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► **To cite this version:**

Marion Vincent, Sébastien Vanstavel, Cédric Patin, Sandrine Mejias, Anahita Basirat. Brain responses to lexical attestedness and phonological well-formedness as revealed by fast periodic visual stimulation. *Brain and Language*, 2022, 232, pp.105150. 10.1016/j.bandl.2022.105150 . hal-04377160

HAL Id: hal-04377160

<https://hal.science/hal-04377160>

Submitted on 6 Apr 2024

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Brain responses to lexical attestedness and phonological well-formedness as revealed by fast periodic visual stimulation

Marion A. Vincent^{a,*}, Sébastien Vanstavel^a, Cédric Patin^b, Sandrine Mejias^a, Anahita Basirat^a

^aUniv. Lille, CNRS, UMR 9193 - SCALab - Sciences Cognitives et Sciences Affectives, F-59000 Lille, France

^bUniv. Lille, CNRS, UMR 8163 - STL - Savoirs, Textes, Langage, F-59000, Lille, France

Abstract

We investigated the mechanisms underlying the online-processing of phonological constraints using oddball fast-periodic visual stimulation coupled with EEG. We focused on the Sonority Sequencing Principle and examined whether steady-state visual evoked potentials (SSVEPs) are sensitive to the sonority constraint on syllable onsets. Native French speakers were presented with streams of CCVC non-words (C: consonant, V: vowel) at a fixed 6-Hz base rate. We manipulated the phonological well-formedness and lexical attestedness of CC onsets in two conditions. SSVEPs were observed at the base rate associated to visual stimuli. As expected, they did not differ between conditions. Oddball SSVEPs were observed at 1.2 Hz (and its harmonics) and differed in the two conditions. These results showed that SSVEPs are sensitive to sublexical features. They also suggest that the processing of phonological constraints rely on mechanisms which could be dissociated from those underlying the processing of statistical properties of the lexicon.

Keywords: Steady-state evoked potentials, fast-periodic visual stimulation, sonority sequencing principle,

Phonological constraints processing, sublexical features

1. Introduction

Phonotactic constraints are defined as the way specific patterns known as phonological units can be combined. One of the phonotactic constraints which have extensively been studied in the literature is the Sonority Sequencing Principle (hereafter SSP) defined by Clements (1990). The SSP states that ‘between any member of a syllable and the syllable peak, only sounds of higher sonority rank are permitted’ (Clements, 1990, p. 285).

Hence, onset clusters such as ‘lp’ do not satisfy the SSP, since the sonority of the stop [p] is lower than the sonority of the liquid [l]. However, such clusters are a suitable coda cluster. A well-known approach to

*Corresponding author at: Laboratoire SCALab UMR CNRS 9193, Université de Lille, Rue du barreau, BP 60149, 59653 Villeneuve d’Ascq Cedex, France

Email address: marion.vincent@univ-lille.fr (Marion A. Vincent)

examine the sensitivity of speakers to the SSP is to compare the acceptability of non-words¹ respecting the
18 SSP or not. Several studies have shown that speakers consider non-words beginning with rising sonority
clusters (e.g., onset ‘pl’) more acceptable as potential new words than those beginning with falling sonority
20 clusters (e.g., onset ‘lp’), even when the degree of lexical attestedness of the clusters (i.e., whether they exist
as clusters of the words of the language) was controlled for. Such effects, known as sonority projection effects
22 (Daland et al., 2011), exist in various languages (for a review Parker, 2017). These results raise two main
questions: first, do phonological constraints such as the SSP reflect the existence of abstract phonological
24 rules or do they rather emerge based on the statistical properties of languages (e.g., syllable frequency
in the lexicon)? Second, what are the underlying neurocognitive mechanisms during on-line processing of
26 utterances which violate phonological constraints?

The first question has been extensively investigated in experimental and modeling studies. Overall,
28 sonority projection effects are thought to demonstrate the existence of a formal phonological rule concerning
the SSP (e.g., Berent et al., 2007; Berent, 2017). Although some modeling studies have shown that these
30 effects can be predicted by lexicon statistics if the frequency of features in the lexicon (not only the frequency
of syllables or clusters) is taken into account (Hayes, 2011), it has been shown that speakers do not solely
32 rely on their lexicon-based knowledge but also use a set of constraints which are irrespective of the lexicon
(Hayes & White, 2013). Regarding the second question about the neurocognitive mechanisms which underlie
34 phonological constraints processing, few studies have been conducted. The present study therefore intended
to investigate this aspect.

We aimed at examining the interest of specific brain responses known as steady-state visual evoked
36 potentials (SSVEPs) to study the sensitivity of speakers to the SSP. SSVEPs rely on the periodicity of
stimuli presentation that drives the periodic electrophysiological responses of the brain. SSVEPs are obtained
38 using the fast-periodic visual stimulation (FPVS) paradigm coupled with electroencephalography (EEG)
recordings (Rossion et al., 2015). They are characterized by their temporal frequency that match the visual
40 stimuli stream flickering frequency and its harmonics (Regan, 1977; Norcia et al., 2015). Two substantial
advantages of the FPVS-EEG compared to the classical event-related potential (ERP) approach are: (1) the
42 high sensitivity, i.e., high signal-to-noise ratio, of the response that can be obtained within a few minutes;
44 (2) its objectivity, as the neural response is constrained to the specific known stimulation frequency.

Until recently, SSVEPs have mainly been used in studies on low-level visual perception. However, there is

¹Throughout the manuscript, we will use the term ‘non-word’ to refer to a sequence of letters or phonemes that does not constitute a word. We will not distinguish between non-words and pseudo-words (i.e., non-words which resemble real words) unless when indicated.

46 an increasing number of SSVEPs studies on higher-level functions such as face perception (e.g., Liu-Shuang
et al., 2014), quantity discrimination (e.g., Guillaume et al., 2018) and semantic categorization (e.g., Stothart
48 et al., 2017). Recently, SSVEPs are also investigated in research on lexical processing (e.g., Lochy et al.,
2015).

