Visual Neuroscience

Spatial Resolution Evaluation Based on Experienced Visual Categories With Sweep Evoked Periodic EEG Activity

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Purpose. Visual function is typically evaluated in clinical settings with visual acuity (VA), a test requiring to behaviorally match or name optotypes such as tumbling E or Snellen letters. The ability to recognize these symbols has little in common with the automatic and rapid visual recognition of socially important stimuli in real life. Here we use sweep visual evoked potentials to assess spatial resolution objectively based on the recognition of human faces and written words.

Methods. To this end, we tested unfamiliar face individuation[1] and visual word recognition[2] in 15 normally sighted adult volunteers with a 68-electrode electroencephalogram system.

Results. Unlike previous measures of low-level visual function including VA, the most sensitive electrode was found at an electrode different from Oz in a majority of participants. Thresholds until which faces and words could be recognized were evaluated at the most sensitive electrode defined individually for each participant. Word recognition thresholds corresponded with the VA level expected from normally sighted participants, and even a VA significantly higher than expected from normally sighted individuals for a few participants.

Conclusions. Spatial resolution can be evaluated based on high-level stimuli encountered in day-to-day life, such as faces or written words with sweep visual evoked potentials.

Keywords: EEG, visual acuity, sweep visual evoked potentials, face individuation, word recognition

Visual function is most often assessed in clinical settings with an explicit behavioral measure of visual acuity (VA),[3] defined as the ability to determine that two objects at high contrast levels are separate in space.[3] In such behavioral tests, participants are usually required to name or match letters, numbers or other pictures (e.g., tumbling E, Landolt-C) of different sizes. Matching is used instead of naming by children or patients who have not been able to learn optotype recognition.[4] However, the ability to recognize these symbols explicitly without time constraints has little in common with the visual skills at play in real-life visual environments, which require fast and automatic (i.e., not under volitional control) recognition of more complex visual stimuli. In behavioral evaluations, a reduction of the duration of optotype presentation, especially in the subsecond range, is known to have a strong detrimental effect on VA, with little difference between participants with normal and degraded vision.[5] A test of spatial resolution based on stimuli encountered in day-to-day life, such as human faces or written words, is currently not available in clinical settings. Because these high-level stimuli involve brain areas that are not associated with conventional tests such as Snellen letters, it is expected that they will highlight deficits or strengths different from those tapped by conventional tests. In particular, it is important to know whether deficits in low-level vision truly affect these recognition functions or are relatively well tolerated.[6]

Electroencephalographic (EEG) recordings potentially offer a richer approach to assess VA, which is particularly useful in participants who cannot or will not reliably complete subjective tests, such as infants or young children, individuals with cognitive deficits, or in the case of malingering.[7–9] Measures based on EEG are implicit, as opposed to what is typically proposed in behavioral neuropsychological approaches. In the latter approaches, an explicit task, usually with stimuli that are presented for relatively long times, involves many additional cognitive processes, and its outcome is influenced by many factors (task instruction, decisional and motor components, subject motivation/stress, etc.).

Typical EEG measures used in ophthalmology are based on potentials evoked by flashes or checkerboard/grating reversals, which are expressed as peaks and throughs (visual evoked potentials [VEPs]) in the time domain.[10] However, in practice, the benefit of standard VEP measures is limited by their low signal-to-noise ratio and the subjectivity of identification of the VEPs and quantification of their parameters (amplitude and latency). An alternative approach is to present a visual stimulus at a (relatively fast) periodic rate to produce an EEG signal over the occipital cortex exactly at the frequency of stimulation.[11] After Fourier transform of the EEG,[12] this signal, often referred to as a steady-state VEP, can be identified and quantified objectively in the frequency domain. A sweep-evoked periodic EEG activity is obtained when the property under measurement, the spatial frequency of a grating, for instance, is increased progressively or decreased during the stimulation.[13] It allows to determine a threshold of VA when the signal in the frequency domain significantly emerges or disappears from noise level. (Note that in these studies, threshold is defined by extrapolation to zero amplitude, not by when the signal was above the noise level).[14]

These sweep VEPs (sVEP) have largely been used with stimuli such as gratings and checkerboards to evaluate VA (as reviewed in Almoqbel, Leat, and Irving [2008],[8] Hamilton et al. [2021],[7] Zheng et al. [2020][9]). More than 50 studies have been reported as assessing VA with sVEP in children as of a few days of age.[7] In adults, 15 studies found that the behavioral VA values are above the sVEP VA measures by approximately 0.2 to 0.6 log units.[7] Knowing this relationship between sVEP VA and behavioral VA, typically used in clinics, allows to use sVEP VA to estimate behavioral VA when it cannot be determined reliably with explicit tests.

However, an important factor that prevents a meaningful comparison between behavioral and EEG VA values is that sVEP measurements are performed with low-level stimuli typically, whereas behavioral tests are performed with high-level stimuli (i.e., categories, such as letters/words or object pictures). Because fast periodic visual stimulation has been extended successfully in recent years to measure higher level human visual recognition functions in EEG such as face, letter, and word or even quantity recognition,[2,15,16] this confound could be overcome. Collectively, these latter studies have identified objectively and quantified high signal-to-noise EEG signals with specific patterns of localization and lateralization for these functions (e.g., right or left occipitotemporal for face or letter/word recognition, respectively). These EEG responses obtained during fast periodic visual stimulation also seem to be highly reliable within[17] and even across[18] recording sessions.

Here our goal is to introduce sVEP paradigms to assess VA reflecting face and visual word recognition (VWR) in a normal adult population. To do that, we present visual stimuli in progressively decreasing sizes, focusing on two major visual recognition functions: (1) face identity recognition (FIR) and (2) VWR.

FIR can be considered as the most challenging face recognition function (e.g., compared with emotional facial expression recognition, gender, etc.), and perhaps even as the ultimate recognition function for the human brain.[19–21] Besides very rare cases of specific impairment at FIR after brain damage to ventral occipitotemporal regions (i.e., prosopagnosia), difficulties at FIR have been observed in a wide range of clinical conditions, including Alzheimer's disease,[21] as well as low-level disorders (glaucoma, cataracts, amblyopia, etc.[22–26]). Amblyopia (strabismic) or a lack of early visual experience owing to cataract associated with vision deficit in adulthood can also cause significant FIR deficits.[27,28]

FIR has been measured successfully with pictures of unfamiliar faces presented in an oddball paradigm.[1,29] The neural response obtained on the scalp is right lateralized, focused on the occipitotemporal cortex, and highly reliable. In neurotypical adults, it is decreased substantially when the exact same images of faces are presented upside down, showing that the response does not merely reflect physical differences between stimuli (which are identical at upright and inverted orientations), but a high-level brain function built from experience.[1,29]

VWR involves the recognition of letters and their combinations, a function that is lateralized to the left hemisphere from an early age, even before formal reading acquisition.[30] This VWR function has been measured successfully with fast periodic visual stimulation in adults[2] and during reading acquisition in young children.[31]

To assess VA during FIR and VWR, here we progressively decrease the visual angle encompassing the face or word stimuli and estimate the point until which facial identities can be discriminated, and words can be discriminated from flipped nonwords (fNWs). VA thresholds are assessed at the most sensitive electrode (MSE), which is determined for each participant as the electrode with the highest baseline-corrected amplitude for the sum of the first relevant harmonics.

