
Main river, Mainz

Forest at *can Camp* from Corró d'Amunt
Bosc de can Camp a Corró d'Amunt
Les Franqueses del Vallès
Barcelona

MJ Corral Electrophysiological indexes of the detection and processing of auditory distractors

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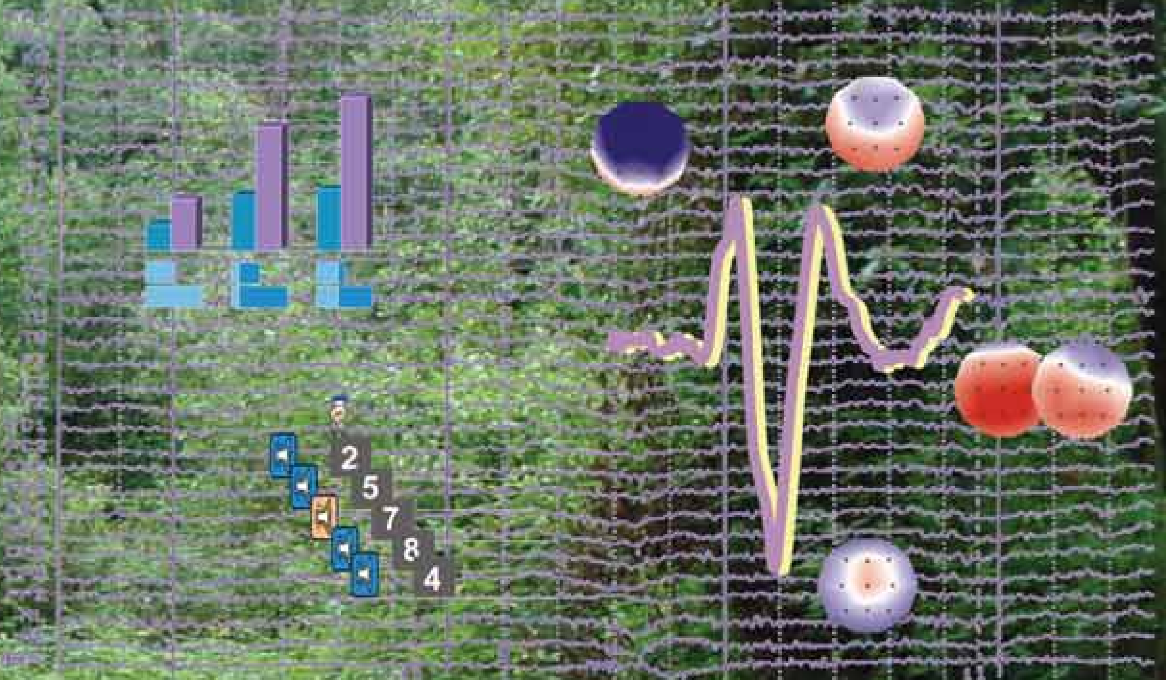

MJ Corral

UNIVERSITAT DE BARCELONA

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ELECTROPHYSIOLOGICAL INDEXES OF THE DETECTION AND PROCESSING OF AUDITORY DISTRACTORS

MJ Corral

Thesis submitted to
the Department of Psychiatry and Clinical Psychobiology
Faculty of Medicine
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for the doctoral degree (PhD) in Psychology
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BrainLab

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to all the people
that participated in our experiments
with dedication and interest

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...thanks to God

Abstract

The occurrence of auditory changes in a stable environment may cause distraction. The pattern of this effect in the present thesis depended on the salience of the feature undergoing auditory change, the temporal distance and the spatial location between the task-irrelevant and task-relevant information. Moreover, the electrophysiological recordings helped to elucidate the cognitive processing underlying behavioral distraction. First, an early and automatic call for attention triggered by mismatch negativity (MMN) was generated by various types of changes, which corroborated its role as a genuine change detector. Second, the effective orienting of attention to the unexpected changes indexed by P3a appeared sensitive to the spatial location of the distractors, suggesting that the orienting of attention could be indeed an attentional spatial switch. And third, the cognitive processing of returning to primary task performance after a momentary distraction associated with the reorienting negativity (RON) component depended on the impaired stage of the ongoing target processing. Taken together, the results shed new light on the mental chronometry of auditory distraction.

List of publications

Theoretical reviews

Escera, C. & **Corral, M.J.** (2003). The distraction potential (DP), an electrophysiological tracer of involuntary attention control and its dysfunction. In I. Reinvang, M.W. Greenlee & M. Herrmann (Eds.), ***The cognitive neuroscience of individual differences*** (63-76). Oldenburg: Bibliotheks-und Informationsystem der Universität Oldenburg.

Escera, C. & **Corral, M.J.** (2007). Role of mismatch negativity and novelty-P3 in involuntary auditory attention. ***Journal of Psychophysiology***, 21 (3-4), 251-264.

Study I

Escera, C., **Corral, M.J.** & Yago, E. (2002). An electrophysiological and behavioral investigation of involuntary attention towards auditory frequency, duration and intensity changes. ***Cognitive Brain Research***, 14, 325-332.

Study II

Corral, M.J. & Escera, C. (2008). Effects of sound location on visual task performance and electrophysiological measures of distraction. ***Neuroreport***, *in press.*

Study III

Corral, M.J., Berti, S., Jacobsen, T., Widmann, A., Yago, E., Schröger, E., & Escera, C. *(submitted).* Distraction effects with different distractor-to-target intervals: a combined behavioral and event-related brain potential study.

Glossary of abbreviations

ADHD	Attention Deficit Hyperactivity Disorder
ANOVA	Analysis of variance
DEV	deviant (tone)
DP	Distraction Potential
EEG	Electroencephalogram
EOG	Electro-oculogram
ER	Error rate
ERPs	Event-related brain potentials
HR	Hit rate
MEG	Magnetoencephalography
MMN	Mismatch Negativity
MR	Miss rate
NOV	Novel (tone)
RON	Reorienting Negativity
RT	Response time
SCD	Scalp current density
SD	Standard deviation
SOA	Stimulus-onset asynchrony
STD	Standard (tone)

Contents

Appendices

1. Introduction

In everyday life, our senses are constantly bombarded by information reaching our various sensory epithelia, although we can only process a subset of the incoming information at any given moment in time. The adaptive control of behavior requires the integration and coordination of information originating from different input modalities or locations in external and internal space (Eimer & Driver, 2001; Spence, 2002).

Unexpected events may catch our attention automatically, allowing an evaluation of the relevance of the new information. This ability is an advantage when a child suddenly crosses the road while we are driving or when we locate a strange smell coming from the kitchen. However, this detector of differences is a real disadvantage if we want to read in a crowded railway station or if we are trying to work while people are coming in and out of our office. Therefore, detecting sudden changes in the environment allows us to react to potentially dangerous events, but if there is no relevance associated to the change it merely distracts us from our focus of interest.

Recent empirical evidence stresses the importance of the interplay and coordination of stimulus-triggered (bottom-up) processes with top-down mechanisms as the basis for adaptive behavior (Berti, Roeber, & Schroger, 2004; San Miguel, Corral, & Escera, 2008a). Therefore, in order to be able to react to unexpected changes, the cognitive system needs to maintain its openness or distractibility even when focusing on task demands. On the other hand, the cognitive system must be effective enough to shield us from irrelevant changes in the environment.

1.1. Auditory distraction paradigms

Various kinds of distraction paradigms have tried to recreate the interference of unexpected task-irrelevant changes to the task at hand in the laboratory setting. In these paradigms (Figure 1), participants are instructed to classify auditory (Schroger & Wolff, 1998a) or visual (Escera, Alho, Winkler, & Naatanen, 1998) stimuli while ignoring concurrent, task-irrelevant auditory information.

In the auditory-auditory version of the distraction paradigms, participants are instructed to concentrate on a particular dimension of the auditory stimuli, i.e., duration, while ignoring any other aspect of the auditory input, i.e., a task-irrelevant change in, for example, frequency. The sequence is arranged so that in random order, half of the stimuli have a particular duration, while the other half are longer, and the participant is instructed to press the response button corresponding to the duration of the stimulus. In a few of the trials, the standard frequency is slightly increased or decreased, and this task-irrelevant frequency change also yields a behavioral cost in the duration discrimination task: participants respond more slowly and make more errors in these "deviant" trials (Schroger & Wolff, 1998a,b; Schroger, Giard, & Wolff, 2000). Moreover, the paradigm provides reliable and replicable measures of distraction (Roeber, Berti, & Schroger, 2003). and It has proved its usefulness for exploring attention in children (Wetzel, Widmann, Berti, & Schroger, 2006; Wetzel & Schroger, 2007a; Wetzel & Schroger, 2007b), even in children as young as five/six years of age, using a modified version with animal sounds instead of pure tones, (Wetzel, Berti, Widmann, & Schroger, 2004).

In the auditory-visual version of the distraction paradigm, participants are instructed to classify visual stimuli into two particular categories, as fast and as accurately as possible, and to ignore the concomitant auditory stimuli, which are presented one at a time preceding the visual stimulus, usually with an stimulus-onset asynchrony (SOA) of 300 ms, onset-to-onset. These task-irrelevant sounds are manipulated so that the “standard” stimulus (occurring in 80% of the cases) is occasionally and randomly replaced by a "distractor", i.e., a stimulus slightly higher/lower (“deviant”) in frequency or by a single environmental (“novel”) sound (i.e., telephone ringing, a glass breaking, or a drill). In the original version of the task, participants were instructed to classify digits into odd and even categories (Alho, Escera, Diaz, Yago, & Serra, 1997; Escera *et al.*, 1998; Escera, Yago, & Alho, 2001; Escera, Corral, & Yago, 2002; Escera, Yago, Corral, Corbera, & Nuñez, 2003; Jaaskelainen, Alho, Escera, Winkler, Sillanaukee, & Naatanen, 1996; Yago, Escera, Alho, & Giard, 2001; Yago, Escera, Alho, Giard, & Serra-Grabulosa, 2003), but in subsequent versions of the auditory-visual distraction paradigm the task was modified to classify digits vs. letters (Polo, Escera, Yago, Alho, Gual, & Grau, 2003), or to decide whether the present digit was bigger or smaller than 5 (San Miguel, Escera, Erhard, Fehr, & Herrmann, *in preparation*).

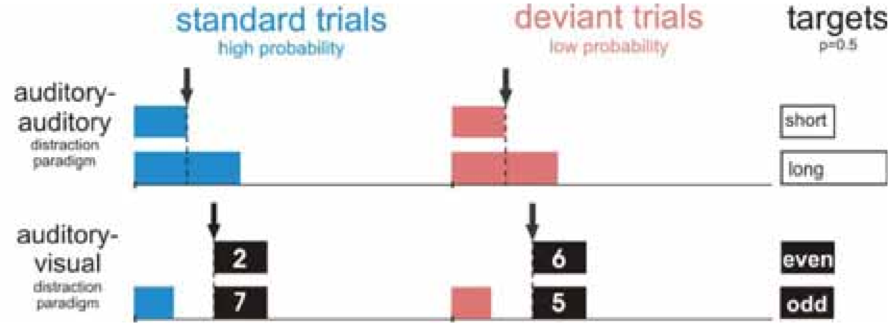

Figure 1. Auditory distraction paradigms. Arrows indicate the target onset.

