How voicing, place and manner of articulation differently modulate event-related potentials associated with response inhibition.

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Abstract

The experimental investigation of response inhibition and the neuropsychological assessment of impulsivity are classically conducted with Go/Nogo tasks, where the participant presses a key for standard (Go) stimuli and withholds the response for deviant (Nogo) ones. However, auditory Go/Nogo tasks frequently fail to elicit the typical ERP correlates of response inhibition (N2, P3). We elaborated an auditory Go/Nogo experiment with speech stimuli (VCV) and sufficient difficulty level (Go and Nogo stimuli differed by one phonetic feature only) to strongly involve response inhibition. An N2 wave – the earlier correlate of inhibition – was recorded in 15 healthy adults. This result encourages the use of auditory Go/Nogo tasks to assess impulsivity, which results in decreased N2 amplitude. Additionally, a substantial P3 was observed as a secondary correlate of inhibition. Its amplitude was clearly modulated by the perceptual salience of the phonetic difference: P3 was highest for manner of articulation, then voicing, and it was smallest for place differences. ERP indices of the right-hemisphere involvement in voicing processing are also reported. This auditory Go/Nogo task therefore appears useful as a clinical tool for impulsivity assessment and an experimental way to address phonetic issues.

Index Terms: phonetic features, ERP, inhibition

1. Introduction

Impulsive symptoms are frequent in neuropsychological, neurological, and psychiatric disorders (e.g., Attention Deficit Hyperactivity (ADHD), brain injury, obsessive-compulsive disorder, chronic substance abuse, etc.). They are due to deficits of the executive control system – more precisely to impaired inhibition – and affect everyday functioning and quality of life [1]. Therefore, the development of refined tools to assess impulsivity, or its decrease after medical treatment, is required. The Go/Nogo paradigm can be used to evaluate the ability to withhold motor responses to rare deviant stimuli (Nogo condition) in a series of standard stimuli (Go condition) for which participants are asked to press a button. Provided that deviant stimuli are rare and that fast responses are required, numerous false alarms (i.e., unwarranted responses in the Nogo condition) occur, which reflects impulsivity. Behavioral performance in Go/Nogo tasks is known to measure impulsivity deficit in children with AD/HD more efficiently than other neuropsychological tools such as Stroop tasks [2], but it misses subtle inhibition deficits [3].

Event-Related Potentials (ERPs) can provide helpful refined information on this covert process. ERPs are electroencephalographic changes time-locked to sensory, motor, or cognitive events. Cerebral activity related to response inhibition is reflected in the increased magnitude of two ERP components. Compared to the Go condition, the Nogo condition is characterized by 1) the enhancement of the N2 wave recorded on fronto-central sites 200-300 ms after stimulus onset, and 2) the P3 wave mostly recorded on centro-parietal sites 300-500 ms after stimulus onset and which may reflect a later stage of the inhibition process.

A relation has been reported between low N2 amplitude and inhibitory control weakening as revealed by poor behavioral performance in Go/Nogo tasks in healthy adults who made numerous false alarms [4], children with ADHD [5, 6], impulsive-violent offenders [7], in depression [8], and more subtle inhibition deficiency observed in addictive behaviors [9]. Regarding the P3, atypical low amplitude of the wave has also been reported in case of inhibition deficiency. Interestingly, such neurophysiological indices of inefficient inhibition of prepotent responses have been found in patients (ADHD children) whose behavioral data hardly showed any sign of impulsivity in Go/Nogo tasks [6, 10].

Auditory stimuli are sometimes useful to investigate response inhibition in psychiatric disorders [8], or in persons suffering from visual disabilities. Unfortunately, most studies employing auditory Go/Nogo tasks failed to find increased amplitude of N2 [11] or only observed very low N2s [4, 12, 13] for Nogo stimuli, which has led researchers to avoid auditory stimuli in the assessment of impulsivity. In contrast, some studies reported large ERP correlates of response inhibition in auditory Go/Nogo experiments [14, 15]. The examination of the material and design used in these studies clarify why some of them did find ERP markers of inhibition processes in this modality.

Firstly, one study [14] reported the typical N2 increase for Nogo stimuli when there was a great perceptual overlap between standard and deviant stimuli. This was in contrast with previous experiments, where auditory stimuli were easier to discriminate than visual stimuli. When the deviant-standard difference only involved place of articulation, the N2 amplitude was higher in the Nogo than in the Go condition, which was not the case when the difference involved both manner and place of articulation [14]. When two features differed, the tendency to activate the Go response in Nogo trials was probably not important enough for the non-response to require a true inhibitory process. In an experiment with pure tones at different pitches, a significant N2 Nogo effect was also observed only for the most similar tones (1000 Hz and 1100 Hz) but not for less similar ones (1000 Hz and 2000 Hz) [3]. It is therefore important to use auditory stimuli with appropriate perceptual overlap to assess impulsivity in auditory Go/Nogo tasks.