Methods

Participants

We tested 15 healthy volunteers, including 11 females, aged 20 to 30 years (mean age, 24 ± 3 years). One participant was excluded because she was taking psychiatric medication. In the remaining participants, all reported a best-corrected VA of 10/10 or better for each eye; none reported any ophthalmologic, neurological, or psychiatric disease. Written informed consent was obtained from all participants after they were informed about the goal of the study. Participants received a monetary compensation at the end of the recording session. The research protocol followed the tenets of the Declaration of Helsinki and was approved by the University of Louvain's Human Biomedical Ethics Board under the Belgian registration number B403201732407.

Stimuli and Procedure

We evaluated human face individuation in all individuals with the typical oddball paradigm[1] (pilot experiment 1) and then with an original size-sweep version of the paradigm, the face sweep (experiment 1). In addition, we tested participants' ability to recognize written words among fNWs with a standard paradigm[2] (pilot experiment 2) and a sweep paradigm, the word sweep (experiment 2). The goal of the pilot experiments was to ensure that every individual tested here showed a significant response at a typical stimulus size and a full stimulation duration as used in published studies, as well as to define, for each participant, the MSE for the sweep condition. Pilot experiments also allowed to determine the number of harmonics to consider in the word experiment and to evaluate a correlation between the magnitude of the response in a typical paradigm and the threshold as defined on an individual basis.

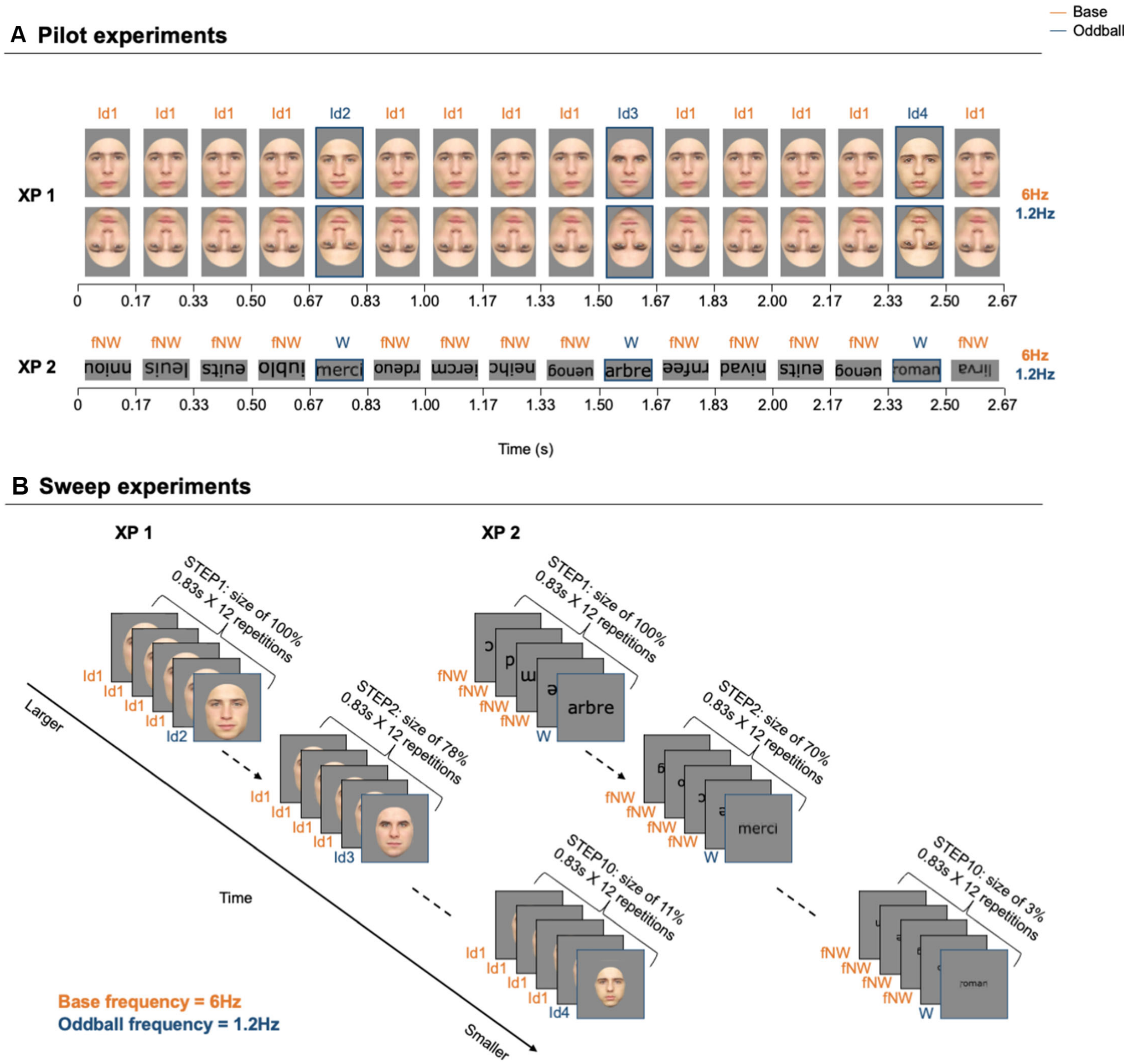

Figure 1. (**A**) Examples of the pilot experiments. XP 1 is the face individuation experiment. The face of a given unfamiliar individual (Id1), the base stimuli, is presented at a fixed rate of 6 stimuli per second (i.e., 6 Hz), with the faces of other individuals (Id2, Id3, etc.), the oddball stimuli, appearing at every fifth stimuli (i.e., 1.2Hz). XP 1 was presented with upright and inverted faces in different conditions. Images in these two experiments were presented with a sinusoidally modulated contrast. XP 2 is the word recognition condition. fNW, the base stimuli, were presented at a fixed rate of 6 stimuli per second (i.e., 6 Hz), with words (W), the oddball stimuli, appearing at every fifth stimuli (i.e., 1.2 Hz). (**B**) Schematic illustrations of the sweep experiments. In XP 1 and 2, stimuli were presented during 10 seconds (0.83 seconds × 12 repetitions) at the largest size allowed by the stimulation screen at step 1, then, consecutively, during 10 seconds at the following 9 steps, in which the size of the stimuli was progressively reduced. The factor of size decrease was taken from a range of 10 logarithmically spaced values.

