ACTA NEUROBIOLOGIÆ EXPERIMENTALIS

Omitted Stimulus Potential depends on the sensory modality

Oscar Hernando Hernández[1,2]*, Karla María Hernández-Sánchez[3]

[1] *Centro de Investigaciones Biomédicas, Universidad Autónoma de Campeche, Colonia Buenavista, San Francisco de Campeche, Campeche, México*, [2] *Hospital General de Especialidades "Dr. Javier Buenfil Osorio", San Francisco de Campeche, Campeche, México*, [3] *Facultad de Medicina, Universidad Autónoma de Campeche, Colonia Buenavista, San Francisco de Campeche, Campeche, México*, *Email: ohhernan@uacam.mx*

Determining the characteristics of Omitted Stimulus Potential (OSP) parameters using different sensory modalities is important because they reflect timing processes and have a substantial influence on time perception. At the same time, the central mechanisms of time perception associated with sensory processing can modulate cortical brain waves related to cognition. This experiment tested the relationship between parameters of the whole OSP brain wave when trains of auditory, visual or somatosensory stimuli were applied. Twenty healthy young college volunteers completed within-subjects trials with sensory stimuli at a fixed frequency of 0.5 Hz that ceased unpredictably. These passive trials required no behavioural response and were administered to measure the complete set of OSP (i.e., the rate of rise, amplitude and peak latency). OSPs showed a faster rate of rise for auditory stimuli compared to visual or somatosensory stimuli. Auditory stimuli also produced a shorter time to peak and higher amplitude waves. No significant differences were obtained between visual and somatosensory waves. The results suggest that the brain handles interval timing and expectation with greater efficiency for the auditory system compared to other sensory modalities. This auditory supremacy is congruent with previous behavioural studies using missing stimulus tasks and could be useful for clinical purposes, for example, designing auditory-based brain-computer interfaces for patients with motor disabilities and visual impairment. The rate of rise is a dynamic measure that should be included in the ERPs analysis.

Key words: cognitive, OSP, auditory, visual, somatosensory

INTRODUCTION

The omitted stimulus potential (OSP) is a special form of event-related potential that is associated with cognition in humans and is considered to represent an objective sign of moderately high-level brain processing (Decker and Weber 1976, Bullock et al. 1994, Hughes et al. 2001; Wu et al. 2016). The OSP appears to reflect an "expectation", because it occurs after a train of stimuli ceases and it has a time-locked occurrence when it is measured from the expected time for the first missing stimulus (Sutton et al.1965, Sutton et al. 1967, Karamürsel and Bullock 2000, Janata 2001, Jongsma et al. 2004, Jongsma et al. 2005, 2006). It has also been suggested that the OSP may be sensitive to uncertainty and might be delayed until the uncertainty is resolved (Sutton et al. 1965, 1967). The OSP appears after slow trains (0.3–1 Hz) of stimuli and has a slow time course and long duration with a positive peak approximately 400–1100 ms after the due time of the first omitted stimulus (Simson et al. 1976, Stapleton et al. 1987, Hamon et al. 1989, Bullock et al. 1994, Tarkka and Stokic 1998, Karamürsel and Bullock 2000, Jongsma et al. 2004, 2005, 2006, Nakano et al. 2014). The OSP is totally attention-dependent and belongs to the "slow" type seen in humans and other vertebrates (Bullock et al. 1994, Takasaka 1985, Bullock et al.1994, Jongsma et al. 2004). For extensive literature on human OSP, see Bullock et al. (1994) and Karamürsel and Bullock (2000).

The omitted stimulus task has also provided an opportunity to measure behaviour in the form of a stop reaction time task (Penny 2004). Hernández et al. (2005) fractionated reaction times into independent pre-motor (cognitive) and motor components. When this task was applied to test three sensory modalities, the results showed that the cognitive fraction was faster for auditory stimuli compared to visual or somatosensory stimuli, whereas the motor fraction was not affected by sensory modality (Hernández et al. 2005, Rousseau and Rousseau 1996). A study examined the relationship between the duration of cognitive processes measured by

*Correspondence should be addressed to OH. Hernández
Email: ohhernan@uacam.mx*

pre-motor reaction time (PMRT) to a missing stimulus and some aspects of the positive OSP in active trials, where the behaviour introduces artefacts in the EEG recording (Hernández and Vogel-Sprott, 2008). As a consequence, the only components of the brain wave that could be obtained were the onset of OSP from the due time of the first missing stimulus, and the delay time (called OSPd) between the OSP onset and the initiation of the muscle action, recorded as an electromyogram (EMG). The OSPd was strongly associated with a PMRT under 0.5 and 7 Hz of auditory stimulus. When this correlation was tested using three sensory stimuli, PMRT and the OSPd were shorter for auditory stimuli compared to visual or somatosensory stimuli (Hernández and Vogel-Sprott 2010a). Similar results were reported by Penny (2004) when comparing stop reaction times for applying visual and auditory stimuli to frequencies of 1.3 or 2.1 Hz. Most importantly, PMRT in each sensory modality predicted the delay between the OSP onset and muscle activation. Hernández and Vogel-Sprott (2009) also showed that a faster rate of rise in the entire OSP wave was associated with faster PMRT using auditory stimuli in passive and active trials.