Secondly, the N2 component associated with Nogo auditory trials has been discovered to be characterized by both the classical fronto-central negativity and a concurring positivity recorded on inferior fronto-temporal sites [12].

Consequently, the negative wave observed in the 200-300 ms window may be obscured over fronto-central areas by the overlap of the emerging fronto-temporal positivity. By not using electrodes in the inferior frontal area, many studies probably mistook the absence of negative fronto-central negativity for a lack of N2 increase in Nogo trials. When the modulation of the fronto-temporal positivity was taken into account, ERP correlates of response inhibition have been found in auditory Go/Nogo experiments [8, 16].

Thirdly, earlier studies mainly focused on the N2. However, P3 enhancement in the Nogo condition has been reported in several auditory Go/Nogo experiments [3, 12-15]. They can be considered as informative indices of inhibitory processes, because their magnitude was modulated by difficulty only in the Nogo condition, which involves inhibition.

The current research aimed at designing a Go/nogo task involving speech stimuli which would be sensitive enough to record the typical enhancement of N2 and P3 in Nogo trials associated with response inhibition. We used natural speech because previous results using stimuli which differed by only one phonetic feature were encouraging [14]. However, since perceptual salience varies among phonetic features [17], our second motivation concerned potential differences in the perceptual impact of voicing, place, and manner of articulation on the ERP correlates of response inhibition.

Some models of phoneme identification in connected speech assume that the identification of articulator-free features (manner and sonorance) provides the basis for the subsequent discrimination of articulator-bound features (place and voicing), since they establish regions in the signal where acoustic evidence for the articulator-bound features can be found [18]. This is in accordance with an advantage for the discrimination of articulator-free over articulator-bound features observed in aphasic patients [19]. In a meta-linguistic task requiring adults and children to sort CV audio-visual syllables, manner also emerged as the most salient phonetic feature [20]. Manner of articulation is also assumed to be at the prominent level, as it defines the representation of a segment within a syllable [21]. The major impact of manner of articulation has been challenged by data from perception in noise showing greater importance of voicing, but this reversal may mainly reflect the robustness of voicing under noisy listening conditions [17]. Therefore, a greater enhancement of P3 – and perhaps N2 – in Nogo condition for deviant stimuli differing in manner rather than place or voicing was expected. The relative importance of voicing versus place is more equivocal. Discrimination tasks revealed higher sensitivity to place than to voicing, whereas metalinguistic tasks requiring to rate similarity of pairs of consonants found that voicing contributed equally [22] or more to judgment than did place [23]. By comparing the effects of voicing, place, and manner of articulation, we hope to discover which is best suited for investigating response inhibition. Moreover, to our knowledge, the relative weight of these features and their impact on high-level cognitive processes such as inhibition has yet to be studied

Besides, a specific difference between place and voicing effects on ERP correlates of response inhibition was expected in terms of functional hemispheric asymmetry. Various data from ERP studies [24, 25], performance of neurologically impaired patients [26-30], and performance of healthy participants in phoneme acquisition [31], and dichotic experiments [32], converge to suggest a greater involvement of the right hemisphere (RH) in the processing of voicing than other phonemic contrast. Consequently, the relative impact of voicing and place of articulation difference between standard and deviant stimuli in the current study was expected to differ between the right and the left hemispheres.

2. Experiment

2.1. Methods

2.1.1. Participants

Fifteen healthy participants (11 female; mean age = 23;1, SD = 6;2) participated in the study for payment (15 euros). All were native French speakers without hearing problems; 13 were right-handed and 2 were left-handed [33]. They gave written informed consent and were made aware before the experiment that they could withdraw at any time.

2.1.2. Stimuli and procedure

The experiment was performed with Presentation® software, (v. 14.9). Since ERP recording requires numerous trials, the participants received three blocks of 80 infrequent deviant stimuli pseudo-randomly interspersed between 320 standard stimuli (the high proportion of standards was designed to produce automatized responses). Each block was preceded by 8 practice trials. The Go condition was proposed in 80% of the trials and tested with the /yty/ sequence used as the standard stimulus. Regarding the Nogo condition (20% of the stimuli), /ydy/ was used as the deviant stimulus in one block to test the sensitivity to voicing, /ypy/was used in another block to test the sensitivity to place, and /ysy/ was used to test the sensitivity to manner of articulation in another block. Each deviant was represented by one sound file, while four different sound files were used as standards /yty/.