50 However, it is unclear whether these responses are sensitive to phonological processing. If so, an FPVS
approach coupled with EEG could be promising for investigating research questions related to phonological
52 constraints. In fact, an inherent drawback of the previous approaches is that they used behavioral tasks such
as the acceptability rating task (e.g., Daland et al., 2011; Basirat et al., 2021), which involve explicit stimuli
54 processing and decisional factors (e.g., participants hear or read non-words, rate them using a Likert scale,
and give their responses). Although the exact mechanistic account of SSVEPs remains to be determined,
56 these responses are implicit and less sensitive to such factors compared to responses collected using classical
approaches (Rossion et al., 2020). The objective of the present study was to investigate the sensitivity of
58 SSVEPs to phonological processing.

The number of SSVEP studies in language research has recently increased. Two main approaches have
60 been used. In some studies, flickering letter strings were presented to participants while the characteristics
of the stimuli were manipulated. For instance, Montani et al. (2019b) manipulated lexical frequency by
62 presenting participants with a series of high- and low-frequency words at a 18.75-Hz rate. The EEG analyses
performed in the frequency domain showed that the SSVEPs at 18.75 Hz were larger for high-frequency than
64 for low-frequency words. Another approach, used in the recent years, is the ‘oddball’ FPVS paradigm. In this
approach, a periodic ‘oddball’ stimulation sequence is presented: oddball stimuli are periodically scattered
66 among the base – regular, stimulus presentations. For instance, Lochy et al. (2015) presented participants
with written stimuli (e.g., ‘aacln’, ‘arbre’) at a periodic rhythm of 10 items per second, corresponding to a
68 10-Hz frequency rate. While the rare stimuli presented every five items were selected among a list of words
(e.g., ‘arbre’ in French, ‘tree’ in English), the base stimuli were selected from a list of items corresponding
70 to other categories, such as non-words (e.g., ‘aacln’). In this experimental design, words were therefore used
as oddballs and presented at a 2-Hz rate. The analyses of the elicited responses revealed SSVEPs at 10 Hz
72 corresponding to the base rate of visual stimulation. Crucially, specific responses were also observed at the
2-Hz oddball rate.

74 Although the exact mechanisms underlying SSVEPs at the oddball rate are not fully understood, it
has been suggested that oddball stimuli can lead to a brain response only if the specific properties which
76 differentiate oddballs from base stimuli are processed. Therefore, when two different categories of stimuli such

as non-words and words are presented as base and oddball stimuli, cortical *generalized* activities common to both categories are elicited at the base frequency, whereas the activities specific to the oddball stimuli are expected to appear at the oddball frequency (Norcia et al., 2015; Lochy & Schiltz, 2019). Therefore, unlike neural responses to base stimuli, oddball responses may be elicited by a differential activation of underlying neural networks.

To our knowledge, no oddball FPVS study to date has focused on the SSP. However, a few existing studies using ERP approaches provided valuable information. In an EEG study, Ulbrich et al. (2016) investigated the processing of phonological well-formedness (i.e., respecting or violating the SSP) in German during language processing. To do so, the authors manipulated the coda clusters of non-words with a CVCC structure. Participants performed a matching task between auditory presentation of non-words and pictures. In addition to phonological well-formedness, the authors manipulated the frequency of clusters in the lexicon using attested and unattested clusters. This helped investigate the potential interaction between these two dimensions. Two time-windows were analyzed: 450–500 ms and 700–1050 ms post-stimuli. The results showed distinct but interacting responses to phonological well-formedness (earlier responses) and lexical attestedness (later responses), suggesting that both dimensions play a role during language processing. Wiese et al. (2017) obtained similar results in Polish with the same experimental design. In a passive-listening EEG study in English, White & Chiu (2017) also observed distinct responses to the attestedness of CC onsets and their phonological well-formedness (i.e., respecting or violating the SSP). In line with the results of Ulbrich et al. (2016), these activities were observed in two time-windows: around 400 ms and 600 ms post-stimuli, corresponding to the processing of phonological well-formedness and lexical attestedness, respectively. Altogether, these results support the view that during online language processing, speakers rely on both formal phonological rules and statistical properties of the lexicon, with earlier responses reflecting pre-lexical phonological processing.

To our knowledge, the study of Montani et al. (2019a) is the only SSVEP study on syllable processing. In this study, participants were presented with French written words and asked to name them aloud when the words disappeared from the screen. Each word was split into two segments. While the first segment flickered at 18.75 Hz, the flickering frequency of the second segment was set at 25 Hz. Two experimental conditions were defined, depending on whether the first segment matched or did not match the word's first syllable (congruent and incongruent conditions, respectively). For instance, for the French word 'balade' (walk' in English) whose first syllable is 'ba', the flickering segments at 18.75 Hz and 25 Hz were respectively 'ba' and 'lade' in the congruent condition, while they were 'bal' and 'ade' in the incongruent condition.

108 Interestingly, the triggered SSVEP at 18.75 Hz was larger in the matched condition than in the unmatched
condition. As mentioned above, SSVEPs seem to be related to the synchronization of neural assemblies to
110 an external rhythm. According to the authors, the larger SSVEPs to syllables would reflect a more efficient
synchronization, which would suggest that syllables are important units in visual word recognition. Import-
112 tantly, this study did not manipulate syllable structures as the research question was related to the relevance
of syllables vs. bi/trigrams during written word processing and not specifically phonological processing.

114 In the current study, we investigated SSVEPs in response to syllable processing using an oddball FPVS
paradigm. We aimed at examining the responses to lexical attestedness and phonological well-formedness
116 with respect to the SSP by manipulating the onset of non-words. The first objective was to test the sen-
sitivity of SSVEPs to these dimensions. The second objective was to examine whether oddball responses
118 to phonological well-formedness would be dissociated from the response to lexical attestedness. To do so,
non-words were presented at a fixed 6-Hz base rate. Oddball stimuli, which were non-words with lexically-
120 unattested CC, were inserted every five standard items, which were non-words with lexically-attested and
sonority-rising CC onsets (see Figure 1). Two conditions were included in the study. In one condition, the
122 onsets of the oddballs were sonority-rising CC, while they were sonority-falling CC in the second condition.
Based on SSVEP literature, we expected responses at the base rate associated to the presentation of peri-
124 odic visual stimuli. These responses would not differ between conditions. Based on prior studies on syllable
frequency (e.g., Mahé et al., 2014), we hypothesized that oddball SSVEPs would be observed in response
126 to our lexical attestedness manipulation. In addition, if SSVEPs are sensitive to the SSP, distinct oddball
responses to the manipulation of well-formedness should also be observed.

