presented, which can be objectively measured (i.e., at the predetermined stimulation frequency) in the EEG frequency spectrum (Adrian and Matthews, 1934; Regan, 1966; for review, see Norcia et al., 2015). Following early evidence with block designs (Rossion and Boremanse, 2011), highly sensitive measures of FIR have been provided consistently over the last decade with this approach by presenting the same (usually unfamiliar) face identity at a rapid base rate (i.e., 6 Hz, 6 faces per second, allowing only one fixation per face) interrupted by a change of face identity every fifth stimuli (i.e., 6 Hz/5 = 1.2 Hz) (Liu-Shuang et al., 2014; about 30 studies published over the past decade; see Rossion et al., 2020 for review; also more recently Verosky et al., 2020; Retter et al., 2021; Hagen et al., 2024). After a few minutes of visual stimulation only, two clear brain responses are extracted: (1) a base rate response, measured at 6 Hz at medial occipital sites, reflecting the general visual processing of faces; and (2) most interestingly, a response at the identity change frequency, measured at 1.2 Hz at occipito-temporal sites, reflecting a neural signature of FIR (Liu-Shuang et al., 2014; Retter et al., 2021; Rossion et al., 2020 for review). This FPVS-EEG approach presents numerous advantages, as it provides objective (i.e., at the predetermined stimulation frequency), high signal-to-noise ratio (SNR) measures of single-glance FIR without requiring any explicit task. It is also highly reliable (i.e., stable across individuals tested repeatedly within and across sessions; Dzhelyova et al., 2019; Stacchi et al., 2019; Xu et al., 2017) and critically relates to FIR ability (Liu-Shuang et al., 2016; Retter et al., 2021; Volfart et al., 2022).

These considerations thus make it ideal for investigating neural responses to FIR with and without mask. Considering previous behavioral studies, we expected to observe reduced brain responses for identity changes with faces wearing a mask than without a mask over occipito-temporal regions. Additionally, by presenting sequences of faces either at upright or inverted orientations, with each face presented for less than 200 ms (i.e., allowing only a single glance), we tested the impact of face mask wearing on holistic face perception. That is, if mask wearing disrupts holistic face processing (Estudillo and Wong, 2024; Freud et al., 2020, 2022a; Stajduhar et al., 2022), the inversion effect measured at the level of face identity change frequency should be significantly reduced, or even abolished, for masked faces compared to unmasked faces.

## 2. Materials and methods

### 2.1. Participants

Eighteen participants (N = 18; 8 males, 9 females, 1 non-binary; mean age = 26 years old, SD = 3.22, range = 19–29 years old) were recruited through campus ads and social networks. Sample size was determined prior to the beginning of the study based on the number of participants that have led to robust effects in FPVS-EEG studies with this paradigm (characterized by a high SNR) (e.g., N = 12 in Liu-Shuang et al., 2014; N = 16 in Retter et al., 2021; N = 18 in Yan et al., 2019). All participants provided signed and informed consent, and received a financial compensation for their participation in the experiment, which was approved by the Ethical Committee of Ile de France X (n° 2021-A02807). They were all right-handed, except for one participant. All participants reported normal or corrected-to-normal vision and no history of psychiatric or neurological disorder. Prior to the study, a computerized version of the Benton Face Recognition Test (BFRT; Benton and Van Allen, 1968; BFRT-c; Rossion and Michel, 2018) was administered to all participants (mean = 45.94 out of a total score of 54, SD = 3.63; normative data mean = 44.81, SD = 3.44 (Rossion and Michel, 2018)). Due to a technical issue with the EEG recording, one participant was excluded, leading to a final sample of 17 participants.

### 2.2. Stimuli

Stimuli were colored photographs of 25 male and 25 female faces, which were previously used by Liu-Shuang et al. (2014). All faces were cropped to remove hair, ears, backgrounds, and everything below the chin and were placed against a grey background. Facemasks were added and modified to fit each face, adjusting their shape in respect to the nose and chin using the software Procreate (5.3 version). The opacity of the masks was lowered by 10 % to better replicate their appearance on a face and give them a more natural look. Image size of the stimuli was 200 x 270 pixels.

### 2.3. Procedure

The procedure was similar to previous studies (Liu-Shuang et al., 2014; Retter et al., 2021; Xu et al., 2017; see also for a review, Rossion et al., 2020) using fast periodic visual stimulation (FPVS) to identify a neural measure to individual face recognition. After electrode cap placement, participants were seated in a dimly lit room, at a viewing distance of 80 cm from a computer monitor (LED monitor (BenQ XL2420T) with a refreshing rate of 60 Hz and 1920 × 1080 pixels resolution). During the experiment, stimuli appeared in the center of a uniform light grey background and subtended a visual angle of approximately 9.1° in height and 8.5° at this distance. Participants were asked to fix their attention to the center of the screen and to press the space bar when the 2 vertical bars located at the left and right side of the face changed from black to white but not to press when there was no change in color or when only 1 bar changed color. At the beginning of each sequence, both vertical bars were black. Eight times during each sequence, one or both vertical bars turned white. These changes were randomized; for example, participants could encounter sequences in which 2 bars could change color one to eight times, and in the latter case, without a single bar changing color, or vice versa. At all other times in the sequence, both bars were black. Each change lasted for 200 ms and there was a minimum interval of 200 ms between the offset of the white bar(s) and the onset of the next white bar(s). Unlike previous

FPVS-EEG studies (Liu-Shuang et al., 2014; Rossion et al., 2015, 2020; Verosky et al., 2020) based primarily on the use of a color change detection task of a cross located between the two eyes, at or even slightly below the nasion, our choice of task (as also used in e.g., Lochy et al., 2024; Yan et al., 2022) aimed to avoid bias as much as possible by encouraging participants to focus on the whole face rather than on the mask itself, given that the fixation cross would have been located approximately at the junction with the upper part of the mask. This orthogonal task was designed to maintain the participants' attention to the images throughout these sequences.