The auditory-visual distraction paradigm has also been tested in tasks using more complex visual stimuli and decisions, such as classifying drawings into animate (animals) or inanimate (objects) categories (Gumenyuk, Korzyukov, Alho, Escera, & Naatanen, 2004), or in deciding whether the color of a figure (a face) was the same or different from that of its surrounding frame (Dominguez-Borras, Trautmann, Fehr, Ehrard, & Herrmann, & Escera, 2008b), or even whether two natural pictures presented simultaneously were the same or different (Dominguez-Borras, Garcia-Garcia, & Escera, 2008c). In all the tasks described so far, the unexpected occurrence of a distracting sound preceding the visual stimulus causes a delay in participants' responses, "distracting" current task performance. In some studies, the response time increase in deviant trials was accompanied by a hit rate decrease, caused by an error rate increase (Alho *et al.*, 1997; Escera *et al.*, 1998, 2001, 2002; Jaaskelainen *et al.*, 1996).

Like the auditory-auditory distraction paradigm, the auditory-visual distraction has been applied to different populations, showing sizeable distracting effects in participants over 8 years of age (Gumenyuk, Korzyukov, Alho, Escera, Schroger, Ilmoniemi, *et al.,* 2001; Gumenyuk *et al.*, 2004), in elderly people without disabilities (Andres, Parmentier, & Escera, 2006), and also in a range of persons with specific disabilities, including children with ADHD (Gumenyuk *et al.,* 2005) or dyslexia (Corbera & Escera, *in preparation*), adults with closed head injury (Polo, Newton, Rogers, Escera, & Butler, 2002), chronic alcoholism (Polo *et al.*, 2003), or schizophrenia (Cortinas, Corral, Garrido, Garolera, Pajares, & Escera, 2008). Moreover, these clinical studies demonstrated increased distractibility in most disability groups (ADHD, dyslexia, schizophrenia), and even with aging people without disabilities (Andres *et al.*, 2006).

1.2. Locus of the auditory distraction

So far, a number of parameters have been manipulated in order to identify the cause of distraction. It is well established today that the behavioral distraction effects depend on the size (Berti *et al.*, 2004; Jaaskelainen *et al.*, 1999), predictability (Sussman, Winkler, & Schroger, 2003), and channel proximity of the change to the task-relevant information (Schroger & Wolff, 1998a). That is, large and unpredictable distracters such as a telephone ringing, may obviously yield larger distractions than small distracters, which are physically similar to standard auditory background, or than predictable stimuli (e.g., visually cued ones).

The magnitude of the distracting effects has been reported to be proportional to the frequency difference between the deviant and the standard tones (Berti *et al.*, 2004; Jaaskelainen *et al.*, 1999) as observed by Schröger (1996). In the same line, larger distraction effects were found for novel than for deviant trials (Escera *et al.*, 1998; 2001), and for meaningful than for non-meaningful novel sounds (Escera *et al.*, 2003).

The predictability of deviant sounds was studied by Sussman *et al.* (2003). In their experiment using the auditory-auditory distraction paradigm, each sound was preceding by a visual cue. In a predictable condition, the visual stimuli indicated the pitch of the tone. In the unpredictable condition, the visual stimuli were randomly paired with the sounds, but did not provide any information on their pitch. Deviant tones occurring in the unpredictable condition elicited clear behavioral distraction. However, deviant tones in the predictable series failed to increase response time.

Channel-separation relates to the psychological distance between distractor and target, being larger in the auditory-visual paradigm, where distractor and target are presented in different sensory modalities, and smaller in the auditory-auditory paradigm, where distractor and target are embedded in the same stimulus which could give rise to a unitary perceptual object. Distraction effects can be also observed with tones deviating in features other than frequency, such as tone duration or intensity (Escera *et al.*, 2002), and similar behavioral and electrophysiological effects could be elicited using deviances in intensity (Rinne, Sarkka, Degerman, Schroger, & Alho, 2006), and location and duration (Roeber, Widmann, & Schroger, 2003). In fact, Jankowiak & Berti (2007) presented fixed auditory sequences with high deviant probabilities (one, two or three standard stimuli to each deviant stimuli), in different conditions and participants. Deviant stimuli varied either in pitch, in loudness or in sound source locations, in such a way that the temporal position of the deviant sound was predictable, but not the deviant feature. Deviant stimulus prolonged reaction responses, in comparison to standard tones, when the deviant stimulus was presented every two ($p=0.33$) or three ($p=0.25$) standard stimuli, but not when deviant and standard stimulus were alternated ($p=0.5$). These results suggested that distraction is affected by the probability and the auditory feature channel of the deviant stimulus.

The distracting effects in the auditory-auditory distraction paradigm might be accounted for by the moving of attention from one auditory dimension (e.g., task-relevant duration) to another (e.g., a task-irrelevant pitch change) of the same perceptual object, leading to large behavioral effects (Berti & Schroger, 2003; Escera *et al.*, 1998; Escera, Alho, Schroger, & Winkler, 2000; Escera & Corral, 2007; Jankowiak & Berti, 2007; Schroger & Wolff, 1998a,b; Schroger *et al.*, 2000). Less obvious is the stage of visual task-performance that is interfered with by the occurrence of the task-irrelevant sound change. For instance, Alho *et al.* (1997) observed that a visual ERP component generated in extrastriate visual areas, the N1 elicited to visual targets (Heinze *et al.*, 1994), was attenuated when the preceding sound deviated in pitch compared to when preceded by standard sounds, suggesting that early visual target processing was impaired in distracting trials. However, Parmentier, Elford, Escera, Andres, & San Miguel (2008) failed to confirm this suggestion for novel sounds. In their study, visual stimulus identification was made more difficult by masking the visual target with white noise, which, as expected, prolonged response time considerably, but left the magnitude of the distracting effects of novel sounds similar to those of a control condition with mask. They also tested whether the distractor interfered at a later stage of target processing, instructing participants to classify digits into two or four categories. Again, longer reaction times were found for the four category condition than for the two category condition. However, the magnitude of distraction did not differ significantly between conditions. These authors therefore suggested that the distracting effect of the novel sounds occurs “before” the presentation of the imperative visual stimulus.

To confirm this hypothesis, Parmentier *et al.* (2008) quickly (50 ms) flashed a shrinking cross in the time period between the auditory, task-irrelevant stimulus and the visual target, in what they called a “re-capture” condition. Their results showed that the distracting effects of novel sounds were abolished in the re-capture condition, suggesting that the unexpected task-irrelevant change in the auditory environment engaged, and retained, attention in the auditory modality, and that the response time increase observed in the distracting trials would reflect the time necessary to move attention back from the auditory to the visual modality upon the occurrence of a fresh sensory event in the task-relevant modality, i.e., vision. However, as discussed by the authors (Parmentier *et al.,* 2008), this pattern of results could also be explained by the time necessary to move attention between spatial locations instead of sensory modalities, as the visual stimuli were displayed on a screen located in front of the participant, whereas the sounds were presented through headphones.

However, how does a distractor interfere to cause impaired performance? May the task-irrelevant stimulus affect any stage of the task-relevant processing or, is there a particularly vulnerable temporal window between the distractor and the target stimulus which determines more distraction?

In a previous study, Schröger (1996) showed impoverished performance (hit rate decrease and reaction time increase) when the task-irrelevant stimulus change was presented at 200 ms from the task-relevant tones, whereas no detrimental performance was found when the interval was extended to 560 ms. Later, Escera *et al.* (2001) also used two different asynchronies between the task-irrelevant sound and the subsequent imperative visual stimulus. Participants were slower to classify the visual stimulus when it was preceded by a slightly higher deviant tone or a novel environmental sound than when the visual target was preceded by a repetitive standard tone. However, no performance differences were found, irrespective of whether the asynchrony between the task-irrelevant sound and the task-relevant visual stimuli was 245 or 355 ms.

In the auditory-auditory distraction paradigm, the temporal distance between distractor and target onset was also manipulated. In this task, the distractor onset coincides with the stimulus onset, whereas the time difference between the short and the long stimuli determines the target onset. For example, when participants are to classify short stimulus of 200 ms and long stimulus of 400 ms, the distractor (task-irrelevant change) begins with stimulus onset, whereas the task-relevant target onset occurs 200 ms later (when the stimulus should have finished, if it was a short stimulus). With this paradigm, it has been shown that asynchronies between deviance onset and target onset of 200 ms (Roeber, Berti, & Schroger, 2003; Roeber, Widmann *et al.*, 2003; Schroger & Wolff, 1998b; Schroger *et al.*, 2000) and 100 ms (Schroger & Wolff, 1998a) are sufficient to cause behavioral distraction. Moreover, Rinne *et al.* (2006) showed that task-irrelevant decreases or increases in intensity when participants had to discriminate between two equiprobable sounds which differed in pitch, that is, when the distance between the task-relevant and the task-irrelevant feature was 0 ms, also caused distraction. In addition, Roeber, Widmann *et al.* (2003) found slower responses when infrequent long stimuli (400 ms) appeared in a sequence of repeated short stimuli (200 ms) and participants had to discriminate the localization of the sound (front or left), that is, when the task-irrelevant feature came 200 ms after the task-relevant information. So it seems that task-irrelevant changes presented from -355 ms to 200 ms to the target onset could impair performance.

1.3. ERPs elicited during auditory distraction

The recording of event-related brain potentials (ERPs) during the performance of the auditory-visual distraction paradigms described above allows the investigation of the spatio-temporal dynamics of activation of the cerebral network underlying attention control. The typical ERP recorded in this scenario shows a complex morphology, both for the standard and the distracting trials, as it includes auditory and visual responses. However, a simple arithmetic computation, i.e., the subtraction of the responses elicited to standard trials from those elicited to the distracting ones isolates the neuroelectric activation underlying behavioral distraction; for convenience, Escera & Corral (2003) termed this activation pattern the "distraction potential" (DP). The DP shows a characteristic tri-phasic shape, starting with a negative wave followed by a positive one, and ending in a final phase of a more or less sustained negative potential (Figure 2). Each of these waveforms provides a neurophysiological index of what are considered the three main processes involved in involuntary attention control (Escera *et al.*, 2000):

1) the mechanism of attention capture, associated with the mismatch negativity (MMN) and/or to the N1 ERP,
2) the orienting of attention, associated with the P3a or novelty-P3, and
3) the reorienting of attention towards main task performance after a momentary distraction, associated with what is termed reorienting negativity (RON).

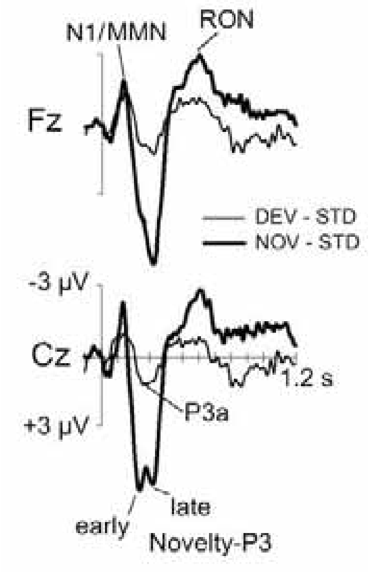

Figure 2. The "distraction potential" (DP). Data in the figure are taken from Escera *et al.* (2001).