128 **2. Material and Methods**

2.1. Participants

130 Twenty-two native French speakers (mean age: 23.4 years, SD = 2.6, 20 females) were included in
this study. Their mean number of years of education was 16.3 (SD = 2.4). All had self-reported normal
132 or corrected-to-normal vision without any hearing or language problems. Five additional individuals were
tested but excluded owing to a noisy EEG signal (three participants), excessive blinking (one participant)
134 or absence of the SSVEP at the base rate (one participant) (see section 2.4 for more details). Participants
were recruited among the corpus of the University of Lille’s students. No monetary compensation was given
136 for their participation. However, they were provided with credits for courses when asked. The study was

conducted in accordance with the tenets of the Declaration of Helsinki and approved by the local ethics
138 committee (N° 2017-8-S55). Before testing, all participants gave their written informed consent.

2.2. Stimuli

140 The stimuli were adapted from a behavioral study where the sensitivity of French speakers to both
lexical attestedness and phonological well-formedness (i.e., rising or falling sonority) was observed (Basirat
142 et al., 2021). The task was an acceptability judgment task during which speakers made judgments about
the acceptability of written non-words in French using a Likert scale.

144 In summary, the stimuli consisted in CCVC non-words generated by concatenating a CC onset with a
VC tail (e.g., dr + al \rightarrow dral) (see Appendix A). They differed in terms of syllable onsets, which were:
146 (1) frequent in French with rising sonority, such as ‘bl’; (2) unattested or very rare in French with rising
sonority, such as ‘kv’, or (3) unattested or very rare in French with falling sonority, such as ‘rb’. In terms
148 of the sonority profile of their onsets, non-words of the attested and well-formed (A-WF) list and those
of the unattested and well-formed (UA-WF) list were matched, while those of the UA-WF list and the
150 unattested and ill-formed (UA-IF) list were significantly different (i.e. sonority profile: A-WF = UA-WF >
UA-IF). In terms of lexical statistics (i.e., frequency of onsets in the lexicon and number of phonological
152 and orthographic neighbors of the stimuli), non-words of the A-WF list and those of UA-WF list were
significantly different, while those of the UA-WF and UA-IF lists were matched (i.e., lexical statistics: A-
154 WF > UA-WF = UA-IF). Each list contained 48 non-words (see the original study for details about stimuli
and methods).

156 For the purpose of the current study, all lists were checked for orthotactics, i.e., patterns of grapheme
combinations. To do so, all stimuli were broken down into bigrams. Their frequency rate, defined as the
158 frequency of a specific bigram/total frequency of bigrams in the database, were then extracted using Lexique
3 dataset and Open Lexicon (New et al., 2004; Pallier & New, 2019). The mean frequency rates of bigrams
160 were 0.54 (± 0.80), 0.44 (± 0.79) and 0.39 (± 0.70) for the A-WF, UA-WF and UA-IF lists, respectively.
The lists were not significantly different in terms of this index (A-WF vs. UA-WF, $t(98) = 0.61$; A-WF vs.
162 UA-IF: $t(109) = 1.02$, UA-WF vs. UA-IF: $t(113) = 0.35$). It is therefore unlikely that any response to the
oddballs would be due to orthotactic cues.

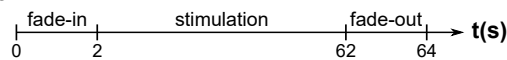
2.3. Procedure

Participants were seated in a dark lit room at a distance of about 1 m from the monitor (refresh rate:
166 60 Hz). Each trial consisted in a 60-s stimulation sequence surrounded by 2-s fade-in and fade-out periods

(Figure 1) to reduce eye blinks and to avoid abrupt stimulation onset and offset. Participants were asked to keep their gaze on the center of the screen. A small fixation diamond form was displayed in the center of the screen along with the presentation of CCVC items. The color of the diamond was blue but randomly changed to red six to eight times during each trial. In parallel to the visual stimulation, participants were asked to press a key on the keyboard when they detected the diamond color changes. Standard stimuli were frequent CCVC items with rising sonority onset. In the first condition, oddball stimuli were non-words with unattested CCVC and rising sonority CC (referred to as phonological well-formedness condition, WF). In the second condition, oddballs were those with falling sonority CC (referred to as phonological ill-formedness condition, IF). In both conditions, the stimulation sequence (Figure 1) was designed so that each single CCVS item appeared at a fixed base rate of 6 Hz (six stimuli during 1 s), with a sinusoidal contrast modulation of each item (0% to 100% to 0%) as in previous studies (Guillaume et al., 2018; Lochy et al., 2015). The contrast peaked six times per second, corresponding to the 6-Hz presentation rate. Stimuli were presented in a sequence pattern of four standard items followed by one ‘oddball’ (Figure 1). Oddball items were thus presented at a frequency of 1.2 Hz (= 6 Hz / 5). For each presentation sequence, stimuli were randomly selected among CCVCs of the corresponding type without immediate repetition. The stimuli were presented in grey against a black background using a MATLAB and Psychophysics Toolbox script adapted from Guillaume et al. (2018). The order of the two conditions was counterbalanced across participants, who completed four trials in one condition before starting four other trials in the next condition. Crucially, participants did not perform any task related to the linguistic stimuli.

Figure 1: Experimental design.

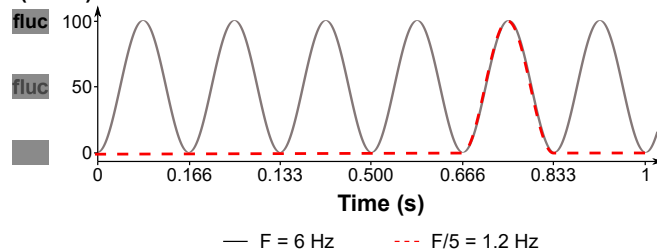
A. Trial timeline



B. Stimulation sequence

	Base	Base	Base	Base	Oddball	Base
Well-formed	fluc	tral	prine	fral	bnir	bluc
Ill-formed	bluc	bruse	dric	tral	lpic	gluc

Contrast (100%)



186 *2.4. Data Acquisition and Preprocessing*

EEG was recorded with an Active Two Biosemi system (Biosemi, Amsterdam, The Netherlands) using
188 a 64-channel system as in the International 10-20 standard. The sampling frequency was set at 1024 Hz and
all electrodes offset were held below 20mV. EEG recordings were synchronized with stimuli presentation
190 using markers sent via a parallel port.