Each sequence started with a grey background displayed randomly for 2–5 s, then 2 s of gradually fading in of the stimuli presentation, followed by 60 s of stimulation sequence, and 2 s of gradually fading out of stimuli. One face identity was repeated at 5.995 Hz (general visual response approximately at 6 images per second, image presentation duration = 167 ms) with the insertion every fifth stimuli of a different face identity (face identity recognition frequency = 5.99 Hz/5 = 1.199 Hz), leading to the following sequence: AAAABAAAACAAAAD … For each sequence, the same identity was presented for the base stimulation rate (A) and different identities were randomly inserted at the identity-recognition rate (B, C, D, …) (Fig. 1). Face images were presented through sinusoidal contrast modulation (from 0 to 100 %). Each pixel of the images reached the full luminance value of the face stimulus after half a cycle, approximately 83 ms after the stimulus onset ((1000/5.995)/2), allowing a smoother appearance and disappearance of stimuli. To minimize low-level effects, the size of the stimuli varied randomly and substantially at each stimulus presentation on a scale ranging from 74 % to 120 % of the original size (as in Liu-Shuang et al., 2014), therefore inducing modulations of pixel intensity that are unrelated to facial identity changes (Dzhelyova and Rossion, 2014a; for review, see Rossion et al., 2020). In the same vein, given that face identity recognition is drastically impaired by stimulus inversion (Yin, 1969; see Rossion, 2008 for review), the presentation of an inverted face condition also allowed these low-level effects to be controlled, since inversion preserves physical differences between faces.

In total, our protocol included 4 experimental conditions: 2 orientations (*Upright* and *Inverted*), and 2 masking conditions (*Mask* and *No Mask*). Only one condition was presented during a stimulation sequence, and each condition was repeated 4 times (2 female and 2 male identities), resulting in 16 sequences. Sequences' order was randomized for every participant.

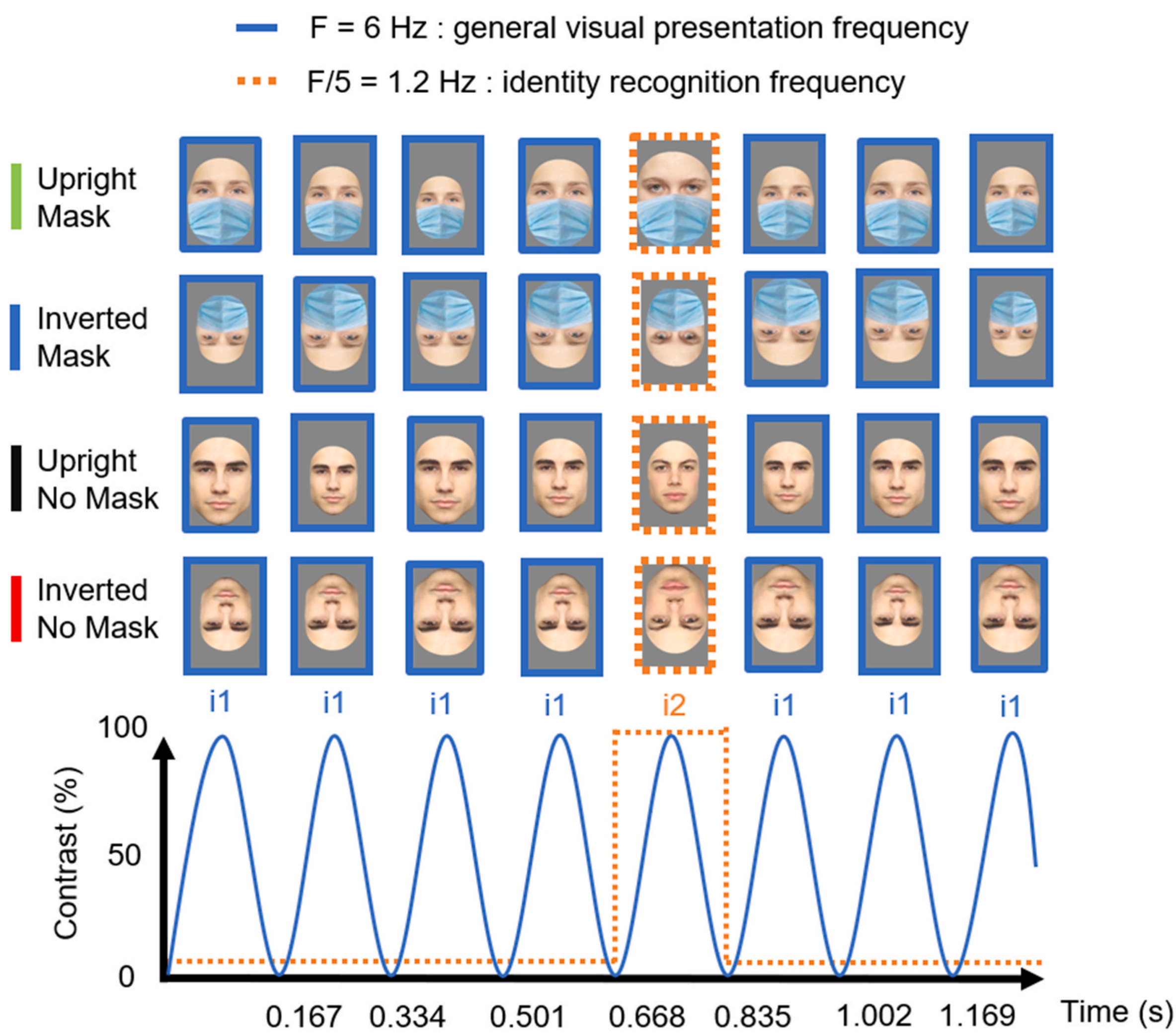


**Fig. 1.** Conditions and experimental design. Example of a sequence with one face identity (here i1) presented at the base rate (6 Hz – blue line) with the constraint that every five stimuli another identity (here i2) was periodically inserted at the face identity recognition rate of 1.2 Hz (6 Hz/5 = 1.2 Hz – orange dotted line). To minimize pixelwise overlap and reduce the influence of low-level visual processes, face size randomly varied between 74 % and 120 % of the original size at each stimulation cycle. Sequences were randomized and each sequence corresponded to one experimental condition, here respectively from top to bottom: Upright Mask, Inverted Mask, Upright No Mask, and Inverted No Mask. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

### 2.4. EEG acquisition

Scalp electroencephalographic (EEG) activity was recorded using a BIOSEMI Active-Two (Common Mode Sense [CMS] active electrode and Driven Right Leg [DRL] passive electrode) amplifier system (BioSemi, Amsterdam, Netherlands) with 128 channels, including both standard 10–20 system locations and additional intermediate positions. Vertical and horizontal eye movements were recorded with electrodes placed respectively at the corner of both eyes and on the top of right eye. EEG and EOG recordings were sampled at 512 Hz.