However, the precise relationship between these neurophysiological phenomena and the cognitive process attributed to them is not entirely clear. In fact, the DP has been recorded without behavioral distraction effects (Munka & Berti, 2006; Polo *et al.*, 2003), as will be discussed in the following sections.

1.3.1. Change detector mechanism and MMN

Automatic detection of potentially relevant auditory events, occurring outside the current locus of attention, has been attributed to at least two cerebral mechanisms. One mechanism is activated by sudden onsets of offsets of stimuli, such as a flashing light or an alarm siren, or when a drilling machine or a refrigerator that has been working all the day suddenly stops. Another mechanism is activated by a particular stimulus that violates a neural trace of the preceding homogeneous stimulation, therefore involving a "change" detection process. A naive application of such a change detector mechanism has been used for years by news broadcasters, who, before starting, usually "call" the listeners' attention by playing a short series of repeating tone pips finishing with another one of longer duration or higher pitch.

The first mechanism is based on a neurophysiological reaction to transient increases/decreases in stimulus energy, and has been associated with the auditory N1 (Escera *et al.*, 1998; Giard, Perrin, Echallier, Thevenet, Froment, & Pernier, 1994; Naatanen & Picton, 1987) or at least with some of its components (Escera *et al.*, 1998; Giard *et al.*, 1994). The second mechanism relies on the dynamic modeling of regularity in the acoustic environment, and on the detection of any stimulus change that does not fit in with a neural trace of this regularity. This is therefore a "change-detector" mechanism which has been associated with the generation of the MMN (Naatanen, 1990, 2007; Schroger, 2007; Winkler, 2007), and can be best isolated by using distractor stimuli that differ slightly from the repetitive stimulation (see a fuller discussion of this issue in Schroger & Wolff, 1998a).

The behavioral data obtained with the auditory-auditory (Rinne *et al.*, 2006) and auditory-visual distraction paradigms support the existence of these two attention capture mechanisms. Specifically, the distracting effects observed with this latter paradigm in novel and deviant trials display a distinct pattern. Whereas novel sounds cause a long (about 25 ms) delay in the response time to visual stimuli, compared to standard trials, deviant sounds increase response time only slightly (about 5 ms), but there is a noticeable increase in the number of erroneous classifications, as mentioned above. ERP recordings also show this differential effect, with a clear MMN generated to deviant distractors and a combined N1-enhancement/MMN elicited to novel distractors (Alho *et al.*, 1998; Escera *et al.*, 1998). A large body of evidence indicates that both the MMN and the N1 are generated within the planum temporale of the auditory cortex (Alho, 1995; Alho *et al.*, 1998; Escera *et al.*, 2000; Naatanen & Picton, 1987), with additional contributions from prefrontal regions (see Giard *et al.*, 1994 for the N1; Deouell, 2007, for the MMN).

However, most of the ‘distraction’ studies described used a pitch change as a deviant feature, i.e., a distractor stimulus differing in its spectral content from the standard sound. Therefore, we cannot conclusively rule out the possibility that the cerebral mechanism leading to attention switching and distraction is associated with the N1 generated by fresh neurons responding selectively to the specific pitch of the deviant sound (Jacobsen & Schroger, 2001; Yago, Escera *et al.* 2001). Subsequent studies using tones deviating in duration (Escera *et al.*, 2002; Roeber, Berti, & Schroger, 2003), intensity (Escera *et al.*, 2002; Rinne *et al.*, 2006) or location (Roeber, Widmann *et al.*, 2003) helped to corroborate MMN as a genuine change detection involved in involuntary attention switching.

1.3.2. Attention switch and P3a

The P3a waveform, generated with large amplitude to novel stimuli and therefore called "novelty-P3" (see Simons, Graham, Miles, & Chen, 2001, for a discussion on whether the P3a and novelty-P3 can be considered the same ERP component), has been taken in the psychophysiological literature as a cerebral signature of the orienting response (Friedman, Cycowicz, & Gaeta, 2001; Knight, 1984; Squires, Squires, & Hillyard, 1975). Studies using the auditory-visual distraction paradigm have shown that novelty-P3 generation is accomplished in two consecutive phases, each of them involving a different scalp distribution and a different sensitivity to attentional manipulations (Escera *et al.*, 1998, 2001). The first novelty-P3 phase, with peak latency between 220 and 320 ms, has a centrally distributed topography and appears to be independent of attentional manipulations (Escera *et al.*, 1998; (Dominguez-Borras, Garcia-Garcia, & Escera, 2008a; San Miguel, Corral, & Escera, 2008a; see however Dominguez-Borras, Garcia-Garcia, & Escera, 2008b). On the other hand, the second phase of the novelty-P3, occurring between 300 and 400 ms, has a right frontal scalp distribution, and appears highly sensitive to attentional manipulations, as it increases in amplitude when, for instance, participants can monitor the sounds, i.e., in the auditory-visual paradigm, compared with a condition of passive listening (Escera *et al.*, 1998; 2003). In agreement with previous results (Herrmann & Knight, 2001), the scalp-current density (SCD) analysis of the novelty-P3 recorded in the auditory-visual distraction paradigm has shown that novelty-P3 generation encompasses at least five different cerebral regions, engaged in clear spatiotemporal orchestration (Yago *et al.*, 2003). This study suggested that the anterior cingulated cortex was activated first (circa 160 ms), followed by simultaneous activation of the bilateral temporoparietal and the left frontotemporal cortices (around 200 ms), to finish with activation of the superior parietal cortex and prefrontal regions (at 300 ms).

Whereas the MMN and N1 mechanisms seem to operate automatically, the subsequent brain response, the P3a or novelty-P3, reflecting, according to the most accepted view, the orienting of attention towards unexpected deviant or novel sounds (Escera *et al.*, 1998; 2000; Friedmann *et al.*, 2001; Herrmann & Knight, 2001; Knight, 1984), is largely dependent on top-down factors. The studies reviewed above have shown that the P3a elicited to deviant tones in the auditory-auditory distraction paradigm the novelty-P3 elicited to novel sounds in the auditory-visual distraction paradigm, can increase or reduce their amplitude in parallel with the effects of similar direction at behavioral level (i.e., enhanced or reduced distractibility) depending on the task at hand. This would support the P3a/novelty P3 as the scalp signature of the involuntary orienting of attention, or in other words, one may take the occurrence of a distinct P3a as proof that an effective orienting of attention towards distracting stimuli has taken place. However, this interpretation has recently been challenged by a study by Rinne *et al.* (2006), who found that behavioral distraction increased as a function of intensity decreases in the absence of any P3a elicitation, contrasting with the results obtained for intensity increases, where behavioral distraction increases as a function of intensity increases were paralleled by similar increases in P3a amplitude. These results call for a reconsideration of the role attributed to P3a generation in involuntary attention models. This is not the only case in which P3a/behavioral-distraction dissociations have been observed using the auditory distraction paradigm. Using its visual version, Munka & Berti (2006) observed the opposite phenomenon: generation of P3a in the absence of any signs of behavioral distraction. Similar results were obtained by (Yago, Corral, & Escera, 2001), who, in a study manipulating parametrically the deviant-standard frequency difference, found that the P3a (and also MMN and

RON) increase linearly as a function of change magnitude, whereas no behavioral effects were observed except in the 10% change condition. These authors even reported a facilitation effect for a condition with 5% frequency change. A further dissociation was observed by Polo *et al.* (2003), where larger (late) novelty-P3s were observed in a group of chronic alcoholics compared to matched controls, in the absence of any differences in behavioral distraction. Using a very different paradigm without auditory stimulation, either deviant or standard stimuli, Berti (2008b) found that P3a was elicited. The task consisted in performing arithmetic operations on stored numbers. These operations could be performed on a previously processed item or on a new item of the three stimuli presented on the screen. Switch and no switch trials were equiprobable and slower responses were recorded for the switch trials. Moreover, switch trials showed an increased P3a around 300 ms.

Therefore, in contrast to the widely held view of the P3a as an orienting attention response or as a distractibility index, the P3a/novelty-P3 may be a signature of the evaluation of the contextual novelty of an unexpected sound, and furthermore, that it may reflect the reconfiguration of a cerebral network involved in updating task-set information for goal-directed action selection (Barcelo, Escera, Corral, & Perianez, 2006).

1.3.3. Working memory and RON

As important as the flexibility to direct attention towards unexpected potentially relevant events outside the focus of attention is the ability to return attention back to original task performance after a momentary distraction. It has been proposed that this attentional process is associated with the generation of another ERP component recorded in distraction tasks, known as reorienting negativity (RON; Escera *et al.*, 2001; Schroger & Wolff, 1998b). In fact, in their recordings Schroger & Wolff (1998b) only found a negative waveform subsequent to P3a when their participants carried out a task where the deviant stimuli acted as behavioral distractors, but not when the participants were asked to discriminate these stimuli actively, or when they were instructed to ignore the auditory stimulation completely and to concentrate on an unrelated visual task. Moreover, Escera *et al.* (2001) argued that in order to indicate the process of reorienting attention back towards main task performance, RON should be time-locked to target stimuli in the task, and not to distracting ones. In their experiment using the auditory-visual distraction paradigm, the asynchrony between the distractor and the visual target was manipulated to 245 or 355 ms, in different conditions. Their results showed that RON peak-latency was about 345 ms, irrespectively of distractor-target asynchrony, i.e., from visual target onset. These results strongly suggested that RON generation reflects the process of returning attention back to primary task performance after a momentary distraction.

On the other hand, Escera *et al.* (2001) observed that RON actually had two different phases or subcomponents, which were dissociated on the basis of their different scalp distribution, and that the late subcomponent was the one time-locked to task-relevant aspects of stimulation, i.e., the visual stimulus. The existence of two RON subcomponents was confirmed in a recent study by Munka and Berti (2006) using the auditory-visual distraction paradigm. These authors found that an early RON component was elicited when the discrimination task had a working memory component, i.e., consisting in making a semantic judgment on the visual stimuli (in fact, a classical odd/even classification). However, when the decision was based on a physical feature of the stimuli (size or color, in different experiments), only a late RON subcomponent could be observed. On the basis of their results, the authors suggested that the early RON was an electrophysiological correlate of attention refocusing as a working memory process in the sense of a switch of the focus of attention, whereas the later RON seems to be related to a more general aspect of attentional allocation or evaluation after distraction (i.e., rehearsal of instructions or self-motivation). Moreover, a recent study using magnetoencephalography (MEG) found the activation of the primary motor cortex during the RON interval (Horvath, Maess, Berti, & Schroger, 2008), suggesting that, in addition to the frontal activation observed in the ERP studies, the primary motor cortex also contributes to the reorientation of attention to the main task.

2. Aims and hypothesis

The general aim of the present thesis was to contribute to our understanding of the neural mechanisms of auditory distraction. Specific objectives and hypothesis are considered separately for each of the three studies, as follows.

Study I

Escera, C., Corral, M.J. & Yago, E. (2002). An electrophysiological and behavioral investigation of involuntary attention towards auditory frequency, duration and intensity changes. *Cognitive Brain Research*, 14, 325-332.