It is clear that a better understanding of the mechanisms of high level sensory processing will improve our knowledge of the way that the brain analyses the changes in a train of different sensory stimuli. In particular, experimental paradigms that provide cognitive electrophysiological responses (OSP) associated with behavioural responses (PMRTs) would be very valuable for studying and understanding the neural and cognitive substrates related to the processing of time intervals (Penney et al. 2000, Penney 2004). In this sense, OSPd is correlated with PMRT and both show faster velocities with auditory stimuli. The auditory OSP rise rate is also correlated to PMRT, but it has not been tested with other sensory modalities. We believe that if some common processes are involved in the generation of these measures, the OSP rise rate for auditory stimuli should be faster for visual or somatosensory stimuli. The rise rate parameter, although less studied than the latency and amplitude measures, can provide additional information because it informs the speed of recruitment of activated nerve fibres at the cortical level (Hernández et al. 2014).

To study the characteristics of OSP parameters using different sensory modalities in a within-subject design is important because they reflect timing processes and have a great influence on time perception (Penney 2004, Droit-Volet et al. 2007). Then, central mechanisms of time perception associated with sensory processing could modulate cortical brain waves related to cognition. This is very useful information for the construction of hybrid brain-computer interfaces

(BCI) that use OSP and are being built to help patients with chronic disabling diseases such as motor paralysis or amyotrophic lateral sclerosis (Wu et al. 2016, Erlbeck et al. 2017).

In the present study, we recorded a complete set of parameters (i.e., rate of rise, amplitude and peak latency) of the entire OSP wave for the first time to study the relationships between parameters and compare them to the results obtained with auditory, visual or somatosensory stimuli. Specifically, we tested the hypothesis that faster OSP rise rate will be obtained when auditory *vs.* visual or somatosensory stimuli are applied in healthy college student volunteers.

METHODS

Participants

Twenty right-handed Hispanic college student volunteers with a mean (*SD*) age of 23.7 years (2.3) participated in the study. Half were women with self-declared regular menstrual cycles and were tested during days 2–4 of the cycle to avoid hormonal effects. All the experimental procedures were explained before the subjects provided informed consent. The procedures were performed according to current ethical standards and were reviewed and approved by our University Ethics Committee.

Apparatus and Materials

Stimuli

The task consists of trials that present repeated sensory stimuli (auditory, somatosensory or visual) at 2 s intervals (i.e., 0.5 Hz) and cease unpredictably when the stimulus is omitted. A given trial presents a random number of three to eight stimuli before the stimulus is withheld and the trial ends. The trials were "passive" and no movement was required from the experimental subject (Hernández and Vogel-Sprott 2009).

Auditory clicks of 10 ms were generated through an electrical stimulator (Grass S48, Astro-Med, Inc., West Warwick, RI) and delivered to both ears through headphones. The auditory threshold was determined by increasing the click voltage until the subject reported its perception, and then the voltage was set at 20 times the threshold for the experiment. This intensity is equivalent to 50 ± 1.8 decibels. A pattern generator (Grass mod. 10VPG) presented the visual stimuli as a black and white checkerboard on a monitor. The electrical stimulator (Grass S48) released a pulse that reversed the

black and white squares. The visual angle of the arc was 10.3° with a luminance of 17 candelas per square metre (cd/m²) and a contrast of 90%. The electrical stimulator also released the somatosensory stimuli through an isolated unit (Grass SIU5) to activate two disc electrodes placed on the anterior surface of the left wrist. The 5 ms electrical stimulus was painless and set at 1.2 times the participant's detection threshold.

Recordings

The trials presenting each sensory stimulus were presented consecutively and in separate blocks counterbalanced across subjects. Each stimulus generated clear changes in the voltage of the brainwaves related to baseline that were collected on-line using a computer fitted with an AD/DA converter (MP100 System, BIOPAC Inc., 2003, Santa Barbara, CA, USA), and the waves were analysed using AcqKnowledge software (v. 3.7.3). The EEG data were obtained with surface disk electrodes (Grass F-E5H). Following the procedure adopted in other research (Karamürsel and Bullock 2000), the active electrode was placed according to the international 10/20 system at the Cz location with an impedance <5 kΩ. The reference electrode was on the left ear and ground electrodes were placed on both ears. Eye blink artefacts were controlled by bilateral EOG recordings from a pair of surface electrodes attached to the external side of each eye. The bioelectrical signals were amplified via AC amplifiers (Grass P511) with a 60 Hz notch filter, and the output was sent through steep analogue bandpass filters set at 0.3-100 Hz for the EEG and 1-1000 Hz for the EOG. The signals were digitized at 1000 Hz and collected on-line on an IBM-compatible computer through the MP100 System.