### 2.5. EEG analysis

All EEG processing steps were carried out using the free software *Letswave 6* (https://nocions.github.io/letswave6/; Mouraux and Iannetti, 2008) and Matlab R2021a (The Mathworks), with similar procedures as previous FPVS-EEG studies with this paradigm (e.g., Liu-Shuang et al., 2014; Retter et al., 2021; Xu et al., 2017; see also for review, Rossion et al., 2020).

#### 2.5.1. Preprocessing

Continuous individual datasets were first bandpass filtered with a cut-off value of .1–100 Hz (Butterworth filter, fourth order) and resampled to 256 Hz. The data were then cropped into 66 s segments (2 s before, 2 s after each sequence, and 2 additional seconds). Noisy or artifact-ridden channels were re-estimated with a linear interpolation of the 3 nearest spatially neighboring electrodes (only 2.84 % of electrodes were interpolated across participants).When needed, artifacts related to eye blinks were corrected for some of the participants (7 participants in total) by applying independent component analysis (ICA) using the runica algorithm (Bell and Sejnowski, 1995; Makeig et al., 1995), as implemented in EEGLAB. This algorithm outputs a square mixing matrix in which the number of components corresponds to the number of channels. For these participants, only the first component, accounting for most of the variance, representing vertical eye movements was removed. Data segments were then re-referenced to a common average reference.

#### 2.5.2. Frequency domain analysis

Pre-processed data segments were cropped down to an integer number of 1.199 Hz cycles beginning after the fade-in, until approximately 59 s, and ending before the fade-out (in total 71 cycles, 14458 time bins ≈ 59 s). An average of these data in time domain was then made separately for each condition (*Upright Mask*, *Upright No Mask*, *Inverted Mask*, *Inverted No Mask*) and for each participant. A Fast Fourier Transform (FFT) was then applied to these averaged segments and amplitude spectra were extracted for all channels. The FFT transformation yielded a spectrum ranging from 0 to 256 Hz with a high spectral resolution of about 1/59 s, i.e., .017 Hz.

Three measures were extracted, namely the baseline-corrected amplitudes, the Z-scores and SNR values for both the general visual response (F = 6 Hz) and its subsequent harmonics (2F, 3F, 4F, 5F, 6F, 7F, and 8F, respectively 6, 12, 18, 24, 30, 36, and 42 Hz) and the face identity recognition frequency (1.2 Hz) and its subsequent harmonics (1F/, 2F/5, 3F/5, 4F/5 and 6F/5, respectively 1.2, 2.4, 3.6, 4.8, and 7.2 Hz). Z-scores were calculated on the FFT grand-averaged data pooled across all electrodes for each condition in order to assess the significance of the responses at different harmonics. As in previous studies (Liu-Shuang et al., 2014, 2022; Retter et al., 2021), Z-scores were extracted based on the mean and the standard deviation of the 20 surrounding bins relatively to the face identity recognition (FIR) frequency (excluding the immediately neighboring bin), resulting in 10 bins in each side. For the FIR response, all harmonics that were significant with a Z-score above 2.32 ($p < .01$, one-sided value since a unidirectional hypothesis was tested, i.e., signal > noise) in at least one condition were selected. For the general visual response, harmonics were considered as significant until the Z-score was no longer above 2.32 ($p < .01$) for all the conditions. This threshold is similar to previous FPVS studies (Angelini et al., 2024; Jacques et al., 2020; Or et al., 2021; Rekow et al., 2020; Retter et al., 2020, 2021a; Yan et al., 2023), but a more lenient threshold of $p < .05$ could also be used without affecting the results (see Rossion et al., 2020 for discussion of this issue). Based on this criterion, the face identity recognition response was quantified as the sum of response harmonics (Retter et al., 2021) until the 6th harmonic (i.e., 1.2, 2.4, 3.6, 4.8 and 7.2 Hz, therefore excluding the 5th harmonic corresponding to the general visual frequency rate (F = 6 Hz) and the response at the general visual frequency rate was quantified as the sum of the general visual rate until the 7th harmonic (i.e. up to 42 Hz).

Then, two distinct approaches were employed for baseline correction to address variations in baseline noise across the frequency spectrum at an individual level. The first method involved a division of the amplitude value by the EEG noise, displaying the EEG spectrum in signal-to-noise ratio (SNR). The second method was a baseline subtraction (SBL), which was processed by subtracting the EEG noise to quantify responses in microvolts (μV). In both cases, EEG noise was computed by averaging the 20 adjacent bins (10 on each side), excluding the immediately neighboring bins as well as the 2 most extreme bins. This methodological choice regarding the removal of the extreme bins, which is generally applied in studies using this paradigm (e.g., Damon et al., 2020; Leleu et al., 2018; Liu-Shuang et al., 2014; Rekow et al., 2020), was adopted as the baseline correction is applied to the entire spectrum and to ensure that our results are not biased by outliers. Subsequently, the baseline-corrected amplitudes were grand-averaged across subjects for each condition and electrode separately to facilitate group-level display.