Until this study was published, most 'distraction' studies used pitch as deviant feature. Because distractor stimuli differed in their spectral content from the standard sounds, the possibility that the cerebral mechanisms leading to attention switching and distraction was associated to the N1 generated by fresh neurons responding selectively to the specific pitch of the deviant sound could not be conclusively ruled out (Jacobsen & Schroger, 2001; Yago, Escera *et al.* 2001).

Aim: The present experiment sought to investigate whether a genuine change detection indexed by MMN was involved in cross-modal attention switching, i.e., in directing attention involuntarily from the current visual performance to unexpected auditory changes. We used a variant of our auditory–visual distraction paradigm in which the 'distracting' sounds were either shorter in duration or softer in intensity, in separate blocks, than the corresponding standard stimuli. An additional condition with frequency deviants was also used.

Hypothesis: Because shorter or softer deviant tones are unlikely to activate new fresh neural elements (Naatanen, Paavilainen, & Reinikainen, 1989; Naatanen, Paavilainen, Alho, Reinikainen, & Sams, 1989), observation of behavioral distraction to these sounds will strongly support the involvement of a genuine change detection mechanism in controlling involuntarily the cross-modal direction of attention. Otherwise, if the change detection mechanism was only presented in the pitch change condition and not in the intensity or duration condition, it would have been difficult to maintain MMN as a genuine change detection mechanism involved in involuntary attention.

Study II

Corral, M.J. & Escera, C. Effects of sound location on visual task performance and electrophysiological measures of distraction. *Neuroreport, in press.*

A critical issue for gaining insight into the neural mechanisms of distraction would be to establish which cognitive process, or processes, during visual task performance are affected by the occurrence of unexpected deviant or novel sounds. Parmentier *et al.* (2008) showed that the distracting novel sound interfered not during visual stimulus identification or during response selection, but before the target processing. The next open question was whether the distraction effects observed with the auditory-visual distraction paradigm were due to the time necessary to move attention between spatial locations or between sensory modalities.

Aim: The objective of this study was to investigate the role of the spatial source of the auditory stimuli in distraction in a visual task-performance. For this purpose, sound location was varied systematically across conditions, while visual target location remained constant.

Hypothesis: If the cause of distraction relies only on moving attention between sensory modalities, placing the source of the task-irrelevant auditory stimuli in different spatial locations should not affect the distracting effects of these sounds. However, if a spatial factor is involved in distraction, the greater the distance between the auditory and the visual stimulus sources the larger the distracting effects of novel distracting sounds on visual task-performance, and eventually on the accompanying ERP signs of distraction.

Study III

Corral, M.J., Berti, S., Jacobsen, T., Widmann, A., Yago, E., Schröger, E., & Escera, C. *(submitted).* Distraction effects with different distractor-to-target intervals: a combined behavioral and event-related brain potential study.

In a previous study, Schröger (1996) showed impaired performance (hit rate decrease and response time increase) when the task-irrelevant stimulus change was presented at 200 ms from the task-relevant tones, but no deterioration when the interval was increased to 560 ms. Later, Escera *et al.*

(2001) also used two different asynchronies between the task-irrelevant sound and the subsequent imperative visual stimulus. Participants were slower to classify the visual stimulus when it was preceded by a slightly higher deviant tone or a novel environmental sound than when the visual target was preceded by a repetitive standard tone. However, no performance differences were found when the asynchrony between the task-irrelevant sound and the task-relevant visual stimuli was of 245 or 355 ms. Moreover, a negative component related to reorienting of attention towards main task performance after distraction (RON) appeared synchronized to the task-relevant information.

Other studies have recorded distraction using a different interval between task-relevant and task-irrelevant information yielded distraction (from -355 to 200 ms; Rinne *et al.*, 2006; Roeber, Berti & Schroger, 2003; Roeber, Widmann *et al.*, 2003; Schroger and Wolff, 1998a,b; Schroger *et al.*, 2000). However, the question of whether there is a particular vulnerable temporal window between the distractor and the target stimulus which determines more distraction has not been systematically studied.

Aim: The present study addressed two specific questions. First, whether the occurrences of the auditory change at different asynchronies from the target feature onset could affect the magnitude of distraction. Second, whether the reorienting of attention indexed by RON is insensitive to the deviance onset, as in the previous study by Escera *et al.* (2001). For this purpose, participants were instructed to respond to short and long stimuli and to ignore all other aspects of stimulation. Most of the tones (p=0.88) had the same pitch from the beginning to the end (standard tones, STD) and in a small set of stimuli (p=0.12) slight task-irrelevant pitch changes were introduced (deviant stimuli). Two time points were selected maintaining a similar distance between them of around 100 ms, as in a previous study (Escera *et al.*, 2001). One pitch deviance was presented early, at 50 ms from stimulus onset (early-DEV). The other pitch deviance was presented late, at 150 ms from stimulus onset (late-DEV). Because the short stimuli lasted 200 ms and the long stimuli 400 ms, the discrimination point between them occurred at 200 ms from stimulus onset (the point when the short stimulus finished and the long stimulus continued). So, target onset remained constant through deviant stimuli.

Hypothesis: If there is a temporal window that determines more distraction, different behavioral responses should be observed between conditions. Moreover, if RON was a pure index of reorienting of attention, its generation has been related with the target onset independently of the distraction onset (as has been shown in auditory-visual paradigm, Escera *et al.*, 2001). However, if RON generation involves deviant information, peaks at different time windows should be expected.

3. Methods

Electrophysiological and behavioral measures were obtained from non-disabled people across all the three studies with the following specifications.

Sample

Participants were undergraduate students from the University of Barcelona for the first and the second study, and from the Institut für Psychologie I of the Universität Leipzig (Germany) for the third study.

Table 1. Sample features

	N	***males***	***mean age***	***minimun age***	***maximun age***
Study I	12	2	21	20	23
Study II	13	7	23	19	30
Study III	12	2	21	18	25

All were right-handed, none reported auditory dysfunction and all participated in the study for either course credits or payment. Informed consent was obtained from each participant after the nature of the study had been explained to them.

Stimuli

Visual and auditory stimuli were presented for the first and second study, while only auditory stimuli were used for the third study. Visual stimuli consisted on the digits from 1 to 8 presented equiprobably during 200 ms on a computer screen.

Table 2. Visual stimuli features

	participant's distance screen	***vertical view angle***	***horitzontal view angle***
Study I	1.50 m	1.78º	1.18º
Study II	1.15 m	2.00º	1.25º

Auditory stimuli consisted of repetitive standard tones occasionally replaced by slightly deviant or novel sounds. All of them were delivered binaurally through headphones, except for the second study which included five conditions with auditory stimuli delivered through loudspeakers.

Table 3. Auditory stimuli features

	stimuli	***pitch***	***duration***	***intensity***	***probability***
Study I	standard	600 Hz	200 ms	85 dB	$p = 0.80$
	deviant-**FRE**	**700 Hz**	200 ms	85 dB	$p = 0.20$
	deviant-**DUR**	600 Hz	**50 ms**	85 dB	$p = 0.20$
	deviant-**INT**	600 Hz	200 ms	**79 dB**	$p = 0.20$
Study II	standard	600 Hz	150 ms	85 dB	$p = 0.80$
	novel	complex sounds (n=60)	150 ms	85 dB	$p = 0.20$
Study III	standard	1,000 Hz	200 ms	72 dB	$p = 0.44$
			400 ms	72 dB	$p = 0.44$
	early-deviant	1,100 Hz after **50 ms from** stimulus onset	200 ms	72 dB	$p = 0.03$
			400 ms	72 dB	$p = 0.03$
	late-deviant	1,100 Hz after **150 ms** from stimulus onset	200 ms	72 dB	$p = 0.03$
			400 ms	72 dB	$p = 0.03$

Procedure

The auditory-visual version of the distraction paradigm was used for the first and the second study, while the auditory-auditory version of the distraction paradigm was carried out for the third study.

In the auditory-visual distraction paradigm, auditory stimuli preceded the visual stimuli by 300 ms (onset-to-onset). Stimulus pairs (auditory-visual stimuli) were delivered at a constant rate of one pair every 1.2 s. Participants were instructed to focus on a small fixation cross appearing in the middle of the screen and to press one response button for even numbers and another response button for odd numbers. In the auditory-auditory distraction paradigm, auditory stimuli were delivered at constant stimulus-onset-asynchrony (SOA) of 1.3 s. Participants were instructed in this case to press one response button for the short stimuli and another response button for the long stimuli.

Both speed and accuracy were emphasized for the task. Participants were also instructed to focus on the task-relevant information and to ignore any task-irrelevant feature (e.g., pitch). Before the experimental session, participants received one practice block without task-irrelevant stimulus. All reached a hit rate level of at least 85%. To avoid tiredness, participants had a short rest period every five minutes or so.

Table 4. Number of stimuli, blocks and duration

	auditory stimuli/block	***visual stimuli/block***	***number of blocks***	***experiment duration***
Study I	n = 500	n= 500	6	60 min
Study II	n = 300	n= 300	6	36 min
Study III	n = 200		12	52 min

All stimuli were delivered in random order, with the only restriction that at least the first four stimuli of each block were standard trials, and that two deviant/novel trials never appeared consecutively.

EEG-Recording

The experiments were conducted in a dimly lit, electrically and acoustically shielded room. The electroencephalograms (EEG) were continuously digitized at a rate of 500 Hz by SynAmps amplifier (NeuroScan Inc., Herndon, Va., USA) from Ag/AgCl electrodes. Table 5 shows the analogical band-pass filter, the number of recording positions and the elastic cap used for each study.

Table 5. Recording settings

	bandpass filter	***EEG leads***	***cap***	***additional positions***
Study I	0.10 – 100 Hz	n = 30	Electro-Cap International, Eaton, OH (USA)	IM1, IM2
Study II	0.05 – 100 Hz	n = 30	Electro-Cap International, Eaton, OH (USA)	O1, O2
Study III	0.05 – 100 Hz	n = 20	Easy Cap FMS, Munich (Germany)	O1, O2

Eighteen electrode positions, in accordance with the 10–20 system, were common for all the studies: Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6 and Oz. Two additional electrodes were placed at left (M1) and right (M2) mastoids for all the studies. Eight more electrodes were used for the first and the second study: TP3 (halfway between T3 and P3), CP1 (halfway between C3 and Pz), FT3 (halfway between F3 and T3), FC1 (halfway between Fz and C3), and the homonymous positions over the right hemisphere (Figure 3). Also, the IN1 (70% of the distance from the left preauricular point to the inion) and IN2 (70% of the distance from the right preauricular point to the inion) lead positions were used for the first study and the O1 and the O2 electrode positions according to the 10-20 system were used for the second and the third study.

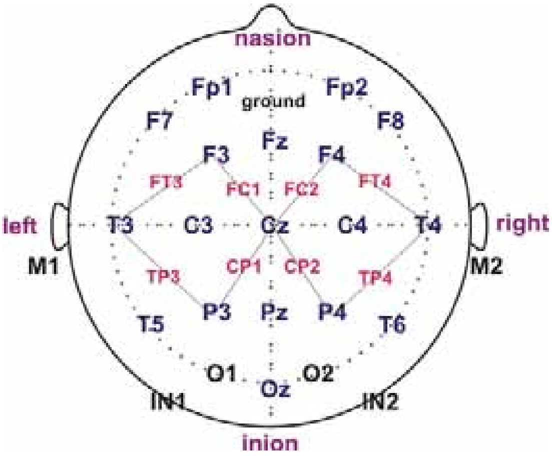

Figure 3. In blue, the common electrode positions for all the studies. In pink, additional positions for the first and the second study

The electro-occulogram (EOG) was recorded with electrodes attached to the canthus and below the left eye. The common reference electrode was attached to the tip of the nose for all the studies.