The task consisted of 32 consecutive passive trials in which the participant simply listened to detect a missing stimulus. The order in which the three sensory modalities were tested was counterbalanced over all 20 subjects. The EEG records from the trials were averaged off-line. Sweeps containing movement or eye blink artefacts were not included. A steep digital low pass filter at 5 Hz removed alpha or higher frequency components. The OSP recordings were inspected from the last stimulus to beyond the due time of the missing stimulus (Karamürsel and Bullock 2000).

The parameters of the OSP were separately averaged and analysed. Amplitude refers to the total increase in microvolts (μV) from onset until the peak is reached. The onset point was identified by an abrupt vertical shift in the voltage line of at least 1 μV of the slow positive OSP. The rise rate is the regression coefficient that describes the μV per unit change in ms from onset to the peak of an OSP wave. The peak latency for the OSP was measured by the total time (ms) from the due time of the first missing stimulus until the peak of the wave was reached.

Procedure

Participants received an explanation of the task before the electrodes were attached and the sensory thresholds were determined. They were familiarized with each of the sensory stimuli and the test by performing five practice trials. The participants were seated in front of a table and received identical task instructions for each sensory modality. Passive trials required the participant to simply wait for the occurrence of the missing stimulus. When the first set of 32 trials was completed, they were told that the second set of trials of another sensory modality would begin in 1-2 minutes. The same result occurred for the third set of 32 trials. To ensure that attention was maintained during the 96-trial test, participants were asked to count the number of stimuli presented during a trial and to report the number of stimuli after each trial. The report was requested approximately 4 sec after the occurrence of the last stimulus to ensure that participants performing the trials remained immobile and movement artefacts were eliminated during the recording of the whole OSP waves.

Data Analysis

The dependent variables that were measured included the rate of rise, amplitude, and peak latency of the OSP. The assumptions of normality and equal variance were tested using the Kolmogorov-Smirnov test and the Levene test, respectively. Stimulus modality effects of the OSP were tested using a 3-way (Stimulus modality) analysis of variance (ANOVA) for each dependent variable, and a Bonferroni *post-hoc test* was used to adjust the alpha level. Partial Eta-squared (η^2) provided the size effects in ANOVA. For each stimulus modality, separate linear regressions were used to test the relationship between the parameters of the OSP. A P value lower than 0.05 was considered to be significant. Overall, 1.6 % of the trials were lost to artefacts.

RESULTS

The *t*-test for independent samples showed no sex differences for any of the OSP parameters across sensory stimuli (*Ps*>0.088). The mean (*SD*) rise rate for males was 0.0129 (0.0034) μV/ms, and 0.0106 (0.0023) μV/ms

for females. The peak latency was 437.6 (119.7) ms for males and 489.8 (110) ms for females. The amplitude was 4.56 (1.1) μV for males and 5.08 (0.92) μV for females. The entire sample population was used for further analysis.

Fig. 1 illustrates the averaged waves from all participants for different task conditions (A). The change in voltage associated with the last three stimuli (long-lasting evoked potentials, LLEPs) and the missing stimulus (OSP) are seen in the recordings. They become clearer when the 20 recordings for each sensory modality were averaged to obtain average waves (B).

Fig. 2 shows a significant effect on the rise rate with $F_{2,38}$=8.12, P<0.001, η^2=0.299 when a 3-way (stimulus modality) repeated measures ANOVA for each variable was used. Paired comparisons with a Bonferroni test indicated that auditory responses were faster than visual responses (P<0.006). However, no differences were observed between auditory or visual and somatosensory responses (Ps>0.05). The ANOVA also showed the main effects for peak latency ($F_{2,38}$=3.51, P<0.040, η^2=0.156), and Bonferroni tests indicated that waves evoked by auditory stimuli reached their peak sooner than waves evoked by somatosensory stimuli (P<0.0026, 1-tailed). This effect was similar to the one that was expected based on the results of Hernández et al. (2016) or Hernández and Vogel-Sprott (2010a). No effects were observed between visual and auditory or somatosensory stimuli (Ps>0.302). Significant effects were also observed in amplitude measures ($F_{2,38}$=4.13, P<0.024, η^2=0.178) in which paired comparisons showed auditory stimuli yielded higher OSPs compared to visual stimuli (P<0.045), but not when compared to somatosensory stimuli (P>0.910). No differences were found between somatosensory and visual stimuli (P>0.144).