For statistical analysis, based on visual inspection of topographical maps (Fig. 2) and previous studies using a similar paradigm (Liu-Shuang et al., 2014; Retter et al., 2021; Xu et al., 2017; see also for a review, Rossion et al., 2020), three regions of interest (ROIs) across the temporal and occipital regions were defined. Each ROI corresponded to the pooling of the four most activated channels in each region and each hemisphere at the FIR frequency. In this vein, we determined for the FIR response, two occipito-temporal regions, over the left (LOT: PO11, PO9, PO7 and P7) and the right (ROT: PO12, PO10, PO8, P8) hemisphere, and for the base frequency response, one medial occipital (MO: POz, Iz, Pz, and Oz) region.

Using the *Jamovi* software (The Jamovi Project, 2022; version 2.3.), repeated-measures analyses of variance (ANOVA) were conducted on the baseline-corrected amplitudes both at the general visual response and at the FIR frequency, with *Orientation* (*Upright, Inverted*), *Mask* (*Mask* and *No Mask*) and *ROI* (*LOT*, *ROT*, and *MO*) as within-subject factors. Partial eta-squared ($\eta p2$) was used to estimate effect size, and the alpha significance value used was .05. For significant interactions, post-hoc analyses were conducted using Tukey ($p$) adjustment.

## 3. Results

### 3.1. Behavioral data of the bar color change detection task

Participants performed the bar color change detection task very well, with an average accuracy of 97 % (SD = .08) and an average response time of 525 ms (SD = .63). Repeated-measures analysis of variance (ANOVA) with *Orientation* (*Upright, Inverted*) and *Mask* (*Mask, No Mask*) as within factors on accuracy rate revealed no significant effect of *Orientation* ($F(1,67) = 1.39$, $p = .242$) and *Mask* ($F(1,67) = 1.63$, $p = 1.000$), or significant interaction between these two factors ($F(1,67) = 1.06$, $p = .307$). In the same way, the same analysis carried out on response times (RT), automatically calculated as the time between the change of bar colors and the moment when the computer registers a tap on the space bar by the participant, revealed no significant effect of *Orientation* ($F(1,16) = .00138$, $p = .971$) and *Mask* ($F(1,16) = .53582$, $p = .475$) factors, and no interaction effect between these two factors ($F$