EEG data preprocessing and frequency analysis were carried out using a combination of home-made
192 scripts and the Letswave6 toolbox (<https://github.com/NOCIONS/letswave6>) running on Matlab R2018b
(The MathWorks, Inc. Na-tick, MA, USA). Visual inspection was first performed on EEG raw data to
194 remove artefact-ridden or noisy channels, leading to the rejection of three subjects. No channel interpolation
was performed.

EEG data were first band-pass filtered (0.1–100 Hz) using a 3rd-order Butterworth filter. A 50-Hz notch
196 filter (4th-order Butterworth filter, [49 – 51] Hz) was then applied. After common averaging, data were
downsampled to 256 Hz to reduce processing time. Finally, EEG recordings were segmented in 60-s trials,
198 from 2 s after trial onset (just after the end of fade-in) until the beginning of fade-out. To reduce non-
stimulus-locked oscillations, and improve the signal-to-noise ratio (SNR), trials were then averaged in the
200 time domain for each condition and each individual (resulting in one epoch per subject and condition).
Finally, one participant was rejected as eye-blinking was excessive (Subject S5) (see Appendix C).
202

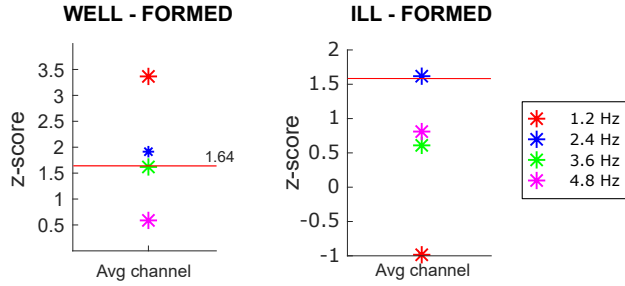
2.5. Frequency-Domain Analysis

Fast-Fourier Transform was applied to these averaged epochs for each subject and condition. Normalized
204 amplitudes were then extracted as the square root of the sum of squares of the real and imaginary parts
divided by the number of data points. The obtained spectra were then baseline-subtracted (*bsub*, Equation 1)
206 by subtracting from each frequency bin fft_i the mean amplitude of 20 neighbouring bins ($bsub_i$, 10 bins on
each side with the exclusion of the directly adjacent bins, and those with maximal and minimal amplitudes).
208

$$bsub_i = fft_i - \mu_{baseline_i} \tag{1}$$

Base and oddball responses were then extracted as the measure of the baseline-subtracted amplitude at
210 stimuli base frequency (6 Hz). Responses were visually checked to ensure the presence of a response at base
frequency on Oz. One subject (Subject S20) was rejected because this response was not present. It was also
212 absent in Subject S5 who had already been rejected owing to too many eye blinks (see section 2.4).

Figure 2: z -score of each harmonics for the average of all electrodes over all participants.



The selection of the relevant harmonics for oddball responses was performed with a z -score transform Z of the raw spectra amplitude (fft) averaged over all subject and electrodes, for each condition. The z -score was defined at each frequency bin, relatively to the mean and standard deviation of the surroundings 20 bins of the spectra amplitude, as for baseline subtraction.

$$Z_i = \frac{fft_i - \mu_{baseline_i}}{\sigma_{baseline_i}} \quad (2)$$

The relevant harmonics were selected using the methodology of Rossion et al. (2020): Harmonics were considered as significant if their z -score was greater than 1.64 (i.e., $p < 0.05$, one-tailed). Since the hypothesis for harmonics detection is that the signal is greater than the noise level, a one-tailed statistical test was used. In both conditions, at least one of the first three harmonics (1.2 Hz to 3.6 Hz, Figure 2) was significant at group level. Indeed, the periodic neural response is constrained not only to the 1.2 Hz frequency but also to its harmonics. Although the stimulation sequence may be considered as a perfect sinusoid, the non-linear neural mechanisms lead to a spread of the response through the harmonics (Norcia et al., 2015). Importantly, the oddball responses should thus be quantified by summing harmonic amplitudes instead of taking only the fundamental frequency or its largest harmonic. Although this could lead to the inclusion of harmonics which are not significant in all participants (see Figure 3 for the between-subjects variability), the quantification of the overall response is not affected by the inclusion of non-significant harmonics (Rossion et al., 2020).

Figure 3: Harmonics detection (z-score) for single subject and group average on average of all electrodes, for both conditions.