The possibility that the rate of rise in the OSP predicts its amplitude and its peak latency was tested by separate regressions for each of the two parameters for rise rate. The faster rise rate was associated with a higher amplitude OSP wave for auditory ($F_{1,19}$=7.01, P<0.016, *SlopeB*=0.186, *SE*=0.070) and somatosensory ($F_{1,19}$=5.05, P<0.037, *SlopeB*=0.189, *SE*=0.084) modalities. This relationship did not reach significance in the visual system (P>0.159), but the *B* value was also positive, which indicated a tendency towards the same association. The faster rise rate also predicts a shorter peak latency ($F_{1,19}$=11.77, P<0.003, *SlopeB*=-15.1, *SE*=4.40) for auditory but not for somatosensory (P>0.126) or visual (P>0.263) stimuli. The associations between amplitude and latency were not significant for any modality (P>0.190).

DISCUSSION

The major new finding of this study was that the rise rate, peak latency and amplitude of the entire OSP wave depend on the sensory modality of the stimulus. Auditory stimuli evoked faster and larger OSP waves compared to somatosensory or visual stimuli. The higher processing speed of auditory signals is consistent with previous studies on brain potentials and reaction times
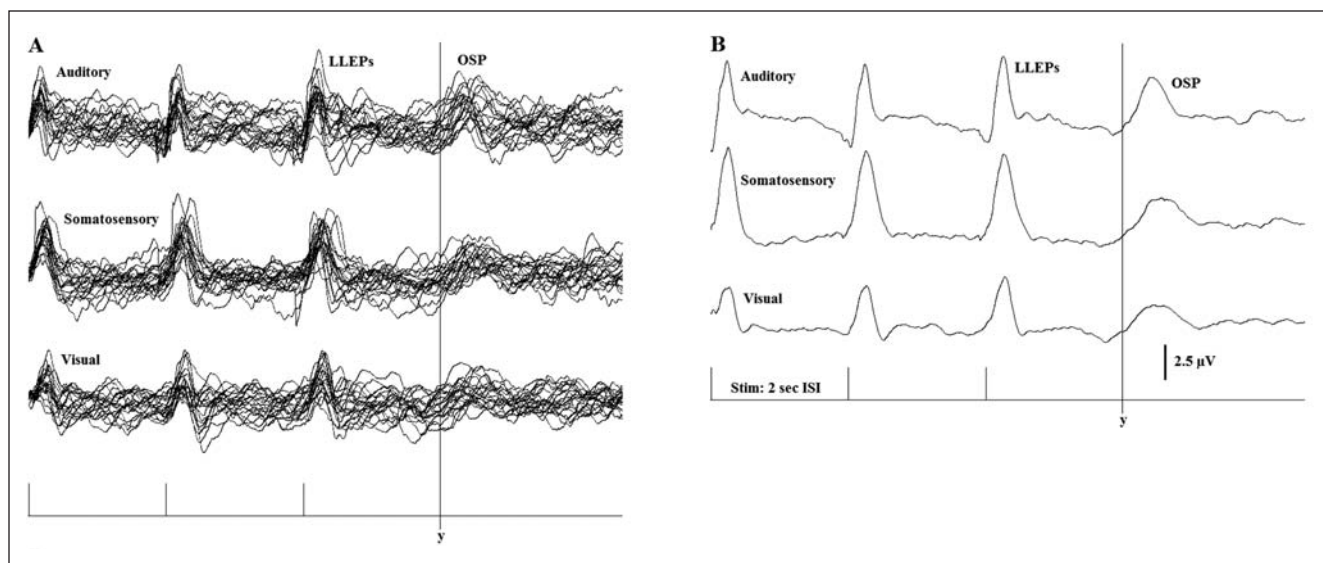

Fig. 1. Illustration of average recordings. A. Average waves from all participants for different task conditions. B. Grand average waves for each sensory modality. The horizontal axis represents the 2-sec ISI train of sensory stimuli. The traces are averaged EEG records that show each stimulus produces a corresponding long-lasting evoked potential (LLEP). The vertical lines at y are the due time of the first omitted stimulus at the end of the train, and then the omitted stimulus potentials (OSP) are observed.