All stimuli were isolated citation-form VCV utterances spoken by a female native French talker and were matched for maximal amplitude. They were 320 ms long and always began with a 23 ms silent chunk before the first vowel. The burst of /yty/s, /ydy/ and /ypy/ occurred 144 to 153 ms after the beginning of the preceding vowel. In /ysy/, the frication associated to /s/ began 57 ms after the beginning of the first vowel. The inter-stimuli interval lasted 1680 ms. The stimuli were played through Beyerdynamic DT 770 Pro headphones at a comfortable listening level.

The participants were instructed to focus attention on the auditory stimuli and to rapidly and strongly press the response key with the index finger of the right hand only for the target /yty/. They had to withhold the response when the deviant stimulus was played (Nogo condition). The order of the three blocks was counterbalanced across participants according to a Latin-square Design. Two rests occurred within each block, 8 practice trials were played after each rest, and a longer rest was proposed between blocks.

2.1.3. Psychophysiological recording

EEG was continuously recorded from 32 scalp sites (Electro-Cap International, INC., according to the international 10-20 system) using the Biosemi EEG system (ActiView acquisition system - Version 5.36, (02-06-2006)) operating at a sampling rate of 512 Hz. Eye movements were monitored by recording horizontal and vertical electro-oculograms (hEOG and vEOG respectively). Electrode impedance was kept below 20 kΩ throughout the experiment. Data were analyzed with the ERPLAB module (v. 1.0.0.42) from the EEGLAB toolbox (v. 9.0.2.3.b) for Matlab (v. 7.0.9 (R2009b)). Evoked responses were band-pass filtered from 0.1 to 30 Hz. The EEG recording was triggered by the stimulus onset, and response epochs of 800 ms were averaged off-line separately for standard and deviant stimuli. Go stimuli occurring immediately after a Nogo stimulus as well as errors (false alarms and misses) were discarded. A 200 ms pre-trigger period was used as baseline. A level-sensitive (± 100 μV) artifact rejection was applied prior to the summing of trials. The signal was re-referenced to the mastoids. For each condition (i.e., voicing, place, and manner), the response epoch to the standard was subtracted from that to the deviant. The N2 and the P3 were quantified as the most negative and positive peaks, respectively, in the 200-280 ms and the 300-390 ms windows determined visually by plotting the average for all participants and for channels AF3, AF4, Fz, F3, F4, FC1, FC2, FC5, FC6, Cz, C3, C4, CP1, CP2, CP5, CP6, Pz, P3, P4, P7, P8, PO3, and PO4. The mean amplitude was measured for each participant.

2.1.4. Data analysis

Repeated-measures ANOVAs were conducted on behavioral responses with Feature (voicing, place, and manner) as the within-subject factor, on the log-transformed mean response latencies to the standard /yty/ trials (in the context of changes that are on the basis of voicing, place, or manner), and on the arc-sin transformed percentages of false alarms and misses.

To determine the presence of a significant N2, 3 two-tailed *t-tests* (one for each Feature condition) were performed comparing the mean amplitude of the difference between Nogo and Go responses in the 200-280 ms temporal window to a test value of zero (representing no significant difference between Go and Nogo waveforms) [3]. The degrees of freedom for all *t-tests* were 14.

Repeated-measures ANOVAs were carried out on mean ERP amplitudes with Feature (voicing, place, manner) and Position (anteriofrontal (AF3, AF4); frontal (Fz, F3, F4); frontocentral (FC1, FC2, FC5, FC6); central (Cz, C3, C4); centroparietal (CP1, CP2, CP5, CP6), parietal (Pz, P3, P4, P7, P8) and parietooccipital (PO3, PO4)), on the N2 and P3 mean amplitudes, separately. Artifact-free trials were averaged separately for Go and Nogo trials and separate ANOVAs were conducted for the Go condition, the Nogo condition, and the Go – Nogo difference. An additional ANOVA was carried out on ERPs from lateralized electrodes pooled over the centro-parietooccipital region (C3, C4, CP5, CP6, P3, P4, P7, P8, PO3, and PO4). Post-hoc Tukey tests were performed and partial eta-squared values were calculated for effect size.

2.2. Results

The effect of feature on the mean response time to Go stimuli did not reach significance, $F(2, 28) = 2.57$, $p = .0955$, $\eta^2 = .16$, despite the short latencies in the manner condition pointing towards the expected effect illustrated in Figure 1. Misses were very rare (mean = .72%, SD = .19), and false alarms occurred more frequently (mean = 15.11%, SD = 2.07) but did not differ with the feature difference, $F(2, 28) < 1$.