In all experiments, images were presented periodically with a sinusoidally modulated contrast, as in previous studies. Stimulus contrast was linearly increased and decreased respectively at the beginning and end of each stimulation sequence, during short fade-in and fade-out periods (2 seconds). These periods were not included in the analyses and aimed at preventing blinking or movement artefacts owing to abrupt (disappearance of) stimulation. Stimuli were presented at the centre of the screen on a three-dimensional LCD monitor, with a resolution of 1920 (H) × 1080 (V) pixels and a refresh rate of 120 Hz. The mean luminance of the monitor was 132 cd/m^2.

Experiment 1: Face Individuation. A sequence (pilot experiment 1) included four base (B) stimuli followed by an oddball (O) stimulus (BBBBOBBBBO…) at a base frequency of 6.0 Hz and an oddball frequency of 1.2 Hz. The base stimulation frequency was identical to previous similar experiments.[1] Stimuli were frontal colored face images that did not show any emotion and without any external features. The base stimuli were the face of a given person (Id1), which remained the same throughout the stimulation sequence, and the oddball stimuli, faces of other persons (Id2, Id3, etc.) (Fig. 1), selected from a set of 25 different faces. To limit the contribution of low-level visual cues to the face individuation task, the face size varied between 80%

Table 1. Dimensions of Stimuli at Every Step in the Sweep Conditions

	Dimensions of Stimuli (Degrees)			
	Face Individuation		Word Recognition	
	Height	Width	Height	Width
Step 1	6.9	4.6	2.00	6.90
Step 2	5.3	3.6	1.40	4.80
Step 3	4.2	2.8	0.94	3.20
Step 4	3.2	2.2	0.65	2.20
Step 5	2.6	1.7	0.44	1.50
Step 6	2.0	1.3	0.30	1.00
Step 7	1.6	1.0	0.21	0.70
Step 8	1.2	0.8	0.14	0.50
Step 9	0.9	0.6	0.10	0.30
Step 10	0.7	0.5	0.07	0.20

and 120% in 5% steps at each 6-Hz stimulation cycle.[32] A condition started with 1s of fade-in, followed by 60 seconds of sequence, and ended with 1 second of fade-out. It was repeated four times with upright faces and four times with inverted faces. Images were 890 ± 180 pixels in height and 595 ± 120 pixels in width (6.9 × 4.6° of visual angle at a distance of 2 m).

In the sweep version of the paradigm (experiment 1), the size of the faces was decreased with a factor from a range of 10 logarithmically spaced values (Fig. 1). The average size was 7° × 5° of visual angle at the first step, and 0.7° × 0.5° at the last step (viewing distance of 2 m) (Table 1). Face size also varied between 80% and 120% in 5% steps. A sweep was comprised of 10 equal log steps, each presented for 10 seconds in a sequence that lasted 100 seconds, in addition to 1 second of fade-in and 1 second of fade-out, respectively at the beginning and at the end of the sequence. The 102-second sweeps were repeated eight times.

Experiment 2: Word Recognition. A sequence (pilot experiment 2) also included four base stimuli followed by an oddball stimulus. To compare the results of experiments 1 and 2, the base frequency was also 6 Hz, as in previous similar experiments.[31] Oddball frequency was also 1.2 Hz (6 Hz/5). Oddball stimuli were five-letter French words (W) commonly used as of primary school (e.g., "merci," "roman"), selected from a set of 28 words. The font used was Verdana, with a spacing between characters of one-quarter of the letter size. Base stimuli were fNW, built one by one on the basis of the words of the oddball stimuli by flipping the letters vertically and randomly mixing them (Fig. 1). A condition started with 1 second of fade-in, followed by 60 seconds of sequence, and ended with 1 second of fade-out. It was repeated four times. Stimuli were 260 ± 50 pixels in height and 890 ± 180 pixels in width (2.0° × 6.9° of visual angle at a distance of 2 m).

The sweep version of the paradigm (experiment 2) was based on the sequence (fNW_fNW_fNW_fNW_W_fNW…) of the pilot experiment. The size of the letters of the words and fNWs was decreased with a factor from a range of 10 logarithmically spaced values (Fig. 1). The size of the letters varied between 2.0° × 6.9° of visual angle at the first step, and 0.07° × 0.20° at the last step (viewing distance of 2 m) (Table 1). The height corresponds to the body height, including ascenders and descenders. A sweep was comprised of 10 equal log steps, each presented for 10 seconds in a sequence that lasted 100 seconds, in addition to 1 second of fade-in and 1 second of fade-out, respectively, at the beginning and at the end of the sequence. The 102-second sweeps were repeated eight times.

For all participants, the order of conditions was blocked: face sweep (2 trials), inverted face individuation (2 trials), upright face individuation (2 trials), word sweep (1 trial), word recognition (1 trial), and word sweep (1 trial). This block was repeated identically one time. It was followed by another block: face sweep (2 trials), word sweep (1 trial), word recognition (1 trial), and word sweep (1 trial). This block was repeated identically one time. The total testing time including breaks was less than 45 minutes. The experimenter manually initiated the recording of each condition after observing an artefact-free EEG signal for at least 10 seconds and confirming the participant was ready.

EEG Acquisition

Recording took place in a dimly lit room. Participants were instructed to maintain fixation at the center of the screen throughout the experiment. Scalp EEG was recorded at a sampling rate of 512 Hz with a 64-channel Biosemi Active 2 system, with electrodes corresponding to the standard 10-20 system locations, and four additional electrodes placed over the occipitotemporal region (PO9, PO10, I1, and I2).

EEG Analysis

Preprocessing. The EEG data were analyzed as in previous studies with these paradigms,[29] but the analysis is nevertheless described fully here. Data were band-pass filtered off-line between 0.1 and 100.0 Hz with a fourth-order zero-phase Butterworth filter and re-referenced to the average of the 68 scalp channels. For each participant and condition, the preprocessed EEG data were averaged across trials. In the pilot and sweep conditions, the data were respectively cropped into one 60-second epoch, and ten 10-secone epochs corresponding with each step of the conditions, excluding the fade-in and fade-out periods, without any correction for artefact. A discrete Fourier transform was applied to each epoch, resulting in a frequency resolution of 1/60 Hz (i.e., 0.0166 Hz) for the pilot and of 1/10 Hz (0.1 Hz) for the sweep conditions. Baseline-corrected amplitudes were then computed by subtracting the mean amplitude of, respectively, 10 and 20 surrounding frequency bins (respectively 5 and 10 on each side, excluding the immediately adjacent frequency bin), from the amplitude at each frequency bin, for the sweep and pilot conditions. In the remainder of the article, the term amplitude refers to baseline-corrected amplitude. For the face individuation condition, the sum of the resulting EEG amplitude at the six first harmonics, excluding the fifth harmonics (i.e., 1.2 Hz, 2.4 Hz, 3.6 Hz, 4.8 Hz, and 7.2 Hz) of the oddball frequency, which we called the summed oddball frequency $\bar{f}_O$, was taken as an index of the sensitivity to the stimulus. The fifth harmonic (i.e., 6 Hz) was excluded, because it coincided with the base frequency. These five harmonics typically include all of the signal in face individuation experiments (See Fig. 4 in 29). To evaluate the sensitivity of the stimulus at the base frequency, the sum of harmonics was similarly calculated, without excluding the fifth harmonic. This summed base frequency was noted as $\bar{f}_B$. A similar approach was followed in the word experiment, with a number of harmonics included in the sum defined based on the pilot experiment.