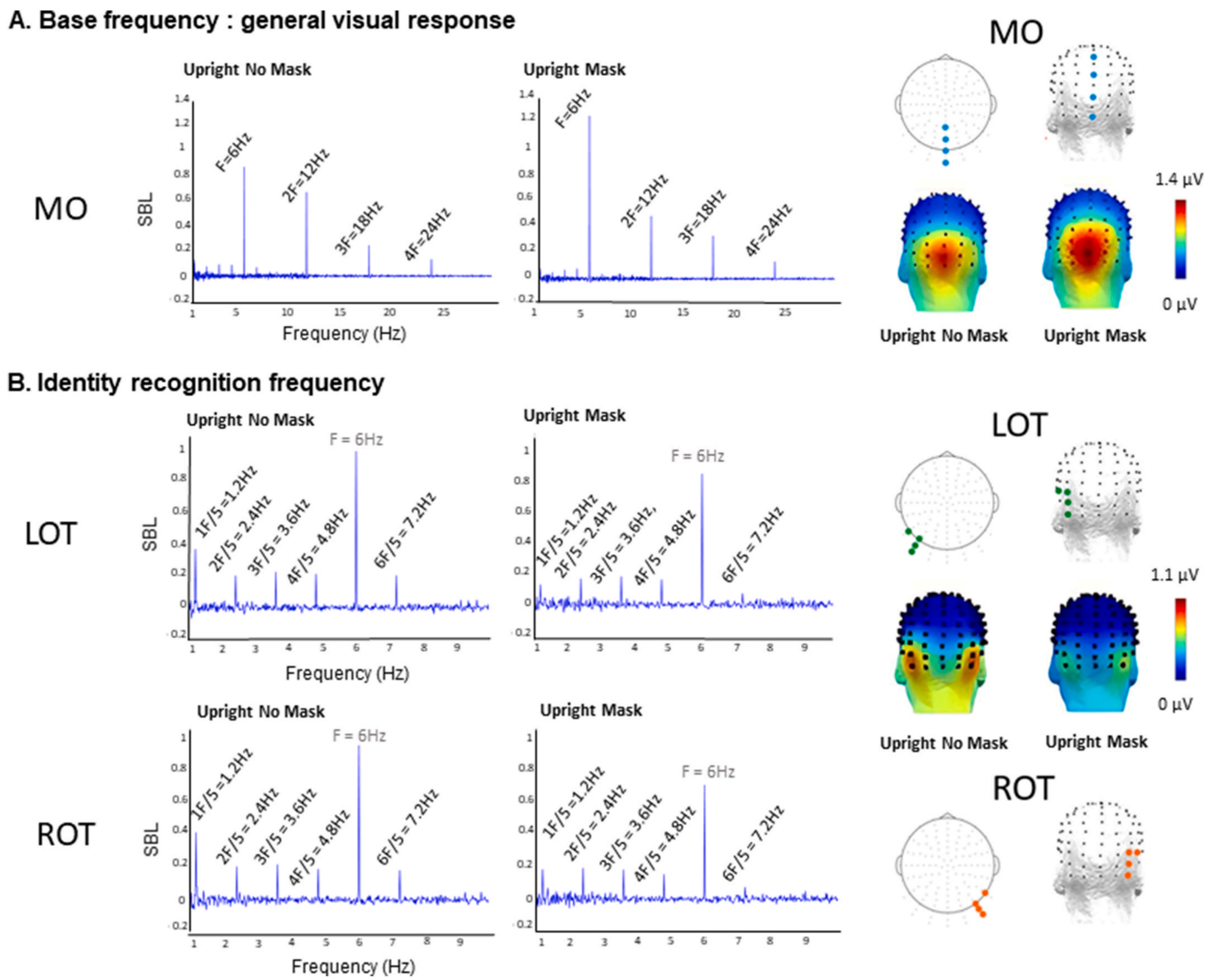


**Fig. 2.** Grand averaged EEG spectra in baseline subtraction (SBL) for No Mask and Mask conditions in Upright orientation. (A) Neural responses to the base frequency (general visual response; F = 6 Hz) and its significant harmonics (2F, 3F, 4F, 5F, 6F, 7F, and 8F, respectively 6, 12, 18, 24, 30, 36, and 42 Hz) over medial occipital region (MO; average responses across POz, Iz, Pz, and Oz). (B) Neural responses to the FIR frequency (F/5 = 1.2 Hz) and its significant harmonics (1F/5, 2F/5, 3F/5, 4F/5 and 6F/5, respectively 1.2, 2.4, 3.6, 4.8, and 7.2 Hz) over Left (LOT) and Right (ROT) Occipito-Temporal regions (averaged across left and right occipito-temporal channels, respectively PO7, PO9, PO11, P7, and PO8, PO10, PO12, P8). Topographical maps (in µV) show the distinct distribution on the scalp for the general visual response (from 0 to 1.4 µV) and the FIR frequency (from 0 to 1.1 µV). The three regions of interest (MO, LOT and ROT), defined on the basis of the topographical maps, are represented by colored points on the maps (blue for MO site; green for the LOT and orange for the ROT). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

(1,16) = .11045, $p$ = .744). These results suggest that participants paid full attention to the screen during the entire stimulation sequences and similarly across experimental conditions.

### 3.2. EEG data: frequency analysis

#### 3.2.1. Base stimulation frequency

Even though the examination of the base stimulation frequency was not directly related to the objectives of the present study, we nevertheless report the obtained results. At this frequency (6 Hz and harmonics), we observed robust and extended responses culminating over the medial occipital (MO) region (Fig. 2A), as in previous FPVS-EEG studies (Dwyer et al., 2019; Dzhelyova and Rossion, 2014a; Liu-Shuang et al., 2014; Rossion et al., 2020; Verosky et al., 2020; Zimmermann et al., 2019). For responses at this frequency, repeated measures ANOVA with *Mask* (*Mask, No Mask*) and *Orientation* (*Upright, Inverted*) as within-factors revealed larger responses for *Mask* than *No Mask* conditions ($F$(1,16) = 7.004, $p$ = .018, $\eta p2$ = .304) and for *Upright* than *Inverted* faces ($F$(1,16) = 11.163, $p$ = .004, $\eta p2$ = .411). However, the interaction between *Mask* and *Orientation* factors was not significant ($F$(1,16) = .266, $p$ > .05). These significant effects are not surprising as such (see also, for similar results with inversion, Jacques et al., 2020; Liu-Shuang et al., 2014; Rossion et al., 2012; Zimmermann et al., 2019; see Rossion et al., 2020 for a review) since these responses, generated by the brain's general periodic response to stimuli, are known to reflect not only low-level visual processing but also high-level, partly face-related, processes (Dwyer et al., 2019; Dzhelyova and Rossion, 2014a, 2014b; Liu-Shuang et al., 2014; see also Rossion et al., 2020 for a review). Moreover, it is also important to note that these effects are related to general visual processing of faces that are distinct from FIR processes that we seek to evaluate more specifically in our study (Rossion et al., 2020).

#### 3.2.2. Face identity recognition frequency (1.2 Hz)

At the FIR frequency (i.e., 1.2 Hz and harmonics), a clear response was elicited over posterior sites (LOT and ROT) in response to the presentation of every new identity (Figs. 2 and 3). This response appeared to be substantially decreased in amplitude both by inversion and face-masks. A repeated-measures ANOVA was conducted to explore amplitude variations of the neural FIR response in left and right occipito-temporal regions (respectively LOT and ROT) according to the Mask and Orientation factors. This analysis revealed no significant difference between LOT and ROT ($F(1,16) = .263$, $p > .05$) in terms of response at the face identity recognition frequency. However, significant effects of Mask ($F(1,16) = 17.493$, $p < .001$, $\eta p2 = .522$) and Orientation ($F(1,16) = 25.750$, $p < .001$, $\eta p2 = .617$) were found. Interestingly, the interaction between Mask and Orientation ($F(1,16) = 16.268$, $p < .001$, $\eta p2 = .504$) was also significant (Figs. 3 and 4). To further explore this interaction, post-hoc analyses revealed a significant effect of Mask only for Upright faces (Upright: $p = .001$; Inverted: $p = .977$), explained by responses in the occipito-temporal regions that were significantly lower for masked faces compared to their unmasked counterparts. A decrease in responses of 35.3 % in the right hemisphere and 41.2 % in the left hemisphere was found between No Mask and Mask conditions for Upright faces (Figs. 3 and 4). Moreover, significant inversion effects, resulting in lower responses in the Inverted condition than in the Upright condition, were observed, but this effect was larger for unmasked faces (68.1 %; $F(1,16) = 31.687$, $p < .001$, $\eta p2 = .664$) than for masked faces (45.6 %; $F(1,16) = 9.597$, $p = .007$, $\eta p2 = .375$). Additionally, when LOT and ROT were considered separately, the face inversion effect for masked faces was no longer significant in the left hemisphere ($p > .05$), while it was small but nonetheless significant ($p = .034$) in the right hemisphere (see Fig. 4). Altogether, these results highlighted drastic difficulties in FIR when a mask is worn, as well as a perturbation of holistic processing of faces with mask.