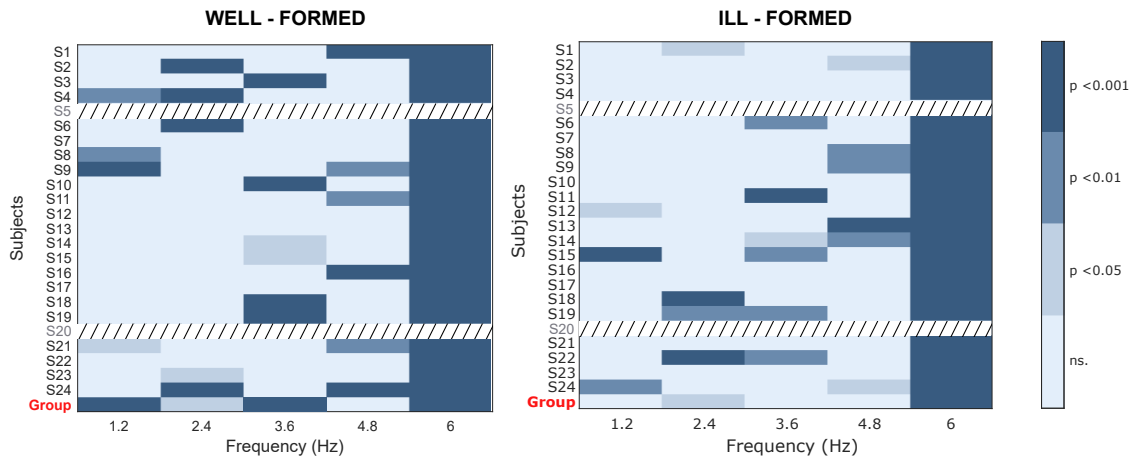
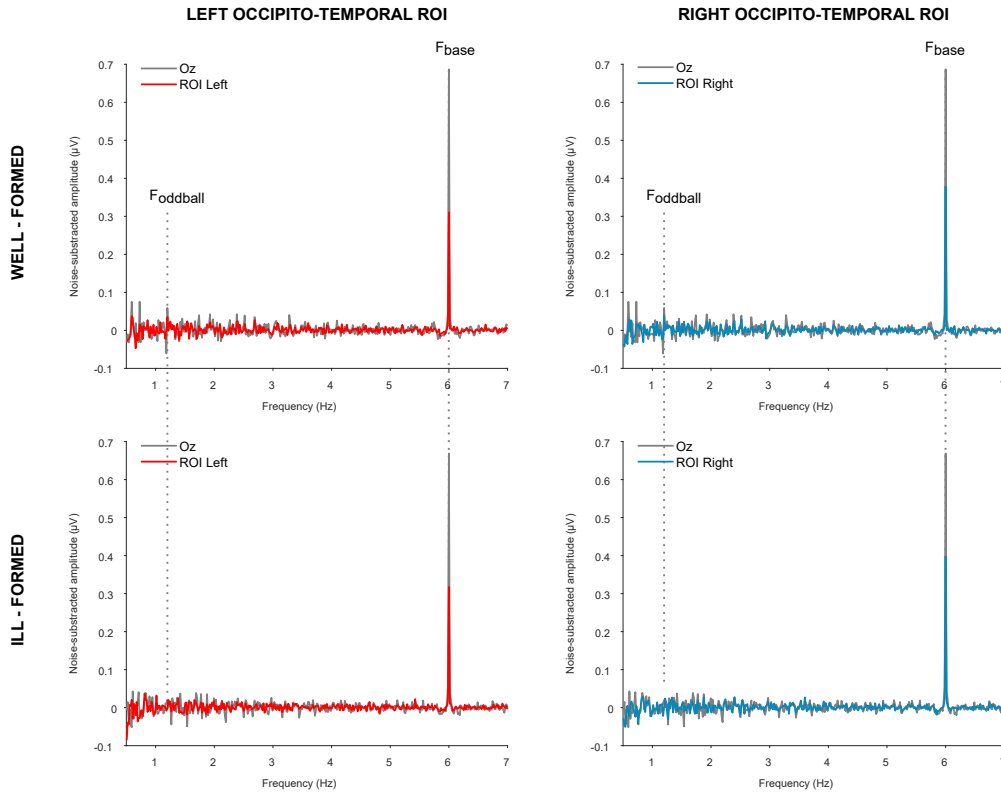


Figure 4: Frequencies distribution over both left and right occipito-temporal ROIs, in comparison to Oz.



228 Based on the literature on SSVEPs in the processing of words and non-words, the EEG signals recorded
 on the occipito-temporal area were expected to show maximal response to the oddball stimuli. The middle
 230 occipital electrode (Oz) was studied for the single-subject base-frequency response. Regarding base and
 oddball SSVEPs, single-subject responses were computed by averaging the baseline-subtracted amplitudes
 232 over each channel of two occipito-temporal region-of-interest (ROI OT Left: P3, P5, P7, P9, PO3, PO7 and

O1; ROI OT Right: P4, P6, P8, P10, PO4, PO8 and O2). In line with the harmonics detection method presented above, the responses at the first three harmonics were then summed to quantify oddball SSVEPs. Group responses over these three ROIs are given in Figure 4.

3. Results

In line with our frequency-domain analysis, further analyses reported in this section were performed on baseline-subtracted amplitudes. For base analyses, responses at 6 Hz and over the middle occipital electrode were investigated. For oddball analyses, the sum of the baseline-subtracted amplitudes of the first three harmonics were averaged over the left and right ROIs and analyzed. These values are hereafter called base and oddball responses, respectively.

Significant responses were found at exactly 6 Hz over the middle occipital electrode in both conditions (z -scores > 3.09 , $p < .001$). Mean responses are shown in Table 1 and Figure 5a. The difference between conditions was not significant: $t(21) = 0.37, p = .71$.

Table 1: Oddball and base responses baseline-subtracted amplitudes (μV). WF: well-formed condition; IF: ill-formed condition

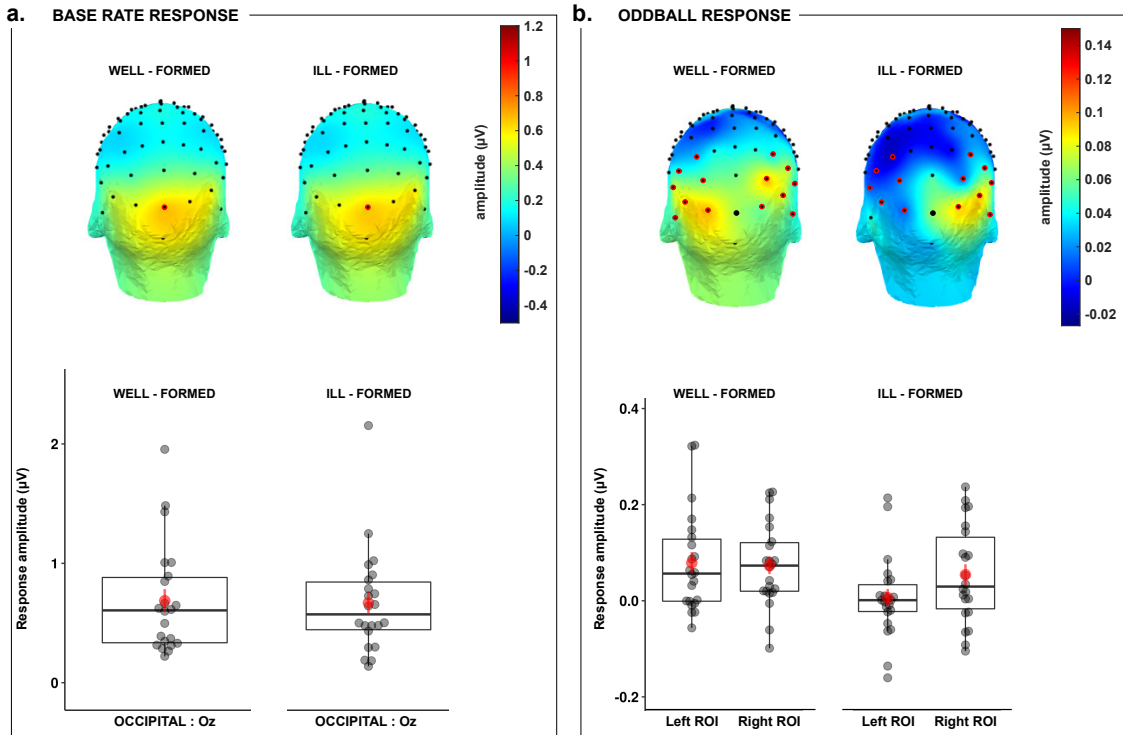
Condition	Oddball response		Base response		Oddball response	
	Left ROI		Oz		Right ROI	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
WF	0.08	0.11	0.69	0.46	0.07	0.09
IF	0.01	0.09	0.67	0.44	0.05	0.10