Data analysis

Mean response times (RT), hit rate (HR), error rate (ER) and miss rate (MR) were calculated for the standard and deviant sounds in the auditory-auditory distraction paradigm and for the visual stimuli that preceded the standard and deviant/novel sounds in the auditory-visual distraction paradigm. RTs were calculated for hit trials only. Distraction effects caused by deviant/novel trials were analyzed by means of analysis of variance (ANOVA) for repeated measures with type of auditory stimulus as within-subject factors, performed on the mean RT, HR, ER and MR. Post-hoc analysis of the magnitude of the distraction as a function of the type of auditory stimuli was based on non-pooled contrasts. *T*-tests comparisons between standard and novel stimuli were carried out in the second study for each condition.

ERPs were averaged off-line for each auditory stimulus type separately. Artifact rejection was performed to exclude trials with muscular or ocular activity. The method used in the first study was to reject any intervals which exceeded in ±100 μV. For the second and third study, standard deviation was calculated within a slide window of 200 ms along all the EEG channels. Intervals exceeding 30 μV at any channel for the second study and 50 μV in the horizontal or 40 μV in the vertical EOG for the third study were not included in the averaging.

Table 6. Recording settings

	total epoch	***baseline***	***off-line filter***	***artifact rejection***
Study I	1300 ms	100 ms	0.01 – 30 Hz	± 100 μV
Study II	1100 ms	100 ms	0.1 – 30 Hz	30 μV SD along EEG
Study III	1200 ms	200 ms	1 – 30 Hz	50 μV SD in the horizontal and 40 μV in the vertical EOG

Standard-tone trials immediately following deviant or novel-sound trials and, at least, the first four epochs of the beginning (and after the short break in the middle of each block from the second study) were automatically excluded from the averages.

Electrophysiological signatures of deviant/novel sound processing were analyzed in the different waveforms obtained by subtracting the standard-trial ERPs from those elicited to the novel-trial ERPs separately for each condition. Mean amplitudes of the three main waveforms of the ERPs elicited during auditory distraction were analyzed (Table 7) by means of ANOVA for repeated measures with type of auditory trial as within-subject factor.

Table 7. Latencies of the analyzed components from deviant onset (in parentheses, the relevant electrode to select the largest peak to center the latency window)

	MMN *(Fz)*			
Study I	frequency: 100 – 200 ms duration: 150 – 250 ms intensity: 180 – 280 ms			
	N1/MMN *(Cz)*	**early n-P3a** *(Fz, Cz, Pz)*	**late n-P3a** *(Fz, Cz, Pz)*	**RON** *(Fz)*
Study II	110 – 165 ms	200 – 260 ms	285 – 345 ms	460 – 560 ms
	MMN *(Fz)*	**P3a** *(Fz, Cz, Pz)*		**RON** *(Fz)*
Study III	early-deviant: 150 – 200 ms late-deviant: 144 – 294 ms	early-deviant: 232 – 332 ms late-deviant: 228 – 328 ms		early-deviant: 378 – 528 ms late-deviant: 356 – 506 ms

When required, scalp distribution analyses were performed on ERP amplitudes at 15 electrodes (F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6) after normalization, to prevent genuine differences in scalp distribution from being washed out by amplitude differences. This normalization was done by dividing the amplitude at each electrode by the square root of the sum of the squared amplitudes at the selected electrodes (McCarthy and Wood, 1985). The scalp distribution ANOVA included three factors: frontality (frontal/central/parietal), laterality (five levels from left to right) and stimulus type conditions.

In the first study, as the MMN inverts in polarity when the nose is used as the reference electrode, significant activation of MMN generators was analyzed by a *t*-test comparison between its mean amplitude at Fz and the left mastoid (M1). Comparison of MMN across deviant conditions was carried out on MMN mean amplitudes at Fz.

In the second study, mean ERP components and behavioral measures were compared between the headphones and the 0º locations. The remaining positions were analyzed with angle (18º, 72º) and hemifield (right, left) as additional factors in the ANOVA.

In the third study, the N2 and the P3b ERPs elicited to the target stimuli were also analyzed. Mean amplitude of the N2 (346-396 ms) and the P3b (496-596 ms) components for the standard targets were compared by *t*-test analysis. The stimulus duration factor was included in the ANOVAs as an additional factor both for behavior and ERPs analyses. Moreover, mean amplitude to the P3b component for the deviant stimulus (early-DEV: 566-666, late-DEV: 632-732 ms) was analyzed by means of an ANOVA for repeated measures with deviant type (early-DEV, late-DEV) and stimulus duration (short, long) as within-subject factors. Peak-latencies over Fz of MMN, P3a and RON were analyzed independent ANOVAs with deviant conditions (early-DEV, late-DEV) and stimulus duration (short, long) as factors.

ANOVAs were carried out with the Greenhouse-Geisser correction. When appropriate we reported *F* value, the uncorrected degrees of freedom, probability level following correction, and the η^2 effect size index.

4. Results

4.1. Study I

Escera, C., Corral, M.J. & Yago, E. (2002). An electrophysiological and behavioral investigation of involuntary attention towards auditory frequency, duration and intensity changes. *Cognitive Brain Research*, 14, 325-332.

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Research report

An electrophysiological and behavioral investigation of involuntary attention towards auditory frequency, duration and intensity changes

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Abstract

We measured behavior and event-related brain potentials (ERPs) in 12 subjects performing on an audio-visual distraction paradigm to investigate the cerebral mechanisms of involuntary attention towards stimulus changes in the acoustic environment. Subjects classified odd/even numbers presented on a computer screen 300 ms after the occurrence of a task-irrelevant auditory stimulus, by pressing the corresponding response button. Auditory stimuli were standard tones (600 Hz, 200 ms, 85 dB; $P=0.8$) or deviant tones ($P=0.2$), these differing from the standard either in frequency (700 Hz), duration (50 ms) or intensity (79 dB), in separate blocks. In comparison to performance to visual stimuli following the standard tones, reaction time increased by 24 ms ($F(1,11)=10.91$, $P<0.01$) and hit rate decreased by 4.6% ($F(1,11)=35.47$, $P<0.001$) to visual stimuli following the deviant tones, indicating behavioral distraction. ERPs revealed the mismatch negativity (MMN) elicited to deviant tones, which was larger for the duration deviant than for the frequency and intensity deviants ($F(2,22)=19.43$, $P<0.001$, $\varepsilon=0.83$), and which had different scalp distribution for all three deviant conditions ($F(16,176)=2.40$, $P<0.05$, $\varepsilon=0.12$). As the shorter duration and softer intensity deviant tones were unlikely to engage fresh neurons responding to their specific physical features, the present results indicate that a genuine change detection mechanism is involved in triggering attention switching towards sound changes, and suggest a largely distributed neural network of the auditory cortex underlying such involuntary attention switching.

Theme: Neural basis of behavior

Topic: Cognition

Keywords: Mismatch negativity; Orienting response; Change detection; Involuntary attention

1. Introduction

Surviving in a challenging environment requires both selective and involuntary attention capabilities. Selective attention is necessary to select relevant stimuli from the wealth of information impinging our senses, in order to allow goal-directed behavior. Involuntary attention, in turn, refers to the ability to switch attention automatically towards potentially relevant events occurring outside the current focus of attention. At least two cerebral mechanisms have been proposed to account for such involuntary orienting of attention. One mechanism is activated by sudden onsets or offsets of stimuli, such as a flashing light or an alarm siren, or as when a drilling machine that has been working all day long suddenly stops. Another mechanism is activated by a particular stimulus that violates a neural trace of the preceding homogeneous stimulation, therefore involving a 'change' detection process. A naive usage of such a change detector mechanism has been used for years by news broadcasters, who, before they begin, usually 'call' listener's attention by playing a short series of repeating tone pips finishing with another one of longer duration or higher frequency. In the auditory modality, sound onsets breaking a long silent period and sound offsets terminating a long noisy period activate a transient-detector mechanism, associated to the auditory N1 event-related brain potential (ERP) [15,29,34], whereas the

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change detector mechanism is reflected in the mismatch negativity (MMN) component of the ERPs [11,29].

The MMN [31] is elicited to deviant stimuli differing from the preceding standard stimuli in any of their physical features, such as frequency, duration, intensity or location. It appears as a negative peak of the difference wave obtained by subtracting the ERPs elicited to the standard tones from those elicited to the deviant tones, at a latency between 100 and 200 ms. MMN has a frontocentral scalp distribution, with polarity reversal at electrode locations below the Sylvian fissure, suggesting generator sources located bilaterally to the supratemporal auditory cortex [16,41]. This auditory cortex location has been confirmed by a range of cognitive neuroscience methods, including intracranial recordings in animals [8,22,24] and humans [17,26,27], source modeling of magnetoencephalographic (MEG) signals in humans [4,9,18], analysis of scalp current density (SCD) of deviant-related negativities [10,16,38,48], functional magnetic resonance imaging (fMRI) [7,35], positron emission tomography (PET) [46], and event-related optical signals (EROS) [39] (for reviews see Refs. [2,11]). A further contribution to MMN from the frontal cortex has been suggested by studies of patients with cerebral lesions [1,5], and confirmed by scalp current density analysis [10,16,38,48].

It has been suggested that the MMN reflects the outcome of a comparison process resulting in disparity between a neural code of the incoming stimulus and a neural trace of the physical features of the repetitive preceding stimulation stored in sensory memory [29,30]. This process is apparently sustained by the neural populations generating the MMN in the supratemporal auditory cortex [23,25]. As a result of this mismatch detection, an attention switching signal is triggered to activate a chain of cerebral events leading to the effective orienting of attention towards the detected change [29,30]. The frontal MMN source has been suggested to underlie such a neural signal triggering the attention switching response [16,30], although the positive correlation between activation of the supratemporal MMN source and orienting of attention towards the eliciting sounds, as indicated by behavioral distraction [48], leaves this issue still open.

The strongest evidence supporting the role of the MMN generating mechanism in triggering attention switches is provided by studies showing deterioration of task performance at the occurrence of unexpected task-irrelevant deviant sounds eliciting the MMN. In a series of these studies, subjects had to classify visual stimuli presented after ~300 ms of the occurrence of an irrelevant sound. Deviant tones in this task-irrelevant auditory sequence elicited the MMN and caused reaction time increases and hit rate decreases to the successive visual stimuli [3,12,13,47,48] (see review in Ref. [11]), indicating behavioral distraction as a result of a transient orienting of attention towards the originally unattended deviant sound. Similarly, in an auditory–auditory distraction paradigm, task-irrelevant changes in sound frequency caused also reaction time increases and hit rate decreases to target or task-relevant aspects of the auditory stimulation [6,42–45].