in missing stimulus paradigms (Rousseau and Rousseau 1996, Penny 2004, Nittono 2005, Quian-Quiroga et al. 2007, Hernández and Vogel-Sprott 2009). The results also agree with a recent study that showed the rate of rise, the amplitude and the peak latency of the P200 wave depend on sensory modality and favours auditory stimuli (Hernández et al. 2015). Because of the strong association between PMRT and OSPd as well as the OSP rise rate in the auditory modality (Hernández and Vo-
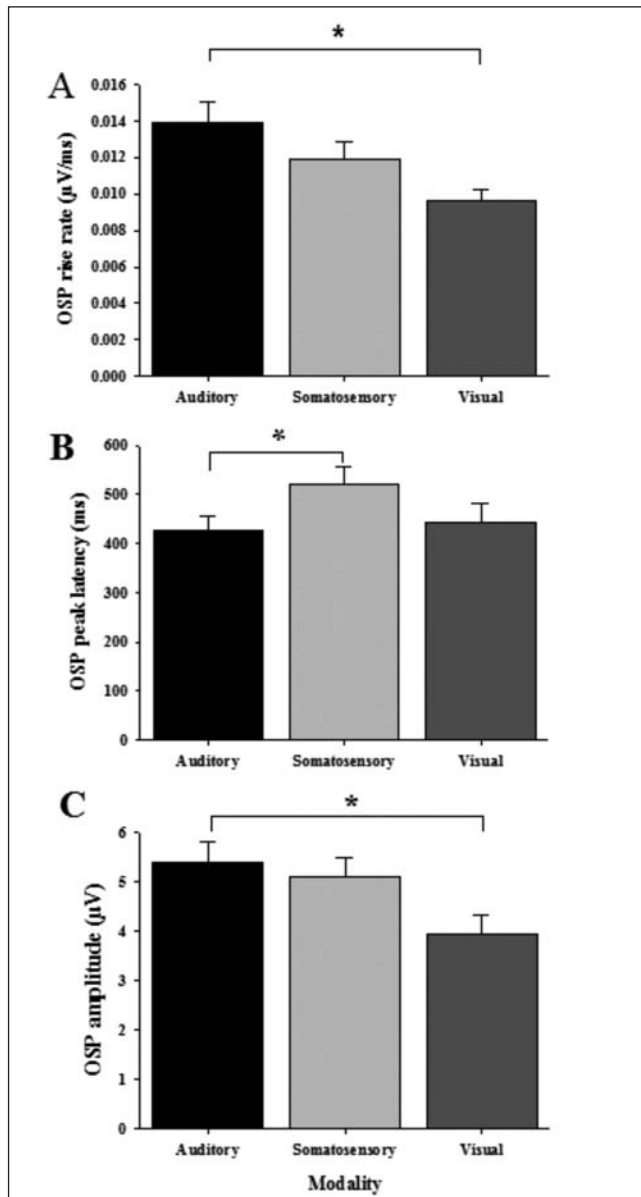

Fig. 2. OSP parameters in auditory, somatosensory and visual modalities. A. OSP rise rate was faster in auditory compared to the other two modalities, and the visual modality was the slowest, *P<0.006. B. The OSP peak latency was shorter with auditory compared to somatosensory stimuli, *P<0.0024, 1-tailed. Visual stimuli had non-significant effects. C. OSP amplitudes were larger with auditory stimuli compared to visual stimuli, *P<0.045. Vertical bars show the standard errors of the mean.

gel-Sprott 2009, 2010a), we expected that the rate of rise of the OSP would be faster in response to auditory stimuli compared to somatosensory or visual stimuli. Our results confirmed this hypothesis by suggesting that some common cognitive processes can participate in the generation of behaviour and cortical waves when a stimulus is missing. As shown in the auditory study (Hernández and Vogel-Sprott 2009), the rate of rise showed a main positive relationship with amplitude in OSPs in the three sensory systems.

Latency and amplitude are the most common measures used in cortical potentials, but it is not common to use the rate of rise. In this study, the rate of rise was added to peak latency and amplitude measures because this parameter provides a dynamic description of a wave (in µV/ms) and provides a better idea of the shape of the wave. Two waves can have the same amplitude but can differ in their rise rate and peak latency. Two waves can also differ in amplitude and peak latency while having the same rise rate or differ in their rate of rise and amplitude but have the same latency (see Fig. 6 in Hernández et al. 2014). Hernández and Vogel-Sprott (2010b) showed that acute alcohol can slow the OSP rise rate and latency but not its amplitude. Later, Hernández et al. (2014), who worked on the cognitive P200 wave, showed that the rate of rise resulted in more sensitivity to alcohol and more resistance to the habituation process compared to the latency and amplitude. The rate of rise was the only parameter modified by alcohol in the same fashion in both P200 and OSP. In diabetic patients, the rise rate of the P200 wave was more sensitive than the amplitude to HbA1c levels (Hernández et al. 2016). These data suggest that the rate of rise can provide additional information in addition to amplitude or latency measures, and it is a useful parameter that should be included in the analyses of averaged brain potential experiments. However, in the present study both the raise rate and amplitude showed the same modality effects.

The amplitude of the OSPs evoked by auditory stimuli was approximately 5-6 µV, which is consistent with previous reports (Penney 2004, Hernández and Vogel-Sprott 2009). As expected, the OSPs of the three modalities showed a slow time course with broad positive peaks approximately 250-700 ms (Nakano et al. 2014). These results also agree with previous studies (Jongsma et al. 2004, 2005, 2006) that showed the latency of the OSP is quite constant in the same subject but varies considerably between subjects (up to 1100 ms), which possibly occurs due to differences in the geometry of the striate convolutions (Bullock et al. 1994, Karamürsel and Bullock 2000, Busse and Woldorff 2003).