Oddball responses were significant at exactly 1.2 Hz and several harmonics at several electrodes over the occipito-temporal ROIs (z -scores > 1.64 , $p < .05$). Table 1 and Figure 5b show mean responses in the WF and IF conditions. A repeated-measure ANOVA was performed with condition and ROI as between-subject factors. The main effects were not significant (condition: $F[1,21] = 3.81, p = .06$; ROI: $F[1,21] = 1.55, p = .23$). The interaction between these two factors was significant: $F(1,21) = 4.94, p < .05$. Post-hoc analyses revealed no difference between conditions over the left ROI, $t(21) = 0.74, p = .47$, but a larger response in the WF condition over the right ROI, $t(21) = 2.77, p < .05$.

4. Discussion

In the current study, we used an FPVS approach coupled with EEG recording to study the processing of lexical attestedness and phonological well-formedness (with respect to the Sonority Sequencing Principle) of

Figure 5: Topography maps and response amplitudes for baseline-subtracted SSVEP at **a.** the 6-Hz base-rate and **b.** summed three first oddball harmonics (1.2, 2.4 and 3.6 Hz).



CC onsets in French. We used an oddball paradigm. Standard stimuli were non-words with lexically attested
 258 and sonority rising CC onsets. The oddball stimuli, which were presented after four standard stimuli, were
 non-words with lexically unattested CC onsets. The study examined the SSVEP to two types of oddball
 260 stimuli, those with sonority rising CC onsets (well-formed onsets, WF condition) and those with falling CC
 onsets (ill-formed onsets, IF condition).

262 In both conditions, we observed SSVEPs at the base frequency of visual stimuli presentations. Responses
 were maximal at the occipital Oz electrode. This is consistent with previous studies using the same type
 264 of oddball FPVS paradigm (e.g., Lochy et al., 2015; Guillaume et al., 2018). Importantly, the amplitude of
 these responses did not differ in the two conditions. This was expected as the base rate responses reflect
 266 low-level visual processing induced by the periodic presentation of the stimuli.

In both conditions, we observed SSVEPs at the oddball frequency and its harmonics, meaning that partic-
 268 ipants discriminated standard and oddball stimuli. This shows that SSVEPs are sensitive to the sublexical
 characteristics of the stimuli as both standard and oddballs were all non-words which differed in terms of
 270 their CC onsets. Oddball responses were recorded on the occipito-temporal electrodes. Responses on these
 sites were also reported in previous studies using FPVS paradigms with written stimuli in French (e.g.,

272 Lochy et al., 2015; Montani et al., 2019b). To our knowledge, our findings are the first to show that SSVEP
are also sensitive to sublexical characteristics of stimuli.

274 4.1. SSVEP to Lexical Attestedness

Oddball responses in the WF condition may reflect the processing of lexical attestedness as standard
276 and oddball stimuli in this condition differed in the frequency of their CC onsets and their phonological
and orthographic neighbors. Among these factors, we believe that the responses may not reflect processes
278 related to sole orthographic factors. Lochy et al. (2015) found that orthographic factors such as a bigram
frequency difference between standard and oddball stimuli is not sufficient to generate an oddball response.
280 In their FPVS study, Montani et al. (2019b) did not observe different responses between pseudo-words with
more orthographic neighbors and those with fewer orthographic neighbors (i.e., ‘familiar’ versus ‘unfamiliar’
282 pseudo-words) showing that SSVEPs are not sensitive to orthographic familiarity.

Although these results suggest that SSVEPs were not generated by orthographic factors alone in these
284 studies, it is possible that a larger difference between oddball and standard stimuli regarding these factors
leads to SSVEP. We thus compared our stimuli to those of Montani et al. (2019b) using OLD20 (Phonological
286 Levenshtein Distance 20) (Yarkoni et al., 2008). This measure indexes the mean number of operations
needed to transform one string of elements into a word in the lexicon (e.g., two operations are necessary
288 to transform non-word ‘dlur’ to ‘plus’, which is a real word in French). OLD20 considers the 20 closest
orthographic neighbors and reflects the familiarity of a given sequence to the words in the lexicon. The
290 calculation was done using the R package ‘vwr’ (Keuleers, 2013) and the Lexique 3 database (New et al.,
2004; Pallier & New, 2019). The results are presented in Appendix B. While the difference between our
292 A-WF stimuli and ‘familiar’ pseudo-words of Montani et al. (2019b)’s study was not significant, our UA-
WF and UA-IF stimuli were both more familiar than ‘unfamiliar’ pseudo-words used in Montani et al.
294 (2019b)’s study. Although the orthographic familiarity of the oddballs in our study was smaller than that
of unfamiliar pseudo-words used by Montani et al. (2019b), we observed SSVEPs. It is thus likely that the
296 oddball responses in our study reflect the processing of other sublexical characteristics than orthographic
familiarity.

298 Interestingly, several methodological differences between the two studies may explain the differences ob-
served in the results. For instance, we used a periodic oddball stimulation sequence while Montani et al.
300 (2019b) used flickering stimuli. Participants in our study did not perform any task related to language pro-
cessing while those in the study of Montani et al. (2019b) were engaged in a reading and naming aloud task.
302 In addition, the structure of our stimuli (all had CC onsets), was different from those used by Montani et al.