However, all these 'distraction' studies reviewed above used a frequency deviant, i.e., a distractor stimulus differing in its spectral content from the standard sound, and therefore it cannot be fully ruled out that the cerebral mechanism leading to attention switching and distraction was associated to the N1 generated by fresh neurons responding selectively to the specific frequency of the deviant sound (see Refs. [21,48]). Only in the study of Schröger and Wolff [45], was a control condition used, in which the deviant frequency was presented among nine different frequencies in the same stimulus sequence. By comparing the performance and the ERPs obtained in this control condition with those obtained when the deviant frequency was presented in the context of a high-probability standard frequency (i.e., in an *oddball* condition), the authors were able to demonstrate that a memory-related change-detection mechanism, as indicated by the MMN, was involved in triggering involuntary attention switches towards stimulus changes within the auditory modality. In the present experiment, we also sought to investigate whether genuine change detection was involved in cross-modal attention switching, i.e., in directing attention involuntarily from the current visual performance to unexpected auditory changes. We used a variant of our auditory–visual distraction paradigm in which the 'distracting' sounds were either shorter in duration or softer in intensity, in separate blocks, than the corresponding standard stimuli. An additional condition with frequency deviants was also used. Shorter or softer deviant tones are unlikely to activate new fresh neural elements [32,33], and therefore observation of behavioral distraction to these sounds will strongly support the involvement of a genuine change detection mechanism in controlling involuntarily the cross-modal direction of attention.

2. Materials and methods

2.1. Participants and procedure

Twelve healthy, right-handed human subjects (mean age 21.2±1.1 years; two males), with normal hearing and normal or corrected-to-normal vision participated in the study after informed written consent. While seating comfortably in a reclining chair in a dimly lit, electrically and acoustically shielded room, subjects were presented with six blocks of 500 stimulus pairs (trials) delivered at a constant rate of one pair every 1.2 s. Each trial consisted of an irrelevant auditory stimulus followed after 300 ms (onset-to-onset) by a visual imperative stimulus. The auditory sequence consisted of repetitive standard tones (600 Hz, 200 ms and 85 dB; $P=0.8$) occasionally replaced, in separate counterbalanced blocks, by a slightly higher (700 Hz), shorter (50 ms) or softer (79 dB) deviant tone ($P=0.2$). All auditory stimuli were delivered binaurally through headphones in random order, with the only exception that the trials in which the visual stimulus followed a deviant tone were always preceded by a trial in which the visual stimulus followed a standard tone. Visual stimuli were the digits from 1 to 8 presented one at a time in random order on a computer screen for 200 ms. They subtended a vertical angle of 1.7° and a horizontal angle of 1.1° at 150 cm from the subject's eyes.

Subjects were instructed to focus on a small fixation cross appearing in the middle of the screen and to press one response button with their right-hand index finger for even numbers and another response button with their right-hand middle finger for odd numbers. Instructions were also given to ignore the auditory stimulation. Both speed and accuracy were emphasized for the visual task. Before the experimental session, subjects received one practice block in which the auditory stimulation was omitted, all of them reaching a hit rate level of at least 85%. To avoid tiredness, subjects had a short rest period after each of the blocks.

2.2. EEG recording

The EEG (bandpass 0.1–100 Hz) was continuously recorded and digitized at a rate of 500 Hz by a SynAmps amplifier (Neuroscan) from an array of 30 scalp electrodes, 18 of them positioned according to the 10–20 system (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, and Oz), and 12 of them from the following additional locations: M1 (left mastoid), IM1 (70% of the distance from the preauricular point to the inion), TP3 (halfway between T3 and P3), CP1 (halfway between C3 and Pz), FT3 (halfway between F3 and T3), FC1 (halfway between Fz and C3), and the homonymous positions over the right hemisphere. Horizontal and vertical EOG were recorded with two additional electrodes placed at the canthus and below the left eye, respectively. The common reference electrode for all EEG and EOG measurements was placed on the tip of the nose.

2.3. Data analysis

A correct button press within 800 ms after visual stimulus onset was regarded as a hit, the mean reaction time being computed only for the hit trials. An incorrect button press during this period was classified as an error, and trials with no response as misses. Hits, errors, misses and reaction time were computed across odd and even numbers. Distraction effects caused by deviant tones were analyzed by means of analysis of variance (ANOVA) for repeated measures with type of auditory stimulus (two levels: standard and deviant tones) and condition (three levels: frequency, duration, and intensity deviants) as factors, performed on the mean reaction time, hit rate and error rate to visual stimuli preceded by a standard tone and those preceded by a deviant tone.

ERPs were averaged off-line, separately for standard and deviant tones, for an epoch of 1300 ms including a pre-auditory stimulus baseline of 100 ms. Epochs in which the EEG or EOG exceeded ±100 μV, as well as the first five epochs of each block, were automatically excluded from averaging. Standard-tone trials immediately following deviant-tone trials were also excluded from the averages. Frequencies higher than 30 Hz were filtered out from the individual ERPs. All ERP amplitudes were measured against the mean amplitude of the 100 ms baseline preceding the auditory-stimulus onset.

MMN was measured in the difference waves obtained by subtracting the ERPs elicited to the standard tones from those elicited to the deviant tones as the mean amplitude in a 100-ms latency window around its maximum peak at Fz. The MMN peaks were identified, for each deviant condition separately, in the grand-average difference wave, yielding the following latency windows: frequency deviant, 100–200 ms; duration deviant, 150–250 ms; intensity deviant, 180–280 ms. As the MMN inverts in polarity when the nose is used as the reference electrode [2,11], significant activation of MMN generators was analyzed by a t-test comparison between its mean amplitude at Fz and the left mastoid (M1). Comparison of MMN across deviant conditions was carried out by means of a one-way ANOVA with deviant condition as factor, performed on MMN mean amplitudes at Fz.

Scalp distribution analyses of MMN were performed on ERP amplitudes at 15 electrodes (F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6) after normalization, to prevent genuine differences in scalp distribution from being washed out by amplitude differences. This normalization was done by dividing the amplitude at each electrode by the square root of the sum of the squared amplitudes at the selected electrodes [28]. The scalp distribution ANOVA included three factors: frontality (frontal / central / parietal), laterality (five levels from left to right) and deviant condition (frequency / duration / intensity).

In the ANOVAs and when appropriate, the Greenhouse–Geisser correction of the degrees of freedom was applied, the uncorrected degrees of freedom, the corrected P values, and the ε factors being reported.

3. Results

3.1. Performance

As shown in Fig. 1, subjects had an overall high performance level of about 90% in the visual classification task across the stimulus and deviant conditions. However, the statistical analyses revealed that hit rate decreased significantly by an average 4.6% when the visual stimuli

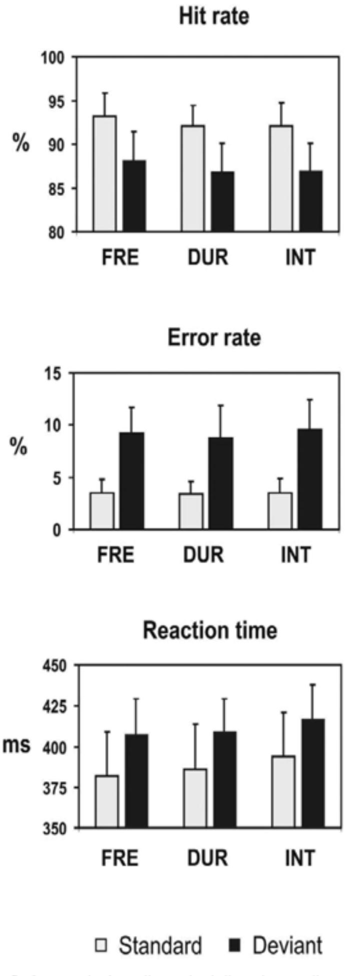

Fig. 1. Performance in the auditory–visual distraction paradigm. Mean hit rate, error rate and reaction time to visual stimuli preceded by frequency (FRE), duration (DUR) and intensity (INT) deviant tones (black columns), and standard tones (white columns) in the corresponding stimulus blocks. Bars indicate the standard error of mean.

were preceded by a deviant tone as compared with those preceded by a standard tone ($F(1,11)=35.47$, $P<0.001$), regardless of deviant condition. This hit rate decrease was due to an increase in the error rate, which changed from 3.5% in the standard trials to 9.1% in the deviant trials ($F(1,11)=32.58$, $P<0.001$), the complementary missing rate being similar across all deviant conditions. Reaction time was also affected by the unexpected occurrence of a deviant tone preceding the visual stimulus, as it was delayed by about 24 ms in comparison to the reaction time to visual stimuli preceded by the standard tones ($F(1,11)=10.91$, $P<0.01$). No statistical differences in reaction time were found between deviant conditions.

3.2. MMN elicited to frequency, duration and intensity deviant tones

The ERPs elicited by the auditory–visual stimulus pairs during visual performance were characterized by a complex waveform, including auditory, visual and target ERP components (Fig. 2). Of interest for the present research was the MMN, which appeared as an increased negativity in the deviant-trial ERPs in comparison to the standard-trial ERPs at Fz, in a latency range varying from 100 to 250–280 ms, depending on deviant condition (Fig. 2). The MMN is usually analyzed in the difference wave obtained by subtracting the standard-tone ERPs from the deviant-tone ERPs. The difference waves thus obtained separately for each of the deviant conditions are shown in Fig. 3, where negative voltages at the frontal electrode line and positive voltages (i.e., polarity reversal) at mastoid electrodes can be seen. Significant MMNs were elicited in all three deviant conditions, as indicated by *t*-test comparisons between the mean amplitude of the MMN at Fz and at the left mastoid (M1) ($t(11)=-3.79$, $P<0.004$ for the frequency deviant; $t(11)=-8.87$, $P<0.001$ for the duration deviant; and $t(11)=-2.65$, $P<0.03$ for the intensity deviant).

As can be seen in Fig. 3, the MMN elicited in the three deviant conditions differed considerably in amplitude, the duration-deviant MMN being the largest. A one-way ANOVA for repeated measures revealed that MMN amplitude differed significantly indeed among conditions ($F(2,22)=19.43$, $P<0.001$, $\varepsilon=0.83$; at Fz). Post-hoc *t*-test comparisons revealed that the duration-MMN was larger than the frequency- ($t=-6.62$, $P<0.001$) and intensity- ($t=-4.94$, $P<0.001$) MMNs, whereas these two latter MMNs were of similar amplitude ($t=-0.69$, $P=0.51$, n.s.).