MSE Selection. The MSE was defined in the pilot conditions as the electrode with the highest baseline-corrected amplitude at the sum of the six first harmonics for the face experiment, excluding the fifth harmonic of the oddball frequency. A similar approach was followed in the word experiment, with a number of harmonics included in the sum defined based on the pilot experiment.

Sensitivity Estimation. In the sweep conditions, the sensitivity of the signal was assessed at each step by transforming the amplitude spectrum into z-scores, taking into account the five surrounding bins on either side of the frequency of interest, excluding the immediately adjacent bin (in case of spectral leakage). The threshold was defined as the last step with a significant response at the summed oddball frequency, with the condition that the preceding step was significant as well. A step was considered as significant it the z-score of the amplitude at that step was above the z-score threshold. The z-score thresholds were set at a z of greater than 2.33 (significance level of 0.01, one tailed; i.e., signal > noise) at the group-average level, that is, averaged across sequence repetitions and individual participants, and a z of greater than 1.64 (significance level of 0.05, one tailed) at the block-average level, that is, averaged across sequence repetitions for each participant individually. A more severe threshold was used at the group-average level than at the block-average level, because a greater number of repetitions was included in the group average, increasing the signal-to-noise ratio.

EEG Interpretation

The scalp topographies and frequency spectrum were first evaluated for the pilot experiments at the block-average level and at the group-average level. The frequency spectrum at the block-average level was evaluated at the individual participant's MSE. At the group-average level, it was determined by averaging across sequence repetitions and across individual participants' frequency spectra. Next, we assessed the evolution of scalp topographies and frequency spectrum at the group-average level throughout the sweep conditions.

Results

Pilot Experiments (Full Sequences)

At the group-average level, in the face individuation conditions, the most sensitive response at the oddball frequency (f_O) and its harmonics was recorded over the right occipitotemporal cortex, followed by the left occipitotemporal cortex (Fig. 2). The response was statistically different, $F(1) = 5.5$; $P = 0.02$, regarding face direction: response was larger with upright (mean = 0.34) than with inverted faces (mean = 0.19), as expected.[1,29] In the word recognition conditions, at the group-average level, the most sensitive response at the oddball frequency (f_O) and its harmonics was located over the left occipitotemporal cortex followed by the right occipitotemporal cortex (Fig. 2). A significant response was

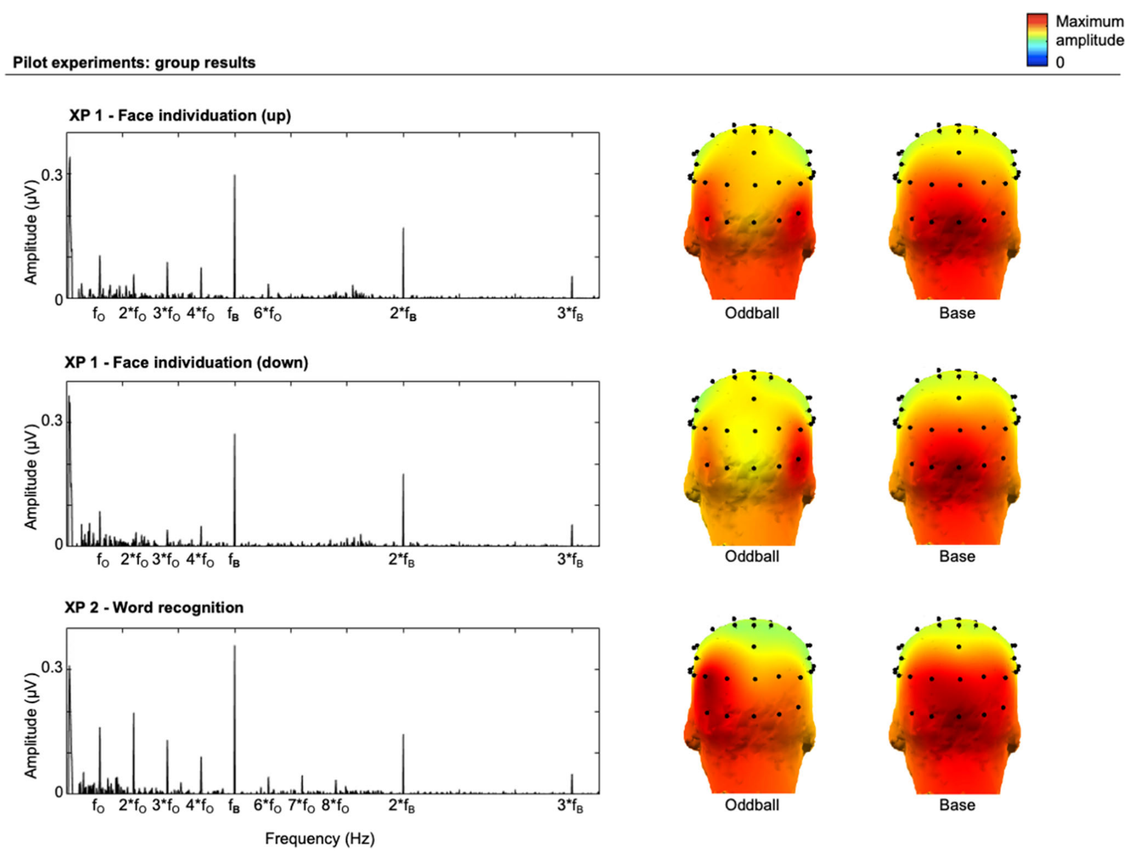

Figure 2. Pilot experiments. Frequency spectrum averaged at the group level over the right occipitotemporal cortex for face individuation experiments, and over the left occipitotemporal cortex for the word recognition condition, and topography of the baseline-corrected amplitude averaged across participants and across sequence repetitions at the summed oddball frequency and the summed base frequency.