(2019b) and the phonological familiarity was not controlled for in their study. Overall, these considerations suggest that, among the various factors involved in lexical attestedness, the SSVEPs observed in the current study may reflect, at least partly, the involvement of phonological factors. This could be explained by models such as the Dual Route Cascaded (DRC) model (Coltheart et al., 2001), according to which non-words cannot activate whole-word forms but activate the sublexical route for grapheme-to-phoneme conversion. A distinct activation of this phonological mediated process by non-words with attested CC onsets compared to those with unattested CC onsets may trigger the SSVEPs observed in the WF condition.

4.2. *SSVEP to Phonological Well-Formedness*

In addition to the responses to lexical attestedness, we also observed SSVEP to oddballs in the IF condition, in which the latter were different from standard stimuli both in terms of lexical attestedness and sonority profile of their onsets. The main aim of including this condition was to investigate whether the processing of these two dimensions could be dissociated. The results show a significant difference between the WF and IF conditions. This suggests that the oddball responses in the IF condition was not due to lexical attestedness alone. This is consistent with behavioral findings on sonority projection effects showing that speakers are sensitive to both dimensions (e.g., Daland et al., 2011; Basirat et al., 2021; Parker, 2017, for a review).

A few studies have shown brain responses to phonological well-formedness with respect to the SSP. In an fMRI study in English, Deschamps et al. (2015) investigated brain responses to the presentation of non-words beginning with CC clusters that had different sonority rankings. The activity of the posterior part of the left inferior frontal gyrus was modulated by the sonority ranking of the CC onsets in the passive reading task. As mentioned in the introduction, few ERP studies have also shown that speakers rely on both SSP and statistical properties of the lexicon with earlier ERP responses, reflecting pre-lexical phonological processing related to the SSP processing (Ulbrich et al., 2016; White & Chiu, 2017; Wiese et al., 2017). The difference between the WF and IF conditions observed in this study is consistent with these findings.

Our results thus suggest that participants were sensitive to the sonority profile of CC onsets. Could the observed effects reflect other processes such as decisional factors and phonological repairs (e.g., ‘lbif’ → ‘lebif’, Berent et al. 2007)? Regarding decisional factors, it seems unlikely that the effect is due to these factors as the stimuli were presented using a FPVS paradigm without performing any explicit language-related task. Importantly, phonological repair may be present while processing phonologically ill-formed non-words (e.g., Di Liberto et al., 2019). Although usually reported for auditory stimuli, they may also be generated from visually presented letter sequences (Hallé et al., 2008). Repairs in the visual modality seem

334 to rely on covert articulation and fail to occur under articulatory suppression (Sun & Peperkamp, 2016).
In future studies, it would be interesting to examine to what extent phonological repairs may occur during
336 FPVS paradigms.

The SSVEP difference between conditions was observed in the scalp distribution: while the oddball
338 responses in both conditions were observed on the occipito-temporal electrodes, the topographic map for
the WF condition showed a wider distribution than in the IF condition. Could this different distribution
340 reflect the engagement of different neural networks for processing phonological well-formedness vs. lexical
attestedness? If the oddball responses reflect specific processes elicited by oddball stimuli after the common
342 processes related to standard stimuli presentation (e.g., Norcia et al., 2015; Lochy et al., 2015; Lochy &
Schiltz, 2019) (see introduction), it would be puzzling if the distribution was narrower in the IF condition.
344 While the difference between oddball and standard stimuli was observed only in the lexical attestedness
dimension in the WF condition, the oddball stimuli in the IF condition differed from the standard stimuli
346 in both lexical attestedness and phonological well-formedness. We would therefore expect wider oddball
responses in the IF than in the WF condition. The issue regarding the interpretation of oddball responses has
348 recently been highlighted by Wang et al. (2021). The authors suggest that oddball responses in such FPVS
studies may rather reflect ‘segregating deviant events out of well-controlled streams of stimuli, rather than
350 reflecting inherent unique processes elicited by deviant events after common processes elicited by the base
events are ‘subtracted’ via the assumption of pure insertion’ (p. 9). To identify various levels of processing of
352 linguistic materials, future research should examine the topographic differences between conditions in FPVS
studies more systematically. The application of spatial filtering techniques to SSVEPs seems promising to
354 identify functional sources with overlapping topographies and time courses (Wang et al., 2021).

4.3. Limitations of the current study

356 This study has several limitations. First, we examined the general group-level responses to the lexical
attestedness and phonological well-formedness manipulations. Even though significant differences between
358 the WF and IF conditions were found at the group level, further investigations should be performed to explain
inter-individual variability. Second, we focused on the SSP to investigate phonological well-formedness. It
360 is not clear whether the dissociation between the WF and IF conditions could be generalized to other
phonological constraints. Third, the oddball responses in our study were small in comparison with previous
362 studies on SSVEPs using words. Future research should compare the sensitivity of SSVEPs to sublexical
and lexical processing. This would be helpful to better understand the underlying computations revealed by
364 SSVEP to linguistic materials. Finally, although we found that the processing of lexical attestedness and

phonological well-formedness are clearly dissociable, any interpretation of topographic differences would be speculative. In future studies, the inclusion of other types of evidence such as data on source localization and temporal dynamics would be helpful to better interpret such differences.

4.4. *Are SSVEPs a robust tool for investigating language processing?*

Recently, SSVEPs have been considered to be a robust index of several types of cognitive processing at both group and individual levels. For instance, FPVS has been proven to induce rather stable and reproducible SSVEPs for face recognition (Rossion et al., 2020). Examining SSVEPs thus seems very relevant in clinical (e.g., Rossion et al., 2020) or developmental contexts (e.g. Lochy et al., 2016; Lochy & Schiltz, 2019). However, the reliability of SSVEPs has recently been challenged. Inter-individual variability has been found even in well-established group-level effects observed for face recognition (Stacchi et al., 2019). Regarding lexical processing, although some authors have demonstrated the possibility of using FPVS to investigate lexical representation (Lochy et al., 2015, 2016), reproducibility at group level was not achieved by Barnes et al. (2021) using the same methodology. As mentioned above, issues have been raised about the interpretation of the SSVEPs of cognitive functions including lexical processing (Wang et al., 2021). They underline the need for further investigation to fully understand SSVEPs in the context of cognitive processing. The FPVS approach combined with EEG was primarily introduced as 'a tool for studying sensory processes and low-level vision' (Norcia et al., 2015, p. 9).