3.3. Scalp distribution of MMN

When the nose is used as the reference electrode, the MMN typically has a frontal negative maximum, and a polarity reversal, i.e., positive voltages, over the electrodes positioned below the Sylvian fissure. This typical scalp distribution was observed in all three deviant conditions in the present experiment. However, as can be seen in Fig. 4, there were pronounced differences in the particular scalp distribution yielded by each type of deviant tone. The duration-MMN was frontally distributed, with little polarity reversal at posterior sites, whereas the frequency-MMN had a clear positive distribution over posterior areas, with small amplitudes over the frontal electrodes. The intensity-MMN, in turn, showed two clear maxima located over the

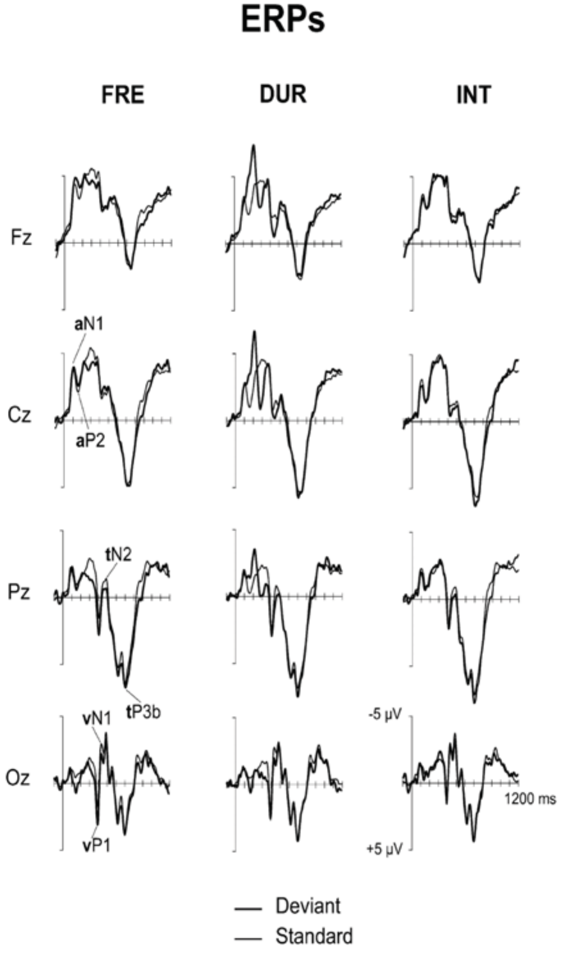

Fig. 2. Event-related brain potentials (ERPs) at Fz, Cz, Pz, and Oz elicited in the three deviant conditions. The left column shows the standard (thin line) and deviant (thick line) ERPs elicited in the frequency deviant condition, and the middle and right columns correspond to the duration and intensity deviant conditions, respectively. Note that the auditory–visual pairs elicited a complex ERP response, characterized by auditory N1–P2 at Cz (**a**N1, **a**P2), visual P1–N1 at Oz (**v**P1, **v**N1), and by target (visual) N2–P3b at Pz (**t**N2, **t**P3b). Notice also that deviant tones elicited the MMN, which appeared as an increased negativity in the deviant tone ERP as compared to the standard tone ERP at Fz, in the latency range comprised between 100 and 250 ms, depending on deviant conditions.

left and the right temporal regions, respectively. A three-way ANOVA for repeated measures, with the factors deviant-type, frontality and laterality performed on MMN mean amplitudes, yielded significant deviant-type× laterality ($F(8,88)=3.75$, $P<0.02$, $\varepsilon=0.45$) and deviant-type×frontality×laterality ($F(16,176)=2.40$, $P<0.05$, $\varepsilon=0.31$) interactions, confirming the existence of such scalp distribution differences.

4. Discussion

The results obtained in the present experiment demonstrate that, in addition to frequency changes [3,6,12,13,42–45,47,48], changes in duration and intensity of unexpected, task-irrelevant sounds activate the cerebral network of involuntary attention to cause behavioral distraction. Indeed, the occurrence of slightly shorter or softer deviant

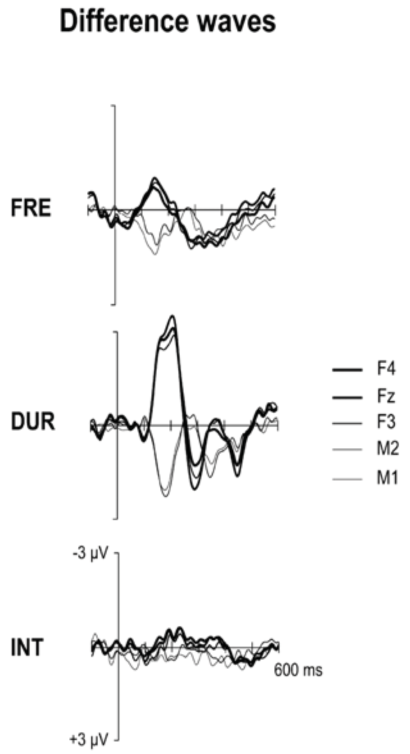

Fig. 3. Difference waves showing the MMN. Difference waves were obtained by subtracting the ERPs elicited to the standard-tone pairs from those elicited to the deviant-tone pairs, for the frequency (upper panel), duration (middle panel), and intensity (lower panel) deviant conditions separately. All three deviant tones elicited a MMN with a polarity reversal at mastoid electrodes, which was largest for the duration deviant tone and smallest for the intensity deviant tone.

tones shortly preceding visual targets increased reaction time and error rate to these targets, as compared to performance to visual targets preceded by standard tones. These distracting effects were of similar magnitude (about 24 ms increase in reaction time and 5.6% increase in error rate) regardless the type of auditory feature changed in the deviant tone with regard to the standard tone. This similar amount of distraction is intriguing because the magnitude of change used in each of the deviant conditions varied from about 7% in intensity to about 17% in frequency, and to 75% in duration, and contrasts with the distracting effects of small and large deviances observed in the study of auditory distraction of auditory performance by Schröger [42]. This author found that a large frequency change (29%), compared to a small frequency change (7%), caused larger behavioral distraction on an auditory discrimination task. However, one should be cautious when comparing the magnitude of change in different sound parameters and the corresponding distracting effects, as it is well established that there are specific rules governing the relationships between the physical and perceptual features of each sound parameter.

The aim of the present experiment was to investigate whether a genuine change detector mechanism, as reflected in the MMN, was involved in triggering involuntary attention switches towards unexpected auditory deviant sounds during visual performance. Previous studies had shown that frequency deviant tones, eliciting the MMN, caused behavioral distraction, as indicated by reaction time delays and hit rate decreases in the performance of a concurrent task, both in the auditory [6,42–45] and visual modalities [3,12,13,47,48]. As in all of these studies the MMN could be recorded, it was concluded that change detection, as reflected in this ERP component, was involved in triggering the attention switching signal to drive attention involuntarily towards those frequency changes. However, this interpretation should be considered with caution, at least for the studies conducted during visual performance. Indeed, as a result of the tonotopic organization of the auditory cortex [36,40], it cannot be ruled out that a frequency change, even of very small magnitude, activate specific neurons responding to its particular frequency, and therefore that the MMN seen in the recordings correspond in fact, at least in part, to the N1 generated by those specific neurons, remaining in a less refractory state than those responding to the standard frequency due to the lower rate of deviant stimulus presentation [21]. Furthermore, in a study of the temporal dynamics of the SCD of the MMN elicited to frequency changes, Yago et al. [48] found that the frontal MMN generating source was activated over the right hemisphere on average 20 ms before than the supratemporal MMN source. The authors suggested that this anticipation may be due to N1 activity associated with the analysis of the physical features of the deviant tone, and therefore concluded that detection of frequency changes leading to behavioral distraction may involve the transient-detector mechanism associated to N1 [29,34]. The data obtained in the present experiment, however, suggest that a genuine change detection mechanism is involved in involuntary attention switching. Indeed, in addition to frequency deviant tones, we also obtained MMNs elicited to both duration and intensity deviant tones as well as concomitant behavioral distraction. As shown by Näätänen and co-workers, shorter duration [33] and softer intensity [32] deviant tones are unlikely to activate new fresh element responding to decreases in stimulus energy, and therefore the MMN recorded in the present experiment may reflect a genuine change detection mechanism of the auditory cortex. Recent studies, however, have shown an ampliotopic organization of the cat auditory cortex [20] (see also Pantev et al. [37]) and the existence of specific duration neurons also in the

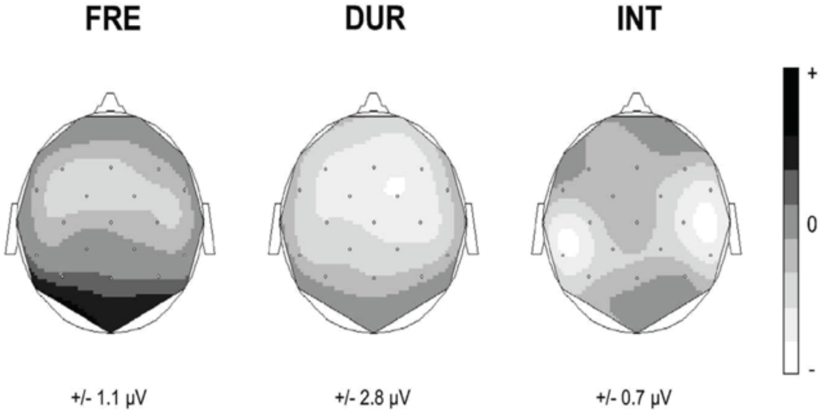

Fig. 4. Scalp distribution of the MMN. Scalp isopotential maps were obtained by spherical-spline interpolation of the MMN identified as the mean amplitude in a 100-ms latency window centered around its maximum peak, for the frequency (left), duration (middle), and intensity (right) deviant conditions separately.

cat auditory cortex [19], and therefore a direct demonstration of the involvement of truly change detection in cross-modal involuntary attention switching would require a control condition similar to that used by Schröger and Wolff [45] with frequency deviants.

The MMNs recorded to the frequency, duration and intensity deviant tones differed considerably in scalp topography. These differences in scalp distribution are in agreement with those reported by Giard et al. [14], who described that the MMN elicited to these same types of deviant tones could be modeled by dipoles differing in location within the supratemporal auditory cortex, and confirm the suggestion that detecting changes of specific auditory features is carried out by different neural populations of the human auditory cortex. As the activation of the MMN generating neural populations was associated with behavioral distraction, and considering the positive correlation between the supratemporal MMN activation and behavioral distraction described elsewhere [48], the present results suggest that a largely distributed neural network of the auditory cortex subserves involuntary attention switching towards auditory change.

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4.2. Study II

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Submission no.: NR-D-08-6766R1
Article title: Effects of sound location on visual task performance and electrophysiological measures of distraction
Corresponding author: Prof. Carles Escera

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Effects of sound location on visual task performance and electrophysiological measures of distraction

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Abstract

Novel sounds embedded in a repetitive stream of auditory stimuli impair performance of the visual task at hand. Parmentier *et al*., [1] suggested that this distraction effect may be due to the shifting cost of moving attention from the task-irrelevant (auditory) to the task-relevant (visual) channel, or from their shifting of spatial locations. Here, the source location of the sounds in an audio-visual distraction paradigm was varied systematically (headphones and 0, -18, -72, 18, and 72 degrees), and the results revealed significant distracting effects of novel sounds occurring in the headphone and the right location conditions. This supports the assumption that in the behavioral cost observed in the audio-visual distraction paradigm a spatial shift of attention is involved.