## 4. Discussion

### 4.1. Impact of facemasks on face identity recognition

The main purpose of the present study was to measure the effect of wearing face masks on single glance FIR by means of FPVS coupled to EEG. In line with previous studies using this approach (e.g., Liu-Shuang et al., 2014; Retter et al., 2021; Xu et al., 2017; for review, see Rossion et al., 2020), we provide further evidence for a neural marker of unfamiliar FIR in humans, through objective measures exactly at the frequency of identity changes (i.e., at 1.2 Hz and its harmonics). These FIR responses are mainly observed over bilateral occipito-temporal regions (with a right hemisphere advantage), regions that are usually associated with high-level visual processes and in particular with face individuation, both in previous FPVS studies (Alonso-Prieto et al., 2013; Dzhelyova and Rossion, 2014a, 2014b; Liu-Shuang et al., 2014; Rossion et al., 2015; Xu et al., 2017; Zimmermann et al., 2019), and in standard ERP studies of unfamiliar FIR (N170; Caharel et al., 2011, 2015; Jacques and Rossion, 2006; see Rossion and Jacques, 2011 for review; N250r: Barrett and Rugg, 1989; Schweinberger et al., 2002). Moreover, FIR responses with this oddball paradigm have been shown to be robust and reproducible across a wide range of stimulus manipulations (e.g., size changes: Dzhelyova and Rossion, 2014a; shape and surface cues: Dzhelyova and Rossion, 2014b; head orientation: Or et al., 2021), face viewing conditions (normal *vs.* degraded faces; Retter et al., 2020), and

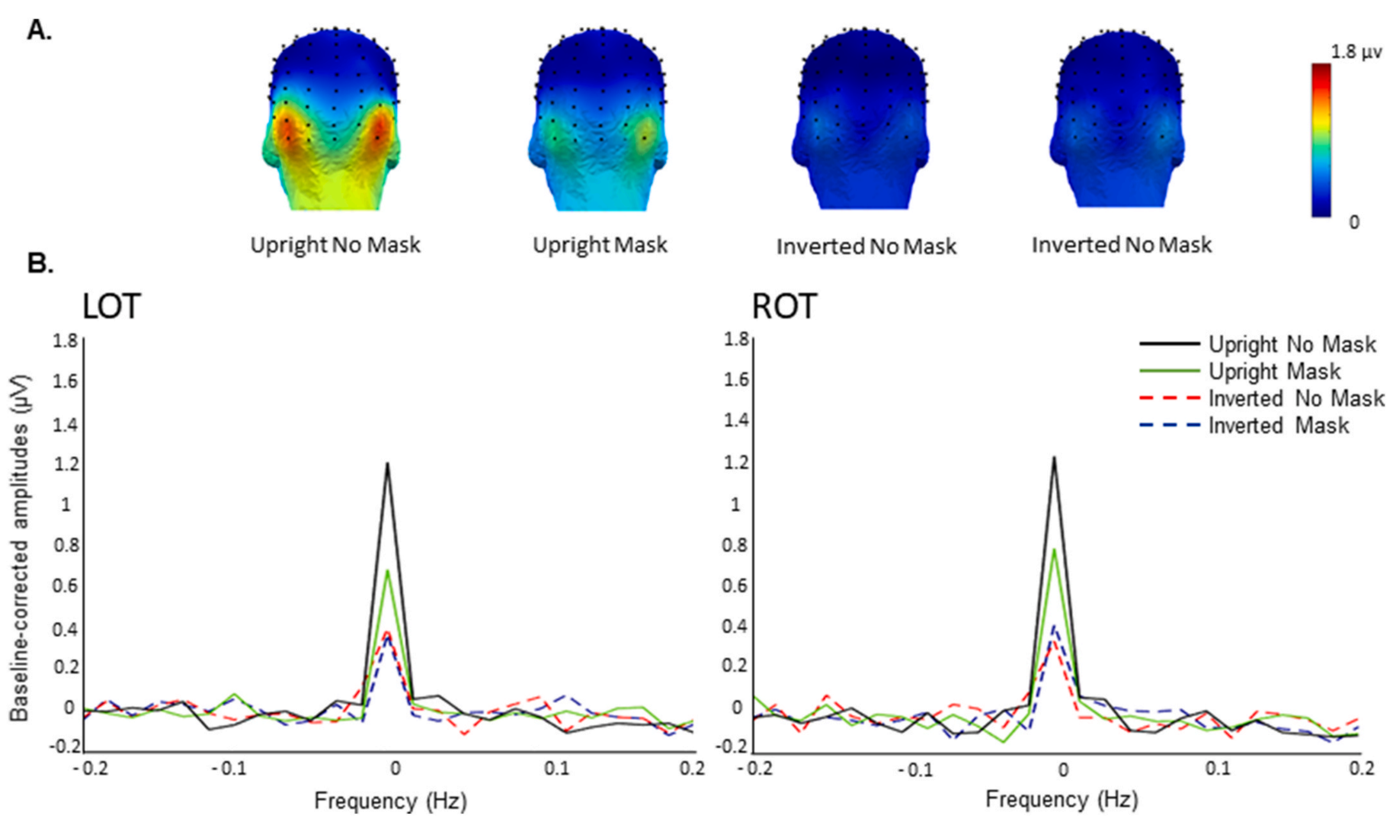


**Fig. 3.** Neural responses to the FIR frequency (i.e. 1.2 Hz and its harmonics) according to the Mask and Orientation conditions. (A) Scalp topographies for each condition (respectively from left to right: Inverted Mask, Inverted No Mask, Upright Mask, Upright No Mask) with the same scale (from −.2 to 1.8 µV) for the summed baseline-corrected amplitude of the 1.2 Hz response and its subsequent harmonics. (B). Spectra centered on the sum of the baseline-corrected (SBL) amplitude at the face identity recognition frequency and its significant harmonics recorded in the left and right occipito-temporal regions (LOT and ROT respectively) for each of the 4 conditions. Neural responses to facial identity recognition are largely reduced for faces with masks than without masks in the Upright orientation. Inversion decreases these responses which no longer differ between masked and unmasked faces.