Another focus for future studies on language processing could be the assessment of the impact of target language on SSVEPs. The studies of Lochy and colleagues (e.g., Lochy et al., 2015, 2016; Lochy & Schiltz, 2019) as well as ours were in French, while Barnes et al. (2021) and Wang et al. (2021) examined the English language. The linguistic properties of the stimuli and the structure of the target language could be factors leading to differences in results.

Apart from syllabification issues addressed by the SPP, which was the focus of the current study, it seems possible to investigate SSVEPs to study other phonological phenomena, such as vowel harmony. Vowel harmony occurs in a language when the vowels of a lexeme must share one or more properties, such as rounding or aperture (Archangeli & Pulleyblank, 2007); a well-known example of a language with vowel harmony is Turkish. Our experience could be adapted to vowel harmony as it occurs in a language like Finnish, whose writing is considered 'phonological'. In Finnish, roots can either integrate only posterior vowels, or only anterior vowels, or a combination of one element of these two sets with the two neutral vowels (Välilmaa-Blum, 1999). By constructing sequences that incorporate both legal and illegal vowel combinations, we could test to what extent vowel harmony is intuitive to speakers. On the other hand, FPVS does not

396 seem to be suitable for phenomena that are generally not transcribed in the graph, such as accentual or
intonational patterns, or assimilation phenomena that are observed in synchrony.

398 **5. Conclusion**

Using an oddball FPVS paradigm, we showed that SSVEPs are sensitive to sublexical features. SSVEPs
400 to non-words were modulated by the lexical attestedness and sonority profile of their onsets. We posit that
both effects reflect phonological processing. Our results extend previous behavioral and ERP findings by
402 showing that the processing of phonological well-formedness relies on mechanisms which could be dissociated
from those underlying the processing of statistical properties of the lexicon. Future studies should investigate
404 neural computations reflected in SSVEPs in response to these two dimensions. We believe that the SSVEP
approach is complementary to classical ERP approaches for studying neurocognitive mechanisms underlying
406 language processing, with advantages such as a high signal-to-noise ratio. However, recently raised issues
regarding the interpretation of SSVEPs need to be addressed and further investigated.

408 **Declaration of Competing Interests**

None.

410 **Acknowledgements**

We thank all participants. We are grateful to Marie-Paule Garravet, Laurent Ott, and Laetitia Zmuda
412 for their help in preparing the stimuli and/or collecting data. We also thank Aliette Lochy and Mathieu
Guillaume for the discussion and Ségolène M. R. Guérin for checking the format of the manuscript.

414 **CRedit author statement**

M. A. Vincent: Formal analysis, Visualization, Writing–Original draft preparation. **S. Vanstavel:** In-
416 vestigation, Methodology, Writing–Reviewing and Editing. **C. Patin:** Conceptualization, Writing –Review-
ing and Editing. **S. Méjias:** Conceptualization, Methodology, Writing–Reviewing and Editing. **A. Basirat:**
418 Conceptualization, Methodology, Formal analysis, Visualization, Writing–Original draft preparation, Project
administration.

420 **Appendix A. Stimuli onsets**

Attested and well-formed CC onset: pl, pr, tr, kl, kr, bl, br, dr, gl, gr, fl, fr, sl

422 Unattested and well-formed CC onset: pv, pm, tv, tm, tn, tl, kv, km, kn, bn, dm, dl, gm

Unattested and ill-formed CC onset: fk, ft, vg, vp, zt, ms, nd, lp, lk, ls, rt, rb, rf

424 Tails: ic, ive, ine, ir, uc, use, ule, ur, age, ane, al, ar

Appendix B. Familiarity of the non-words used in the study compared to those of Montani et al. (2019b) in terms of OLD20

A-WF stimuli versus ‘familiar’ pseudo-words: 1.73 vs. 1.83, $t(106) = -1.94$, $p = .06$

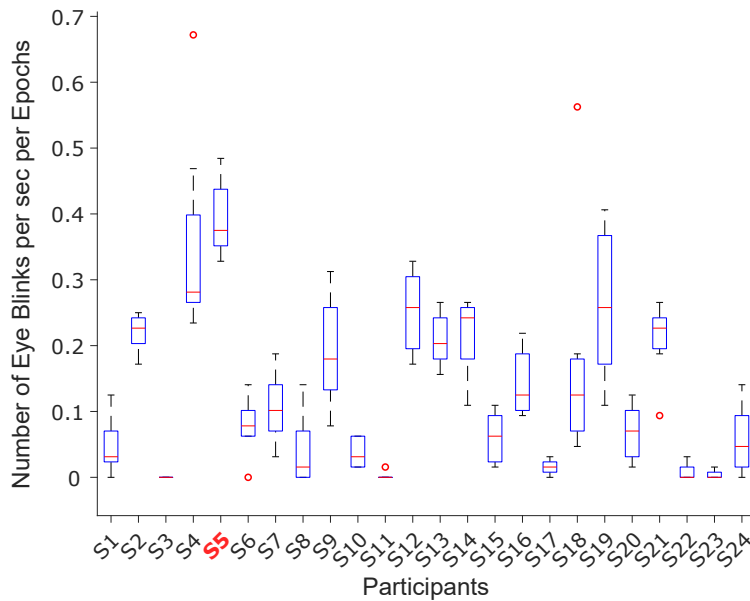
428 UA-WF versus ‘unfamiliar’ pseudo-words: 1.90 vs. 2.51, $t(106) = -9.67$, $p < .001$

UA-IF versus ‘unfamiliar’ pseudo-words: 1.90 vs. 2.51, $t(106) = -9.70$, $p < .001$

430 **Appendix C. Detection of eye blinks**

The number of eye-blinks per epoch was checked for each participant. Participants with an average number of eye blinks/epoch/second exceeding the mean number of eye blinks/epoch/sec ± 2 SD over all subjects were rejected. Only one subject (S5) was rejected on this basis.

Figure C.6: Eye blinks detection.



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512 Group Subject_term: Neuroscience; Psychology Subject_term_id: neuroscience;psychology.

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