Table 2. Most Sensitive Electrode (MSE)*

	Number of Participants	
MSE	Face Individuation	Word Recognition
PO10	5	1
P10	3	2
P9	2	2
O1	1	3
PO9	2	1
PO7	0	3
I1	0	2
P1	1	0

*The MSE is defined individually for each participant as the electrode with the highest baseline-corrected amplitude highest baseline-corrected amplitude at the sum of the six first harmonics for face paradigms, and the eight first harmonics for word paradigms, excluding the fifth harmonics of the oddball frequency in both experiments.

obtained at the first eight harmonics: the eighth harmonic (9.6 Hz) was highly significant (z-score of 6.7, $P < 0.001$), but the ninth harmonic was not significant (z-score of 0.79; $P = 0.21$). At the base frequency (f_B), the largest activity was recorded over the middle occipital cortex in both experiments. In a majority of participants, the MSE was located outside of the middle occipital electrode Oz, for both the face individuation and word recognition conditions (Table 2). Interestingly, for a few participants, the most sensitive response was localized in the left occipitotemporal cortex in face individuation conditions and in the right occipitotemporal cortex in word recognition conditions (Fig. 3). Thus, as already noted in previous publications,[33] recording the EEG with an extended electrode array is important to correctly assess the visual function of each participant. In other words, assessing the visual function at the central occipital electrode Oz, which is a common approach in clinical settings, would miss the most sensitive signal and underestimate visual performance in a large number of individuals.

Sweep Conditions

Recognition Indexes. Next, we studied the evolution of frequency spectrum at the group-average level with decreasing sizes of faces and letter strings (Fig. 4). To examine the lateralization of the response, we determined the average baseline-corrected amplitude in the left (P1, P3, P5, P7, P9, PO3, PO7, PO9, O1, and I1 electrodes) and right occipitotemporal cortex (P2, P4, P6, P8, P10, PO4, PO8, PO10, O2, and I2 electrodes).

In the face sweep condition, the most sensitive signal at the summed oddball frequency $\bar{f}_O$ was lateralized, with a greater response in the right occipitotemporal than the left occipitotemporal cortex throughout the size steps. In the word sweep condition, scalp topographies showed a left lateralization at the summed oddball frequency $\bar{f}_O$ throughout the size steps. Moreover, at the group-average level, different thresholds were obtained for the two experiments: higher thresholds for the face sweep than for the word sweep conditions, that is, respectively, step 9 and step 7, corresponding to sizes of images of 0.9° (height) × 0.6° (width), and 0.2° (height) × 0.7° (width).

Next, we determined the thresholds for each participant using the z-score based on the baseline-corrected amplitude averaged across sequence repetitions at each participant's MSE and at the electrode Oz (Fig. 5). The thresholds of the individual participants were not correlated with the amplitude at the MSE at the summed oddball frequency $\bar{f}_O$ (R^2 for the face condition = 0.35, R^2 for the word condition = 0.39). Thus, higher thresholds are not necessarily associated with higher EEG amplitudes. Threshold assessment was more reliable at the MSE; although it could be defined at the MSE for, respectively, 11 and 12 participants in the face and word sweep conditions, it could be determined for only 8 and 12 participants at Oz. In addition, thresholds were higher at the MSE, as already noted elsewhere in this article.[33] Given the variability of scalp topographies between participants, assessing their visual function at their MSE is important, as the use of a standardized region of interest across participants would underestimate their visual performance.

Base Frequencies. Although the presence of a response at the oddball frequency reflects the discrimination of the oddball stimuli in the sequence, a response at the base frequency merely reflects the global response to the flickering of images. In clinical settings, the presence of a response at the base frequency may be used to assess whether and to what extent the participant actually looked at the screen (Fig. 6). The amplitudes at the base frequency determined at individual participants' MSE and averaged at the group level decreased linearly with stimulus size in both experiments, especially for words ($R^2 = 0.97$ for the face paradigm; $R^2 = 0.99$ for the word paradigm, Fig. 6). This linear trend was less significant at the oddball frequency ($R^2 = 0.51$ for the face condition; $R^2 = 0.77$ for the word condition, Fig. 4).

Discussion

In this study, we aimed to assess VA with commonly experienced categories: face stimuli and written words. To do so, we measured sweep-evoked periodic EEG activity with 64 electrodes plus 4 additional electrodes over the occipitotemporal region. Our data show that it is possible to obtain objective measures of VA based on stimuli encountered in day-to-day life with sVEP. Moreover, because these responses are well-localized to a few occipitotemporal channels in all participants, the total testing time including setting up and removing a limited number of electrodes at these locations could be realized in a short amount of time, allowing to test challenging populations (e.g., infants and children, clinical populations).

Previous studies have determined visual perception thresholds with sVEP. Instead of varying the size of the stimulus, one could use a progressive decrease of the low-pass filter cut-off of the spatial frequency content of the image.[34] In the present study, we describe the first paradigm of sVEP realized by varying the size of faces or words. Varying the size allowed to modify the angle under which faces or words are seen, such as when optotypes such as tumbling Es or Snellen letters are used in the clinical context to measure VA. The difference between tumbling Es on the one hand, and Snellen letters, faces or words, on the other hand, is that the discrimination of complex images such as letters, faces, or words not only requires to see the details that constitute these images, but also to recognize that the result of this arrangement of segments and curves forms a face, a learned category. The decrease in the neural response when faces are presented at an inverted versus an upright orientation

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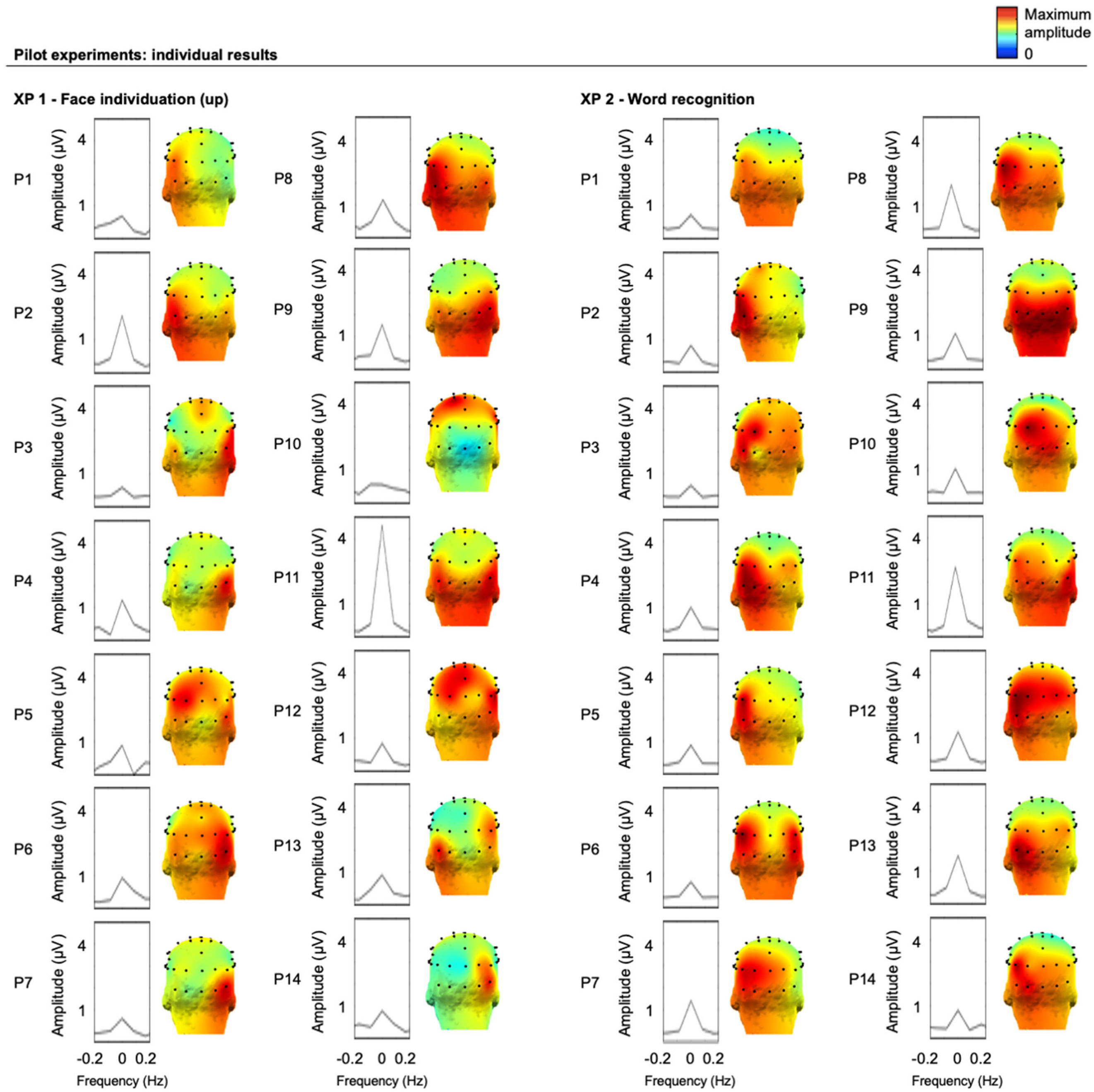