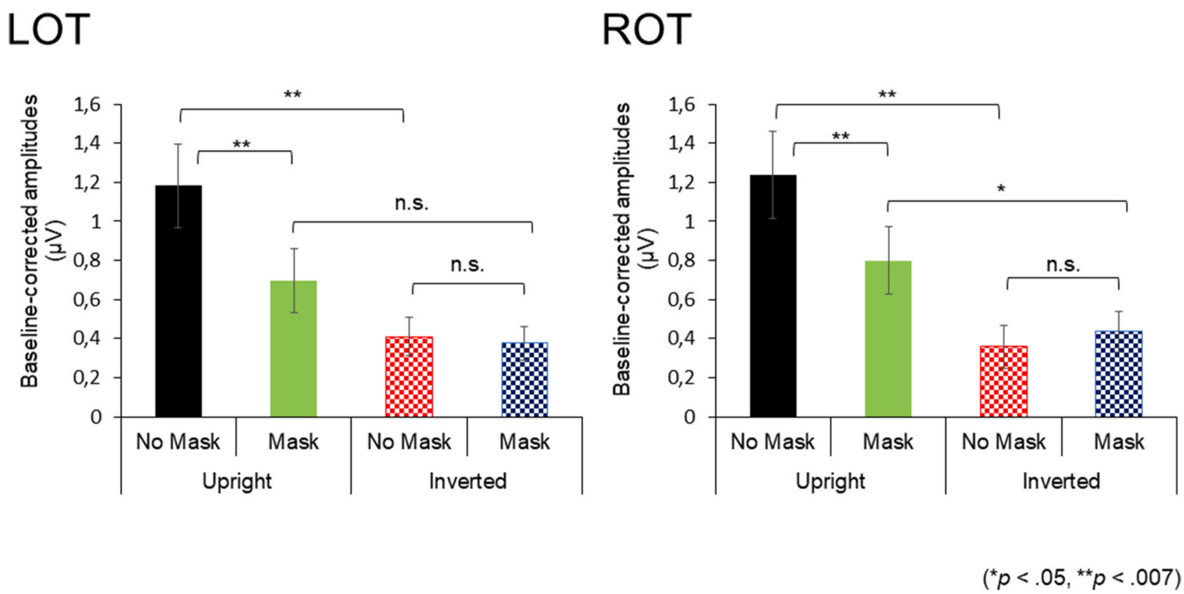


**Fig. 4.** The summed baseline-corrected harmonics at the face identity recognition frequency (i.e. 1.2 Hz and its harmonics) over the right and left occipito-temporal sites for each condition. Error bars are standard errors of the mean (SEM). In Upright orientation, individual face recognition response is reduced for the presentation of masked faces compared to unmasked faces in both ROIs (LOT and ROT). The response is reduced with the reversal with a non-significant difference between No Mask and Mask conditions.

stimulation frequency (Retter et al., 2021) (see Rossion et al., 2020 for review). For these reasons and those advanced in the introduction section (e.g., loss of the response in prosopagnosia; Liu-Shuang et al., 2016), this neural marker of human FIR is therefore particularly well adapted to objectively quantify the extent to which wearing a mask impairs automatic rapid (i.e., single glance) (unfamiliar) FIR.

Critically, our results highlight significant neural FIR responses for masked faces. However, these responses are substantially reduced, by about 40 % (35.3 % in the right hemisphere and 41.2 % in the left hemisphere), for masked compared to unmasked faces, thus pointing to a large impact of face masks on human FIR. While these findings are consistent with previous behavioral studies reporting a reduction in accuracy and RT increase for masked compared to unmasked faces during face identity matching and memorization tasks, the behavioral effects for unfamiliar and learned faces are generally weaker (and quite heterogeneous) (e.g., from 4.3 % to 15 % on average, see Freud et al., 2020; Noyes et al., 2021; and up to 23 % for some individual participants, see Bennetts et al., 2022).

Interestingly, behavioral studies with famous faces have generally reported smaller decreases, of around 3.5 %–4 % in matching accuracy, between masked and unmasked conditions (Noyes et al., 2021; Wong and Estudillo, 2022), suggesting some advantage of familiar faces over unfamiliar faces to compensate, at least in part, the detrimental effects of mask wearing on their recognition. Indeed, with facemasks, people might construct a more accurate representation of the missing parts for a familiar face due to the activation of structural knowledge (Noyes et al., 2021; Rossion, 2018). However, whether this advantage of familiarity would be valid for single glance FIR as measured here remains unclear. FIR (or generic face familiarity) measures with FPVS of (natural) pictures of familiar faces (e.g., Zimmermann et al., 2019; Yan et al., 2020; see also Yan et al., 2023) could be adapted in the future to test the effect of wearing facemasks on familiar face identity recognition.

Beyond face familiarity, the heterogeneity of the results of the different studies in the literature may stem from methodological differences, such as the nature of the tasks, or stimuli databases (Carragher et al., 2022; Freud et al., 2022; Noyes et al., 2021). Most studies (Carragher and Hancock, 2020; Estudillo et al., 2021; Freud et al., 2020, 2022a), such as ours, used superimposed images of masks on photographs of faces, which may not fully reflect the increased visual noise introduced by real facemasks, which typically vary in fit, material, and texture - factors that could further impair FIR in real-world settings (Dhamecha et al., 2014; Fitousi et al., 2021; Noyes et al., 2021; Ritchie et al., 2024). Furthermore, most behavioral studies were conducted online, which might have introduced potential biases or context variability, even though they involved large participant samples (N = 102 to 492; Bennetts et al., 2022; Freud et al., 2020; Noyes et al., 2021; Wong and Estudillo, 2022). Moreover, most of the research was conducted in an experimental laboratory context, therefore including no contextual elements, interactions, conversations, or additional features, which could help in face processing, such as facial identity, or facial expression, recognition (Matt et al., 2021).

### 4.2. *A large face inversion effect*

We observed a large decrease of FIR responses with inversion over occipito-temporal regions for unmasked faces. While this effect is in line with previous studies using similar FPVS-EEG paradigms (e.g., Liu-Shuang et al., 2014; Rossion et al., 2015, 2020; Verosky et al., 2020), it appears to be particularly large here, i.e., 68 % of neural amplitude. However, unlike the previously cited studies based on the use of a color change detection task of a cross presented in the center of the face, the task used in the present study (see also Yan et al., 2022) consisted of detecting changes in the color of vertical bars located on either side of the image, which solicits more peripheral vision and less focal vision on a specific location of the face. Note that the face inversion effect (FIE) also increases when the mouth is cued by a fixation cross or when there is no cue on the face, compared to when the cross is placed on the eye region (Hills et al., 2011). Thus, our task could have induced a more global, holistic, processing of faces, which could explain the particularly large neural FIE observed.