Because of the long-latency nature of OSP, these results cannot be explained simply by a shorter conduc-

tion distance from auditory receptors to cortical areas. Instead, afferent sensory volleys could be modulated by higher brain functions through complex feedback mechanisms (Prosser et al. 1981). It is clear that multisensory convergence volleys arrive at the superior colliculus and the dorsal posterior parietal cortices (Grasso et al. 2016). Single-cell recordings have also confirmed the presence of multimodal neurons with overlapping receptive fields for auditory, visual and tactile stimuli in the superior colliculus of monkeys and cats (Wallace et al. 1996, 1998). Currently though, it is unknown if such neurons participate in the modulation of cortical brain waves elicited by missing stimuli.

It is difficult to adjust the results obtained here to some conceptual model of time perception due to the great variety of experimental procedures used in previous research. The most widely developed model is an information-processing (IP) model (Church 1984, 1999, Droit-Volet et al. 2007) that implies the presence of an internal clock that runs faster with auditory signals compared to visual signals. This difference occurs because a greater number of pulses accumulate in the clock during the presentation of stimuli. However, our results do not fix the IP model because the model uses relatively long-lasting stimuli (with a duration of several seconds). In our study, each stimulus was very brief (<10 ms) and the ISI was very long (2000 ms).

The sensory modulation at higher brain levels opens the possibility of exploring the existence of sensory modality-specific neuronal generators, as recently suggested by Dreo et al. (2017) for the P3 wave. This result is interesting because it has been thought that the OSP wave could share some similar mechanisms to the P3 wave. The P3 is an ERP with a positive component characterized by a maximal parietal scalp distribution. It has a peak latency of 250-600 ms elicited mainly by an infrequent deviant stimulus (target) that is presented randomly within a stream of frequent, homogenous stimuli (standards) in oddball paradigms. For an extensive review of P3, see Polich (2007, 2013). The P3 and the OSP are considered to be endogenous potentials related to cognitive processes (attention, memory, stimulus evaluation, etc.). The latency and the amplitude of the P3 wave can vary depending on stimulus modality (Dreo et al. 2017). As with the OSP, the latency of P3 is shorter for the auditory conditions compared to the visual conditions. However, unlike the results observed here, the amplitude of P3 is greater for the visual conditions (Erlbeck et al. 2017). However, the most important difference between P3 and OSP may be that P3 requires an external physical event (infrequent single-stimulus, rare stimulus or distracter stimulus; Polich 2007) to be elicited, whereas the event that triggers the OSP is entirely internal (missing stimulus; Bullock et al. 1994).

Other cognitive brain potentials that precede events and therefore are related to expectation are Contingent Negative Variation (CNV) and Readiness Potential (RP) (Coles and Rugg 1995). To date, it is not known what relationship they could have with the OSP regarding its generating mechanisms. Although CNV and RP are ramp-like negative potentials involved in motor response preparation, we consider it is an issue worth investigating.

Different cognitive brain waves have been used recently to construct Brain Computed Interfaces (BCIs) used by patients with different chronic disabilities (spinal cord injuries, amyotrophic lateral sclerosis, etc.) to communicate with the environment (Erlbeck et al. 2017). Although most BCI studies use a visual modality and the P3 wave based on the oddball paradigm, hybrid BCIs that use OSP instead of P3 have been developed recently to achieve better BCI performance (Wu et al. 2016). Because BCI performance is influenced by physiological and psychological factors related to the generation of the brain waves, it is important to understand how the OSP parameters are modulated with different sensory stimuli. The advantage observed in the auditory OSP parameters can be useful for the development of faster interfaces using an auditory modality instead of a visual one, which is important to seriously ill patients who are not able to use vision-based communication devices (Nijboer et al. 2008).

The unique recording electrode at Cz was chosen instead of a high-density montage because OSP is maximal at this position in the 10-20 international system, which is independent of the sensory modality that is used (Bullock 1997, Karamürsel and Bullock 2000, Penney 2004, Jongsma et al. 2005, 2006). This position permitted us to compare the parameters of the OSP of the three sensory systems, although Cz is not the location of maximal sensory response for any of these modalities. Additional research with a scalp distribution could lead to a better characterization of the ERP components.

The OSP reflects a type of expectation that is quickly generated with each stimulus (Sutton et al.1965, 1967, Karamürsel and Bullock 2000, Janata 2001, Jongsma et al. 2004, 2005, 2006). It requires few conditioning stimuli but it is essential that subjects be focused because the OSP is not observed in inattentive or drowsy subjects (Takasaka 1985, Bullock et al. 1994, Jongsma et al. 2004). Therefore, the OSP is considered to be a fairly high level cognitive event that differs from ordinary OFF responses, which generally require longer conditioning trains (Karamürsel and Bullock 2000). The model proposed by Karamürsel and Bullock (2000) states that each stimulus causes both excitatory and inhibitory processes, but they behave differently because the inhibitory effect grows and the excitatory diminishes

with repetitive stimuli. Next, every stimulus provides a fresh dose of inhibition to prevent the OSP (Pretch and Bullock 1994, Ramon et al. 2012), which can be maintained for more than 2000ms and is rebound purely by endogenous mechanisms when the suppression is withdrawn because the stimulus is missing at the end of the train. The results of this research show that such rebound is sensory-dependent and is more efficient for auditory stimuli than for visual and somatosensory systems. This adaptive auditory system function in wildlife could provide vulnerable prey with critical time needed to escape predators.