ERP data revealed a clearly visible N2 as a negative deflection peaking roughly 250 ms after stimulus onset in Figure 2. The N2 was significantly different from zero ($p < .0001$) for each of the three Feature conditions. *T-tests* calculated for seven positions along the sagittal axis and each Feature condition confirmed the presence of N2 in all cases with at least $p < .005$, except for the most posterior positions ($p < .04$ for N2 at parietal position for Manner, and a lack of significant N2 at parietooccipital position for Manner). This pattern of results is illustrated in Figure 2 and confirmed the typical frontocentral distribution of this ERP component [34]. Nevertheless, the mean amplitude of N2 was not significantly affected by the Feature which differed between the standard and the deviants, $F(2, 28) = 2.61$, $p = .0913$, $\eta^2 = .16$. However, as can be seen in Figure 3, the results are consistent with behavioral data, since the amplitude for Manner was greater than in Place and Voicing conditions. The Feature × Position interaction, $F(12, 168) = 9.42$, $p < .0001$, $\eta^2 = .16$, revealed that the expected N2 difference between the Manner and Place condition was significant at anteriofrontal ($p < .03$), frontal ($p < .02$), and frontocentral positions ($p < .006$) but not in more posterior positions.

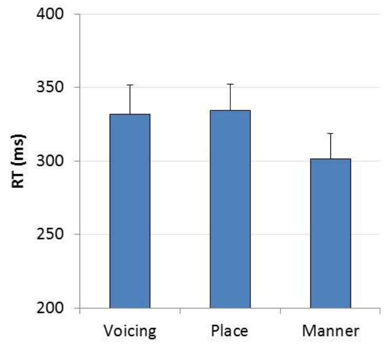

Figure 1: *Mean response times and standard errors in the Go condition as a function of phonetic feature.*

Regarding the amplitude of P3 as calculated from the difference between Go and Nogo conditions, the Feature effect was significant, $F(2, 28) = 19.12$, $p < .0001$, $\eta^2 = .58$, with a clear hierarchy showing greater amplitude in the case of a Manner difference than in case of a Voicing difference ($p < .0001$), and greater amplitude for a Voicing difference than for a Place difference ($p < .0001$). This seems to be mainly due to the impressive Feature effect observed in the Nogo condition, $F(2, 28) = 17.52$, $p < .0001$, $\eta^2 = .56$, where all the pairwise comparisons were significant ($p < .0001$). In the Go condition, the size of the Feature effect was less important, $F(2, 28) = 4.29$, $p = .0237$, $\eta^2 = .23$, and only due to higher amplitude in the Manner condition than in the Place ($p < .0001$) and the Voicing conditions ($p < .0235$), while the Voicing – Place difference did not reach significance.

When recorded from a pool of lateralized electrodes from central to parietooccipital sites, the Feature × Laterality interaction approached significance, $F(2, 28) = 3.31$, $p = .0512$, $\eta^2 = .19$. Post hoc analyses showed that the amplitude of the P3 tended to be higher in the Voicing than in the Place condition ($p <$. 0622) on the right hemisphere (RH), but not on the left hemisphere (LH) ($p = .1736$). After the two left-handed participants had been excluded from analysis, the effect size of the interaction increased, $F(2, 24) = 4.41$, $p = .0233$, $\eta^2 = .24$, due to the tendency towards a Voicing – Place difference on the RH ($p < .0606$) and the absence of a difference on the LH.

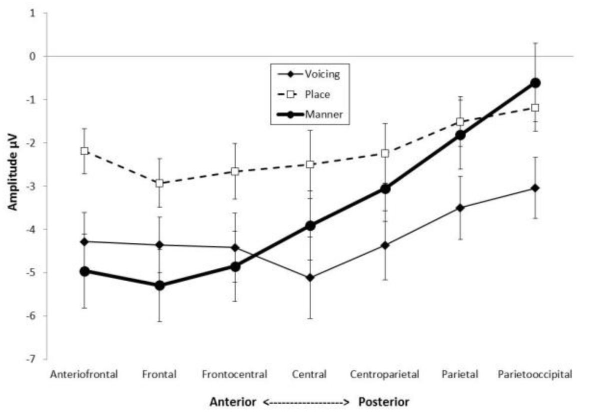

Figure 2: *Mean amplitude and standard error at 7 positions (from anterior to posterior) of the N2 (Nogo – Go difference) modulation in each Feature condition*.