FIGURE 3. Pilot experiments. Frequency spectrum at the summed oddball frequency at the participant's MSE, and topography of the baseline-corrected amplitude at the summed oddball frequency.

shows that high-level recognition goes well beyond the objective physical differences between complex images.

Contrasting words with fNWs derived from our goal, which was to assess the VA with ecological stimuli. By flipping the orientation of the letters, we maximized the contrast between the bases and oddballs, although we ensured that low-level information is constant between the two contrasted categories. We did not use a contrast between words and nonwords only because young children, even after 1 to 2 years of formal reading acquisition, do not yet show words–nonwords effects in this paradigm.[35] Letters have been contrasted previously with pseudoletters at a rate of 3 Hz to evaluate VA using steady-state VEP.[36] In that study, letters were presented in rows of random letter images. The choice of an array to display letters is very interesting, because it introduces the crowding effect, which is also present in letter charts used clinically, and affects the VA in patients with amblyopia. Moreover, the algorithm used in that study controlled for the global power spectrum of the letters as well as additional second-order statistics involving correlations over scale, location, and orientation. However, here, we did not use pseudoletters because it is impossible to strictly control for low-level features when contrasting them with real letters (e.g., in orientation of the strokes).

In the present study, the base rate response remained significant throughout all the steps for face individuation,

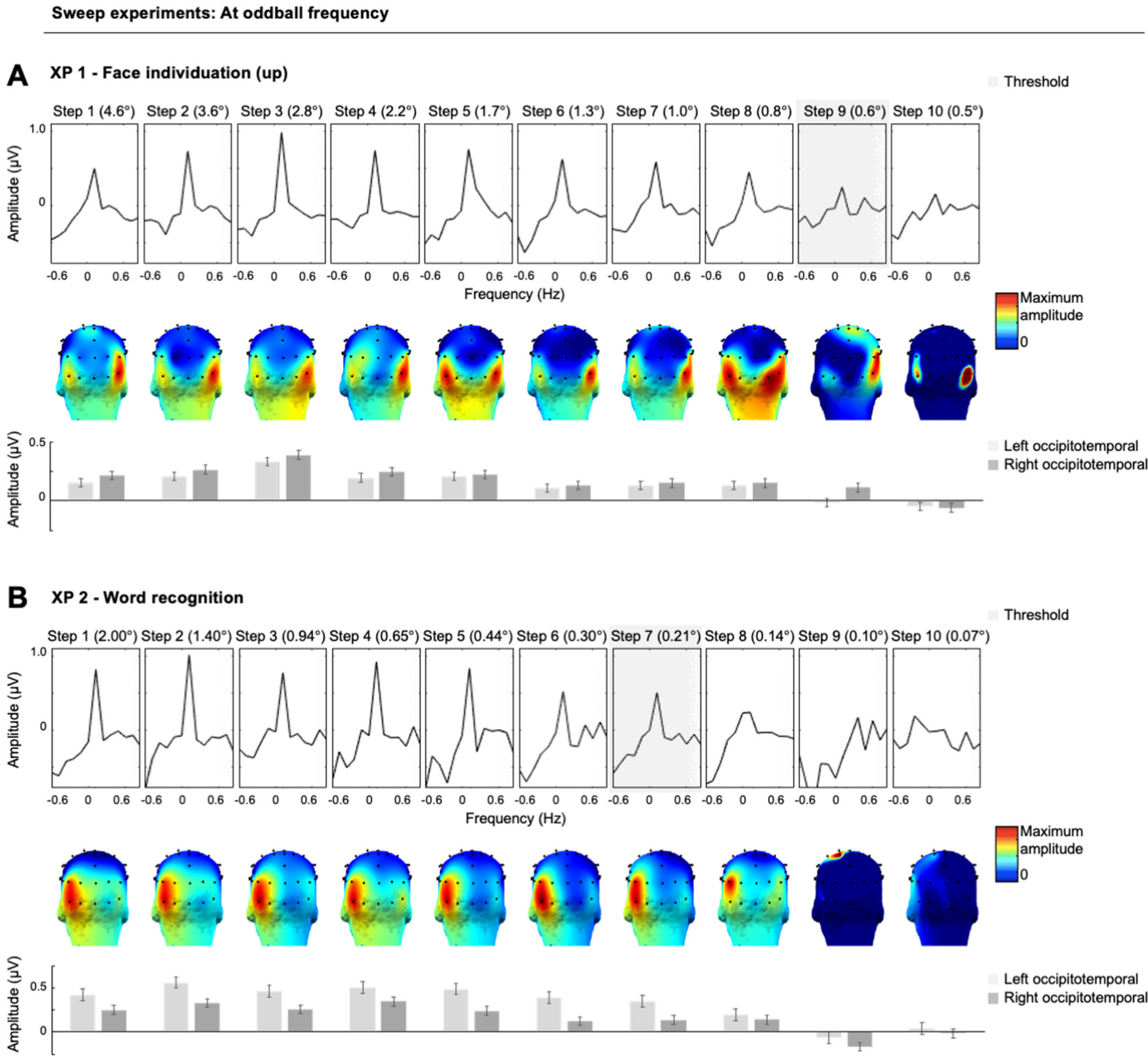

Figure 4. Sweep experiments at the oddball frequency. (**A**) Face individuation. (**B**) Word recognition. From top to bottom: frequency spectrum at the group-level at each participant's individual MSE, group-level scalp topographies, and average amplitudes over the left occipito-temporal (OT), right OT at the 10 steps of the sequence of the baseline-corrected amplitude averaged across participants. Error bars represent the standard errors of these averages. In each experiment, the step corresponding with the threshold determined with the Z-score based on the baseline-corrected amplitude at the MSE is highlighted.

and almost all the steps for word recognition. For words, it became lateralized at small sizes, as if the occipitotemporal regions generated most of the response. The amplitude at the base frequency decreased linearly with stimulus size in both experiments (especially for words). It is likely to simply reflect the size of the cortical area stimulated. It is in contrast with the recognition measures, at the summed oddball frequency, which do not decrease linearly. As for the amplitude at the summed oddball frequency, it was maximal in the face individuation at step 3 (Fig. 4), which corresponds with a human face seen at 2.3 m, a distance that is common in human interactions.