In summary, we showed in this study that some parameters of the entire OSP wave depend on the sensory modality. The evoked waves with auditory stimuli have a higher rate of rise and greater amplitude compared to waves elicited by visual stimuli. The auditory-evoked OSP also has a lower peak latency than waves elicited by somatosensory stimuli. This information is useful for several reasons: 1) it increases our knowledge about the central multisensory modulation of the OSP; 2) it illustrates how the brain processes time intervals, time perception and expectation with various sensory modalities; 3) it supports the use of auditory OSP to build faster BCIs for clinical purposes; 4) it upholds the use of the rise rate parameter in the analysis of cognitive brain waves; and 5) it supports the proposal that common generators exist for behavioural (PMRT) and brain (OSP) processes and that both are obtained from missing stimulus tasks.

REFERENCES

Bullock TH, Karamürsel S, Achimowicz JZ, McClune MC, Başar-Eroglu C (1994) Dynamic properties of human visual evoked and omitted stimulus potentials. Electroencephalogr Clin Neurophysiol 91: 42–53.

Bullock TH (1997) Comparative physiology of acoustic and allied central analyzers. Acta Otolaryngol 532 (Suppl): 13–21.

Busse L, Woldorff MG (2003) The ERP omitted stimulus response to "no-stim" events and its implications for fast-rate event-related fMRI designs. NeuroImage 18: 856–864.

Church RM (1984) Properties of the internal clock. Ann NY Acad Sci 423: 566–582.

Church RM (1999) Evaluation of quantitative theories of timing. J Exp Anal Behav 71: 253–256.

Coles MGH, Rugg MD (1995) Event-related brain potentials: an introduction. In Rugg and Coles Eds. Electrophysiology of Mind: Event-Related Brain Potentials and Cognition. Oxford Psychology Series 25. Oxford University Press. pp. 1–26.

Decker TN, Weber BA (1976) The effects of subject listening state on potentials associated with missing auditory stimuli. J Aud Res 16: 177–181.

Dreo J, Attia D, Pirtošek Z, Repovš G (2017) The P3 cognitive ERP has at least some sensory modality-specific generators: Evidence from high-resolution EEG. Psychophysiol 54: 416–428.

Droit-Volet S, Meck WH, Penney TB (2007) Sensory modality and time perception in children and adults. Behav Proc 74: 244–250.

Erlbeck H, Mochty U, Kübler A, Real RGL (2017) Circadian course of the P300 ERP in patients with amyotrophic lateral sclerosis – implications for brain-computer interfaces (BCI). BMC Neurology. 17: 3.

Grasso PA, Benassi M, Làdavas E, Bertini C (2016) Audio-visual multisensory training enhances visual processing of motor stimuli in healthy participants: an electrophysiological study. Eur J Neurosci 44: 2748-2758.

Hamon JF, Gauthier P, Gottesmann C (1989) Influence of instructions in multi-discrimination experiments on event related potentials. Physiol Bohemoslov 38: 231–240.

Hernández OH, Vogel-Sprott M (2008) The Omitted Stimulus Potential is related to the cognitive component of reaction time. Int J Neurosci 118: 173–183.

Hernández OH, Vogel-Sprott M (2009) OSP parameters and the cognitive component of reaction time to a missing stimulus: Linking brain and behavior. Brain Cogn 71: 141–146.

Hernández OH, Vogel-Sprott M (2010a) Reaction time and brain waves in omitted stimulus tasks: a multisensory study. J Psychophysiol 24: 1–6.

Hernández OH, Vogel-Sprott M (2010b) Alcohol slows the brain potential associated with cognitive reaction time to an omitted stimulus. J Stud Alcohol Drugs 71: 268–277.

Hernández OH, Huchin-Ramirez TC, Vogel-Sprott M (2005) Behaviorally fractionated reaction time to an omitted stimulus: tests with visual, auditory and tactile stimuli. Percept Mot Skills 100: 1066–1080.

Hernández OH, García-Martínez R, Monteón V (2014) Alcohol effects on the P2 component of auditory evoked potentials. An Acad Bras Cienc 86: 437–449.

Hernández OH, García-Martínez R, Monteón V (2015) The relationship between parameters of long-latency brain evoked potentials in a multisensory design. Clin EEG Neurosci 47: 260–265.

Hernández OH, Aguirre-Manzo L, Ye-Ehuan F, García-Martínez R, Maldonado-Velázquez G (2016). P200 parameters in patients with diabetes mellitus type 2 (DM2). Gac Med Mex 152: 313–21.