Since physical differences between face identities were strictly preserved across orientation, this substantial decrease of FIR response observed with inversion in our study (see also, e.g., Hagen et al., 2024; Liu-Shuang et al., 2014; Retter et al., 2021) further indicates that the bulk of the FIR response at upright orientation (i.e., at least 68 %) is not due to low-level sensory processes (see Rossion et al., 2020). Despite this, we cannot entirely rule out that some differences observed between upright and inverted orientations could be explained by different amounts of visual cues, related in particular to the ocular regions, in the upper and lower visual fields depending on the conditions (upright or inverted). An experimental manipulation that could have ruled out this hypothesis is contrast negation, which consists of inverting the luminance values of images while preserving the shape and distances between facial features and is known to severely disrupt FIR (Bruce and Langton, 1994; Itier and Taylor, 2002; Russell et al., 2006; Russell and Sinha, 2007). Notably, with the same FPVS-EEG paradigm, Liu-Shuang et al. (2014) observed that both inversion and contrast negation led to significant reductions of the FIR response over occipito-temporal regions.

### 4.3. Reduced inversion effect for faces wearing masks

More importantly, we found that the FIE was considerably reduced for masked faces (45 %) compared to their unmasked counterparts (68 %), to the point that it was no longer significant over the left hemisphere when considering occipito-temporal responses separately on each hemisphere. Behavioral studies (Estudillo and Wong, 2024; Freud et al., 2020, 2022a; Stajduhar et al., 2022) have also reported reduced FIE for masked faces (e.g., 10 % in Freud et al., 2020; 43 % in Freud et al., 2022). Conversely, another behavioral study found a larger inversion effect for masked than for unmasked faces, but with longer RT and more errors for inverted masked than unmasked faces (Fitousi et al., 2021). However, this was explained by the fact that participants in that study might have compensated a lack of visual facial information by looking more at details to distinguish one face from another. In this vein, eye-tracking studies revealed that when it comes to recognizing faces, wearing facemasks increases observers' eye gaze towards the eye area (DeBolt and Oakes, 2023; Hsiao et al., 2022), resulting in an increase of the number of fixations and the time spent looking at the periorbital area than when no mask is worn (Bylianto and Chan, 2022; Frank et al., 2021; Prahm et al., 2023). Here, observers were constrained by the brief presentations of each face (and identity changes), thus preventing such detailed exploration. Overall, these findings point out a disruption of holistic perception for faces wearing a mask. That is, beyond the loss of diagnostic cues of the bottom half of the face (i.e., mouth and chin shape, texture and color) directly contributing to the reduction of FIR ability and the neural FIR response here, the presence of a (uniform) mask on faces appears to also reduce perceived differences on the top halves of faces (eye/eyebrow region, forehead), similarly to a spatial misalignment of bottom halves of faces (Young et al., 1987; Rossion, 2013).

Moreover, consistent with previous studies (Estudillo and Wong, 2024; Freud et al., 2020; Stajduhar et al., 2022), we found that the FIE (68 %) was more important than the effect of mask itself (38 %), suggesting that holistic face perception is differentially disrupted by these two types of manipulations. Whereas inversion primarily impacts the extraction of spatial relationships between features across the whole face (for review, see Rossion, 2008), wearing a mask would disrupt the overall configuration of the face while preserving the processing of some featural and relational cues located in the upper part, particularly in the ocular region (i.e., the eyes and their spatial relationships). Consequently, these findings suggest that holistic face perception is hindered by mask wearing, but to a lesser extent than by inversion (Estudillo and Wong, 2024; Freud et al., 2020; Stajduhar et al., 2022).

Furthermore, our study highlighted that, unlike at upright orientation, for which masked faces generated reduced occipito-temporal responses compared to their unmasked counterparts, the addition of the mask in the inverted condition did not induce any modulation of the brain response. This is consistent with a behavioral study (Estudillo and Wong, 2024) reporting no mask effect for inverted faces but also with an ERP study (Brunet, 2023) showing no further increase of the occipito-temporal N170 component when combining inversion and masks, explained by the authors by a “potential neural saturation point”. This suggests that inversion disrupts the processing of faces to such an extent that the addition of the mask does not further disrupt their processing.

## 5. Conclusions

The present study sheds light on the effects of wearing facemasks on single-glance human face identity recognition. With FPVS-EEG, we provide original evidence for a drastic impact of facemasks on facial identity recognition, due presumably to the direct loss of diagnostic cues provided by the bottom half of the face but also an indirect decrease of diagnosticity of the top half of the face (i.e., reduced holistic perception effect). It is important to note that our study was conducted after a significant period during which the need to wear a mask in daily life was reduced, and that our results could change if we had to wear them regularly again. Nevertheless, recent studies have indicated that exposure to mask wearing, even after several years, does not improve masked FIR (Freud et al., 2022). A training program based on the use of diagnostic features (anatomical features of the ears, such as lobes or helix, or facial marks, such as moles or freckles) also led to only very moderate improvements in masked FIR accuracy (4.9 %; Carragher et al., 2022). Yet, a recent FPVS-EEG study found that intensive training with faces presented upside-down during several weeks led to a significant reduction of the neural face inversion effect (FIE; Hagen et al., 2024; see also Laguesse et al., 2012), shedding new light on the plasticity of FIR processes. Consequently, the current state of research lacks sufficient perspective to determine whether prolonged exposure to masks might improve FIR, and more longitudinal studies are needed to explore this possibility. More generally, our results offer insights into the broader implications for social interactions in the context of daily health-related measures. Future research could explore adaptative strategies or alternative measures to mitigate these effects while ensuring effective health protection.

## CRediT authorship contribution statement

**P.J.N. Thomas:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **J. David:** Formal analysis, Data curation. **B. Rossion:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **S. Caharel:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Conceptualization.

## Declaration of competing interests

The authors declare no competing interests.

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## Data availability

Data will be made available on request.

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