Word sweep conditions were associated with a response of interest at the group average level until step 7 (0.20° × 0.70°). At the individual level, a response of interest at the MSE was identified in a large majority of participants until at least step 7 (Fig. 5). It is worthwhile to note that these thresholds of word recognition correspond with letter heights of between 0.07° and 0.44° (Table 1), that is, minimal angles of resolution of between 0.8 and 5.3 minutes of arc for letters such as E, or a VA of between −0.1 and 0.7 logMAR. This finding confirms that our test assesses spatial resolution correctly, because participants in this study had a normal VA. In addition, this finding confirms that individuals with a normal visual function can recognize words at a very fast rate.[37] Regarding the participant with a VA estimated at a logMAR of 0.7, this VA evaluated with the letter chart used in the clinical environment is 10/10. Although this lower

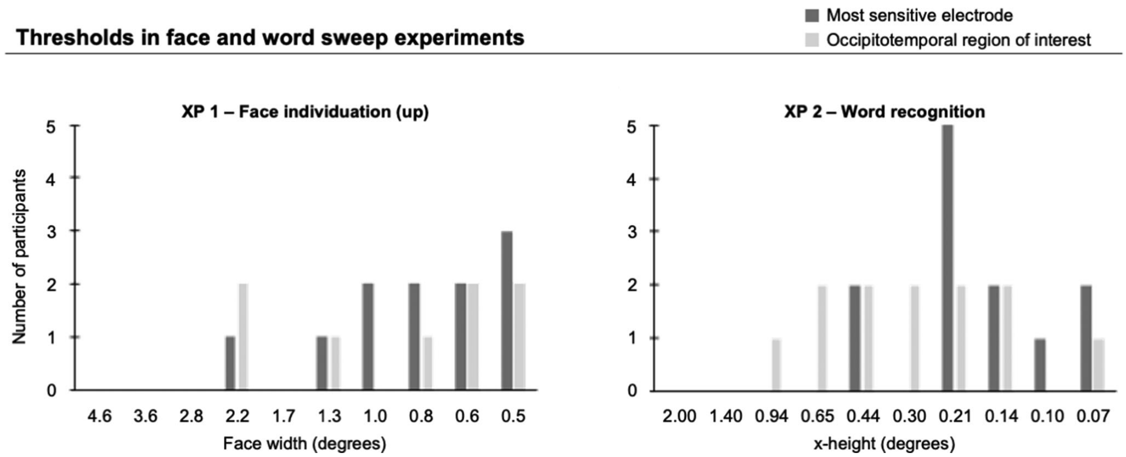

Figure 5. Sweep experiments: number of participants with a threshold at each of the 10 steps of the face individuation (XP 1) and the word recognition (XP 2) conditions. In both experiments, the threshold is determined with a Z-score based on the baseline-corrected amplitude averaged across sequence repetitions at the MSE and at the electrode Oz.

result for the dynamic assessment of VA based on high-level stimuli, compared with its evaluation in clinic, should be confirmed with additional testing, it possibly reflects the fact that different processes (and time constraints) are involved for these two tasks, and a normal performance for one of these tasks does not always imply a normal performance for the other task. Moreover, we acknowledge that the sVEP threshold as defined here by taking into account EEG noise may depend on the number of trials, and we cannot exclude that it would be slightly shifted with a higher number of trials used.

In line with a previous study[38] which showed that reading speed for text was constant over a 10-fold range of 0.2° and 2.0° of *x*-height, the response at the summed oddball frequency in the word recognition experiment was significant between 2.00° and 0.21° of *x*-height (Fig. 4B). Visually, the amplitude at the summed oddball frequency did not present a decreasing trend between 2.00° and 0.29° of *x*-height, which is coherent with the finding that reading speed is maximum and constant over a fluent range of print sizes. The amplitude at the summed oddball frequency started to decrease as of 0.29°, close to the threshold of 0.2° mentioned in that study.[38]

Regarding face sweep conditions, a response of interest at the group-average level was found until step 9 (0.9° × 0.6°). Most participants in this experiment had a threshold between 7 and 10 (Fig. 5). Thus, for future experiments, it can be noted that normally sighted individuals can individuate faces presented at a high frequency of 6 Hz until a face height of between 1.6° and 0.7°. Moreover, preliminary data collected in our laboratory with positive lenses decreasing the VA to 3/10 indicates that this threshold for FIR is not affected by the artificial alteration of VA. This finding suggests that the ability to recognize face identity persists even in low vision conditions, in line with observations made with severely low-pass filtered stimuli in behavioral[39] and more recently sweep-VEP studies.[40] One implication of this finding is that the measure of VA based on face individuation alone could miss patients with high spatial frequency loss, suggesting that measures of acuity with simple low-level stimuli such as gratings could complement the face acuity measurements.

Developing new tests to assess the visual function is important to reflect the visual difficulties encountered in some pathologies, such as cerebral visual impairment (CVI). CVI, one of the most frequent causes of vision impairment in children in the developed world, is a bilateral decreased visual performance owing to a neurological problem affecting the visual part of the brain and unexplained by ocular findings.[41,42] Despite VA, which remain good or are even normal in some individuals, patients with CVI present important difficulties to perform everyday visual tasks, such as extracting visual information from a visually crowded background. The most common symptoms observed in CVI result from dorsal stream dysfunction.[43]

For the diagnosis and follow-up of conditions affecting infants, such as amblyopia or CVI, the tests used could be based on faces and on gratings. In older children, if cognitive abilities allow, VWR tests could also be used. Our paradigm is sensitive not only to differences between words and nonwords, but also to contrast letters and inverted letters. Even though we are unable to determine at this stage the respective contribution of letter order scrambling and letter inversion of the oddball response, because there is evidence of letter selectivity responses at an early age even in pre-readers[30] (5 years old), it may be helpful as a hint to the reading abilities and potential need for support at school. As for patients with CVI, because deficits have primarily been described in the dorsal stream,[44] (partially) spared functioning may be expected for the face and word recognition tasks indeed. A statistically significant peak at the oddball frequency in these two tasks would suggest a (partially) spared functioning. This response should be followed, because it may be absent initially as a result of immaturity of reading and FIR, and subsequently appear with the development of these functions.