Hughes HC, Darcey TM, Barkan HI, Williamson PD, Roberts DW, Aslin CH (2001) Responses of human auditory association cortex to the omission of an expected acoustic event. Neuroimage 13: 1073–1089.

Janata P (2001) Brain electrical activity evoked by mental formation of auditory expectations and images. Brain Topogr 13: 169–193.

Jongsma MLA, Eichele T, Quian-Quiroga R, Jenks KM, Dasain P, Honing H, Van Rijn CM (2005) Expectancy effects on omission evoked potentials in musicians and non-musicians. Psychophysiology 42: 191–201.

Jongsma MLA, Eichele T, Van Rijn CM, Coenen AML, Hugdahl K, Nordby H, Quian-Quiroga R (2006) Tracking pattern learning with single-trial event-related potentials. Clin Neurophysiol 117: 1957–1973.

Jongsma MLA, Quian-Quiroga R, Van Rijn CM (2004) Rhythmic training decreases latency-jitter of omission evoked potentials (OEPs) in humans. Neurosci Lett 355: 189–192.

Karamürsel S, Bullock TH (2000) Human auditory fast and slow omitted stimulus potential and steady-state responses. Int J Neurosci 100: 1–20.

Nakano H, Rosario MAM, Oshima-Takane Y, Pierce L, Tate SG (2014) Electrophysiological response to omitted stimulus in sentence processing Hiroko. Neuroreport 25: 1169–1174.

Nijboer F, Furdea A, Gunst I, Mellinger J, McFarland DJ, Birbaumer N, Kubler A (2008) An auditory brain-computer interface (BCI). J Neurosci Methods 167: 43–50.

Nittono H (2005) Missing-stimulus potentials associated with a disruption of human-computer interaction. Psychologia 48: 93–101.

Penney TB (2004) Electrophysiological correlates of interval timing in the Stop-Reaction-Time task. Cog Brain Res 21: 234-249.

Penney TB, Gibbon J, Meck WH (2000) Differential effects of auditory and visual signals on clock speed and temporal memory. J Exp Psych Human Percept Perform 26: 1770–1787.

Polich J (2007) Updating P300: An integrative theory of P3a and P3b. Clin Neurophysiol 118: 2128–2148.

Polich J (2013) Overview of P3a and P3b. In J Polich (Ed). Detection of change: Event-related potential and fMRI findings (pp. 83–98). Boston, MA: Springer US.

Pretch JC, Bullock TH (1994) Event-related potentials to omitted visual stimuli in a reptile. Electroencephalogr Clin Neurophysiol 91: 54–66.

Prosser S, Arslan E, Michelini S (1981) Habituation and rate effect in the auditory cortical potentials evoked by trains of stimuli. Arch Otorhinolaryngol 233: 179–187.

Quian-Quiroga R, Atienza M, Cantero JL, Jongsma MLA (2007) What we can learn from single-trial event-related potentials? Chaos and Complexity Letters. Hauppauge NY: Nova Science Publishers, Inc V.2 (2/3), p. 345-363.

Ramon F, Hernández-Falcón J, Bullock TH (2012) Brain electrical signals in unrestrained crayfish. In: Modern Approaches to the Study of Crustacea (Escobar-Briones E, Alvarez F, Ed.). Springer Science & Business Media, p. 10–13.

Rousseau L, Rousseau R (1996) Stop-reaction time and the internal clock. Percept Psychophysiol 58: 434–448.

Simson R, Vaughan HG, Ritter W (1976) The scalp topography of potentials associated with missing visual and auditory stimuli. Electroencephalogr Clin Neurophysiol 40: 33–42.

Stapleton JM, O'Reilly T, Halgren E (1987) Endogenous potentials evoked in simple cognitive tasks: scalp topography. Int J Neurosci 36: 75–87.

Sutton S, Braren M, Zubin J (1965) Evoked-potential correlates of stimulus uncertainty. Science 150: 1187–1188.

Sutton S, Tueting P, Zubin J, John ER (1967) Information delivery and the sensory evoked potential. Science 155: 1436–1439.

Takasaka Y (1985) Expectancy-related cerebral potentials associated with voluntary time estimation and omitted stimulus. Psychiatry Clin Neurosci 39: 167–172.

Tarkka IM, Stokic DS (1998) Source localization of P300 from oddball, single stimulus, and omitted-stimulus paradigms. Brain Topogr 11: 141–151.

Wallace MT, Wilkinson LK, Stein BE (1996) Representation and integration of multiple sensory inputs in primate superior colliculus. J Neurophysiol 76: 1246–1266.

Wallace MT, Meredith MA, Stein BE (1998) Multisensory integration in the superior colliculus of the alert cat. J Neurophysiol 80: 1006–1010.

Wu Y, Li M, Wang J (2016) Toward a hybrid brain-computer interface based on repetitive visual stimuli with missing events. J Neuro Eng Rehabil 13: 66.