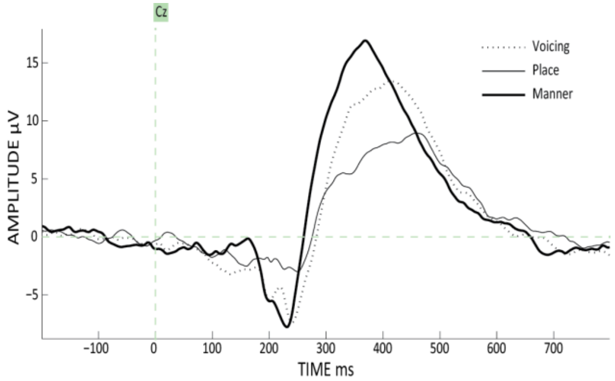

Figure 3: *Difference between mean amplitudes of ERP waveforms in Nogo (deviant) and Go (standard) conditions as a function of the phonetic feature.*

3. Discussion

The main purpose of this study was to demonstrate that auditory Go/Nogo tasks could be of great benefit in the assessment of the ERP correlates of inhibitory processes (N2 and P3), contrary to previous experiments where they were not [11] – or almost not [4, 12, 13] – observed. It also aimed at specifying what phonetic features should be manipulated in such tasks to optimize the chances of observing decent ERPs.

In auditory [14] as in visual [35] experiments using the Go/Nogo paradigm, the general difficulty must be high enough and the situation must require great effort to involve the response inhibition system and therefore cause increased amplitude of N2 in the Nogo condition. In experiments with natural speech stimuli, this appropriate level of difficulty can be reached by using deviant stimuli which differ from standard stimuli by only one phonetic feature [14]. The data reported in the current study replicated this effect by showing a significant N2 as a result of the negative wave in the Go condition subtracted from the negative wave in the Nogo condition in a 200-280 ms window. This result provided new evidence for the (currently debated) possibility to assess inhibition with an auditory Go/Nogo task.

Another electrophysiological correlate of response inhibition was observed in the current experiment. The P3 in the Nogo condition subtracted from the P3 in the Go condition resulted in an ample wave, which has been consistently found in association with successful response inhibition in auditory Go/Nogo tasks [6, 10] and in the auditory Stop-Signal task - another task assessing impulsivity with sound processing [36].

The interpretation of the P3 difference between Go and Nogo conditions is a matter of debate. According to Kiefer et al. (1998) [12], this difference is not the mere result of the lack of movement-related negative potentials in the Nogo condition, as suggested in [37], but it is genuinely associated with the process of response inhibition. They indeed showed that increasing the difficulty of inhibitory processes by using very small perceptual differences between deviant and standard tones decreased the P3 amplitude for Nogo but not Go trials. We replicated this pattern of results in the current experiment where the type of feature effect was clearly greater in the Nogo condition than in the Go condition. These results converged to show that the P3 is associated with response inhibition. They also point out that the difference in perceptual salience between phonetic features must be taken into account when assessing impulsivity with auditory Go/Nogo tasks.

P3 has been shown to be sensitive to Alzheimer's disease during its early stages, with a longer peak latency and lower amplitude than in controls, provided that relatively easy experimental conditions were used [38]. The authors claimed that easy perception tasks were the clinically most useful. As difference in manner of articulation yielded the greatest P3 amplitude in the current study, we suggest that neuropsychologists and experimenters interested in the ERP correlates of impulsivity should use deviant and standard stimuli differing in manner rather than other phonetic features in Go/Nogo tasks.

Finally, the results provided new evidence for differences in the perceptual saliency of various phonetic features. Taken together, the data showed that among voiceless consonants, manner was easier to detect than place. Voicing had an intermediate status. This hierarchy is in line with the results of [23], whose similarity rating data showed that manner was the most important auditory dimension, followed by voicing and then place of articulation. Complementary ERP experiments investigating voicing difference effects with voiced standard and voiceless deviant stimuli, and assessing the impact of manner and place of articulation among voiced consonants are in progress. Finally, we observed the expected difference in hemispheric asymmetry for voicing and place processing, with greater P3 amplitude for voicing only in the RH, which is the electrophysiological signature of the greater involvement of this hemisphere in voicing processing [24-32].

4. Conclusions

ERP data appear to be useful in studying response inhibition, and provided that the appropriate difficulty level is used, ERP correlates of impulsivity can be assessed with auditory Go/Nogo tasks. Such subtle measures of slight inhibitory deficiencies are of interest, for instance to optimize the diagnostic of high-risk patients among the relatives of obsessive compulsive disorder and ADHD patients or in symptom-free youths at familial risk for bipolar disorder [39] who may require some form of clinical support [1]. In addition, this experimental paradigm is promising for the investigation of phonetic issues.

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