In contrast, in older participants, both tasks based on face identity and word recognition would be interesting in patients with central visual field deficits, such as in diabetic maculopathies, in AMD, and in other maculopathies of degenerative, genetic, toxic, or inflammatory causes. Understanding how they are affected for these visual functions required in day-to-day life would help to support them in their daily activities and customize visual rehabilitation programs. The test of VWR could be used in patients with

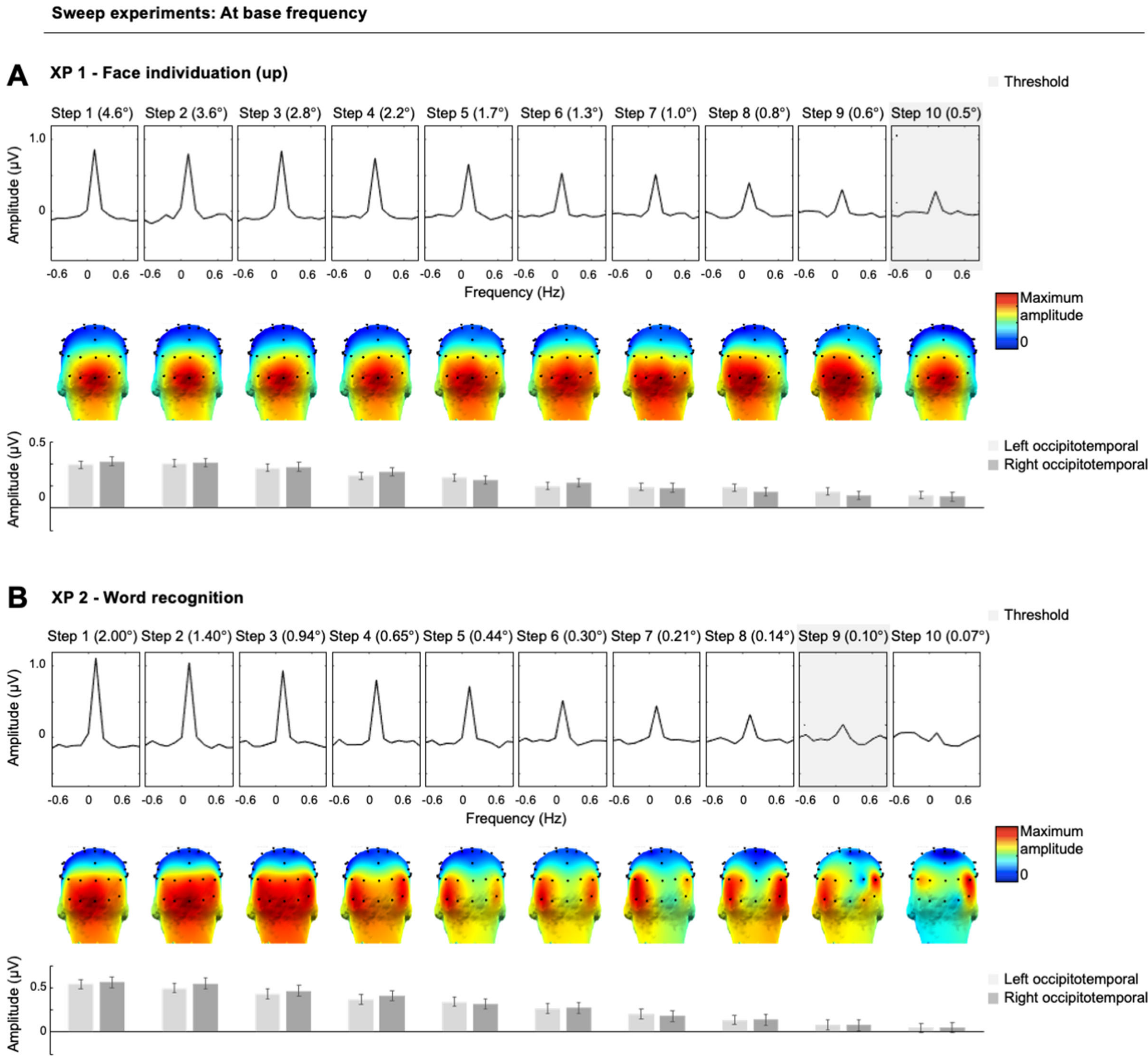

Figure 6. Base frequency response in the sweep conditions. (**A**) Face individuation. (**B**) VWR. From top to bottom: frequency spectrum at the group-level at each participant's individual MSE, group-level scalp topographies, and average amplitudes over the left OT and right OT at the 10 steps of the sequence of the baseline-corrected amplitude averaged across participants. Error bars represent the standard errors of these averages. In each experiment, the step corresponding to the threshold determined with the Z-score based on the baseline-corrected amplitude at the MSE is highlighted.

neurological or ophthalmologic pathologies, in comparison with normally sighted patients, to understand the extent to which their pathology affects word recognition. Thanks to the sweep paradigm, our test will not only allow to answer whether word recognition is possible, but also to what extent it is performant in terms of acuity in comparison with normally sighted controls.

In line with the literature, our study showed on topographies at the group-average level at the oddball frequency, in the face and word sweep conditions, a lateralization, respectively, in the right and left occipitotemporal cortex. However, some participants presented with an atypical lateralization, respectively, in the left and right occipitotemporal cortex for the face and word sweep conditions. Presentation of faces, as opposed to other nonface objects, significantly activates regions in the ventral occipitotemporal cortex, as demonstrated by functional magnetic resonance imaging studies.[45–48] More precisely, human neuroimaging and intracerebral recordings have shown that faces selectively activate the right middle lateral fusiform gyrus, a region called the fusiform face area.[49,50] As for letter strings, their processing largely activates the left ventral occipitotemporal cortex.[51–53] More precisely, intracerebral recordings[54] have shown that, within the ventral occipitotemporal cortex, the areas involved in word discrimination were much more numerous in the left hemisphere, with the highest density around the left fusiform and occipitotemporal sulcus region. In line with the findings in this study, visual word discrimination also activates areas in the right hemisphere, mostly located along the fusiform gyrus.[54]

In the future, these paradigms may allow to determine, for different ophthalmic pathologies that affect VA such as amblyopia, cataract, or glaucoma, whether an impairment of VA is correlated with an impairment of high-level visual performance, with, for instance, an ability to recognize faces until step 5 only. Such a correlation between these impairments of low- and high-level visual functions may be observed in controls in whom VA would be artificially altered with positive lenses. In contrast, an asymmetry between impairments of low- and high-level visual functions, with a more severe impairment of low-level visual function, may derive from mechanisms of cerebral plasticity. These mechanisms might limit impairments for visual functions required in day-to-day life.

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