Keywords: evoked potentials, audition, involuntary attention, orienting response, interlateral asymmetry, hemineglect, pseudo-neglect

Introduction

Research into the neural mechanisms of involuntary auditory attention has experienced considerable progress in recent years thanks to the development of specific “distraction” paradigms [2,3]. In these paradigms, participants classify auditory [4] or visual [4,5] stimuli while ignoring concurrent, task-irrelevant auditory information. The occurrence of any stimulus change in the task-irrelevant auditory channel leads to prolonged response times (RT) in the auditory or visual classification task, reflecting “distraction” of current task performance. This “distracted” performance is accompanied by a pattern of event-related brain potentials (ERPs), the “distraction potential” [3], which includes the mismatch negativity (MMN; [6,7]) and an N1 enhancement for novel sounds [5], the novelty-P3 [8], and a new ERP component discovered in this context of behavioral distraction, the reorienting negativity (RON; [9-11]).

The distracting effects in the auditory-auditory distraction paradigm might be accounted by the moving of attention from one auditory dimension (e.g., task-relevant duration) to another (e.g., a task-irrelevant pitch change) of the same perceptual object, leading to large behavioral effects [2-4,11,12]. Less obvious is which stage of visual task-performance is interfered by the occurrence of the task-irrelevant sound change. Alho *et al.* [13] found that the visual target N1 ERP component was attenuated when the preceding sound deviated in pitch compared to the preceding standard frequency, suggesting that early visual target processing was impaired in distracting trials. However, this could not be confirmed for novel sounds in a study in which visual stimulus identification was made harder by masking the visual targets with a white noise mask [1]. This manipulation enlarged considerably the RT as expected, but left the magnitude of distraction similar to that of a control condition without mask, suggesting that the distracting effect of novel sounds occurred “before” the presentation of the imperative visual stimulus.

To confirm this hypothesis, Parmentier and colleagues [1] flashed quickly (50 ms) a shrinking cross in the time period between the auditory, task-irrelevant stimulus and the visual target. They found that the distracting effects of novel sounds were abolished in this condition, suggesting that the RT increase observed in the distracting trials would reflect the time necessary to move the attention drawn to the auditory distracters back to the visual modality upon the occurrence of a fresh sensory event in the task-relevant channel, i.e., vision. However, as discussed by the authors [1], this pattern of results could be also explained by the time necessary to move attention between spatial locations instead of sensory modalities, as the visual stimuli were displayed in a screen located in front of the subject, whereas the sounds were presented through headphones.

The present study investigated the role of the spatial source of the auditory stimuli on distraction of visual task-performance. For this purpose, sound location was varied systematically across conditions whereas visual target location remained constant. Notice that we did not intend to assess the effects of distracter location on visual task-performance [14], but those of varying the location of the sound source on distraction. If distraction depends on moving attention between sensory modalities, having the source of the task-irrelevant auditory stimuli in different spatial locations should not affect the distracting effects of these sounds. However, if a spatial factor is involved, larger distracting effects of novel sounds on visual task-performance, and eventually on accompanying ERP signs of distraction, should be obtained with larger spatial separation between the auditory and the visual stimulus sources.

Methods

Subjects

Thirteen healthy students (19-30 years; mean age 23 ys; 6 females) participated in the study, which was approved by the Ethical Committee of University of Barcelona. According to their own report, all subjects were right-handed. As the purpose of the study was to investigate the possible role of sound source location on distractibility, only subjects that showed behavioral distraction in a pilot condition using headphones were included in the sample. Informed consent was obtained from each subject.

Stimuli

Visual stimuli were the digits 1 to 8 presented equiprobably on a computer screen placed at 1.15 m from the subject’s eyes. The vertical and the horizontal viewing angles were of 2º and 1.25º, respectively. Two types of auditory stimuli were presented with the same duration (150 ms, rise/fall 10 ms): standard and novel. Standard stimuli were pure tones of 600 Hz occurring with a probability of $p=0.8$. Novel stimuli ($p=0.2$) were 60 environmental complex sounds selected as the more familiar from a previous study [15]. The auditory stimuli preceded the visual stimuli in 300 ms (onset-to-onset). All stimuli were generated and delivered by means of the Stim module of Neuroscan system (Vernon, VA, USA).

Procedure

Subjects were instructed to press with their thumbs, as fast and as accurate as possible, one response button for even and another response button for odd numbers, while ignoring the sounds. Response buttons was counterbalanced across subjects. The task was administered in blocks (one per condition) of 300 pairs of stimuli (auditory-visual trials) at a constant inter-trial-asynchrony of 1200 ms. In different source location conditions, the auditory stimuli were delivered from different spatial locations through loudspeakers located, with regard to the subject's head, at 0º (i.e., by the computer screen), and at -18, -72, 18, 72 degrees (Fig. 1a). In a further condition, the auditory stimuli were delivered through headphones. The sound intensity of all conditions was adjusted to 85 dB SPL at subjects' ears. Before the experimental session, subjects received one practice block without any auditory stimulation, and all of them reached a hit rate level of at least 90%. Short rest periods were allowed at the middle and the end of each block.

EEG-recording

The electroencephalogram (EEG) was continuously digitized at a rate of 500 Hz (bandpass 0.05-100 Hz) by SynAmps amplifier (NeuroScan Inc., Herndon, VA., USA) from 30 scalp tin electrodes (Electro-Cap Int., Eaton, OH) positioned at Fp1, Fp2, F7, F3, Fz, F4, F8, T5, T3, C3, Cz, C4, T4, T6, P3, Pz, P4, O1, Oz, and O2, and at ten additional positions (FC1, FT3, CP1, TP3 and LM, and the homologous positions over the right hemisphere). The electro-occulogram (EOG) was recorded with electrodes attached to the canthus and below the left eye. The common reference electrode was attached to the tip of the nose.

Data analysis

Mean RT, hit rate (HR), error rate (ER) and miss rate (MR) were calculated for the digits preceded by standard and novel stimuli separately. Only responses between 100 and 800 ms after visual stimulus onset were included in analyses. RTs were calculated only for hit trials. No button press or a response 100 ms before or 800 ms after visual stimulus onset computed in the MR. Distraction effects caused by novel stimuli were analyzed by means of analysis of variance (ANOVA) for repeated measures with the type of auditory stimulus (standard, novel) and location (headphones, 0º, -18º, -72º, 18º, 72º) as factors. Subsequent analyses were carried out by Student's *t*-tests between standard and novel stimuli for each location. The magnitude of the distraction was analyzed, in all possible pairs of locations, by Student's *t*-tests on the arithmetical subtraction obtained from the RT to the novel *minus* the RT to the standard trials. The Bonferroni correction was applied when appropriate.

ERPs were averaged off-line for each auditory stimulus type separately over an epoch of 1100 ms, including a pre-auditory stimulus baseline of 100 ms. An artifact rejection algorithm was applied to exclude trials with excessive muscular or ocular activity. This algorithm computed the standard deviation of the amplitude within a slide window of 200 ms along the entire EEG recording, and excludes from averaging any epoch exceeding by 30 µV from this standard deviation at any of the electrodes. The first five epochs at the beginning and after the break of each block were excluded also from averaging. After applying these excluding criteria, a minimum of 42 novel and 168 standard trials was included in every condition, there being no significant differences in the number of averaged trials between conditions. Individual ERPs were band-pass filtered between 0.1 and 30 Hz.

The electrophysiological signatures of novel sound processing were analyzed on the difference waveforms obtained by subtracting the standard-trial ERPs from the novel-trial ERPs, for each source location condition separately. Mean amplitudes of the three main waveforms of the distraction potential were analyzed in latency windows centered at the corresponding peak in the specified electrodes: N1-enhancement/MMN (Cz, 110-165 ms), early novelty-P3 (200-260 ms) and late (285-345 ms) novelty-P3 (F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, P6), and RON (F3, Fz, F4, 460-560 ms). For each ERP component, the headphones and the 0º source location condition were compared against each other. The remaining source locations were analyzed with angle (18º, 72º) and hemispace (left, right) as factors in the ANOVA. In the analysis of the novelty-P3, the factors phase (early, late), frontality (3 levels) and laterality (5 levels) were also included en the ANOVAs. When appropriate, degrees of freedom were corrected with the Greenhouse-Geisser method, and the reported *F*, *p*-values and η^2 effect size index were based on this correction.

Results

Subjects had an overall hit rate of 86%. The ANOVAs revealed no significant effects on HR, ER, and MR. However, visual RT was on average 10 ms slower when the preceding auditory stimulus was a novel sound compared to when it was a standard tone [$F(1,12) = 12.02$, $p = 0.005$, $\eta^2 = 0.50$; Fig. 1b]. The behavioral distraction when the sounds were presented through the headphones was of 8 ms (t(12) = -2.44, p = 0.031).

-- Insert Figure 1 about here --

Subsequent paired *t*-test comparisons revealed, after the Bonferroni correction for multiple comparisons, that the effect on RT was due to a significant distracting effect of novel sounds when sounds where presented at the 18º [15 ms; t(12) = -4.44, p = 0.001] and 72º [19 ms; t(12) = -4.47, p = 0.001] sound source location conditions. Moreover, the magnitude of the distracting effect showed a linear increase from left to right, as supported by the significant linear regression between sound source location and the median RT difference between novel and standard trials [F(1,3) = 24.821, p = 0.016; Fig. 1c].

The statistical analyses on the electrophysiological data did not reveal any significant differences on the mean amplitudes of the N1/MMN, novelty-P3 and RON components for the headphones and 0º source location conditions (Fig. 2a). Moreover, no significant differences were found for the N1/MMN and RON components for the remaining source location conditions. The only significant difference was found to the angle factor upon the novelty-P3 [F(1,12) = 5.55, p = 0.036, η^2 = 0.50; Fig. 2b], which indicated that novelty-P3 was larger over its two phases when the sounds were presented in source locations closer to the computer screen (-18º and 18º) than when they occurred in the locations far apart from the computer screen (-72º and 72º).

-- Insert Figure 2 about here --

Discussion

Subject’s performance to classify digits into odd and even categories was affected, overall, by the unexpected occurrence of novel sounds, as shown by slower RTs to visual target stimuli that were preceded by a novel stimulus than to those preceded by a repetitive standard tone. This behavioral distraction is in agreement with many previous studies using similar paradigms with visual and auditory primary tasks (see [3] for an extensive review). However, subsequent analyses revealed significant effects only at the headphones condition, and when the sounds were presented from sources located only on the right hemispace (i.e., 18º and 72º). In other words, novel sounds had no distracting effects on visual task-performance when they occurred by the computer screen, nor when they originated from a sound source located in the left hemispace.

The most relevant finding of the present study was that the distraction effect of novel sounds was abolished when the sounds shared the same spatial location as the task-relevant visual stimulation, i.e., in the 0º sound source location condition. This result militates against one of the suggestions of Parmentier el al. [1], proposing that distraction in the auditory-visual distraction paradigm would be due to the time required to move attention from the auditory modality to the visual channel at the occurrence of a fresh sensory stimulus in the task-relevant channel. In addition, the increase of the distracting effect as a function of the angular distance between the sound source and the target location support the involvement of shifting spatial attention as the cause of the distracting effects involved in the auditory-visual distracting paradigm, as already suggested tentatively by Parmentier *et al*. [1]. Moreover, the role of the need of shifting spatial attention to elicit distraction in the audio-visual distracting paradigm would explain why previous studies using loudspeakers located by the visual targets as the sound source failed to eliciting measurable distracting effects using deviant syllables [16].

A second interesting finding was that the distraction effects of novel sounds were only significant when they occurred in spatial source locations by the right side of the space. In fact, these effects were, according to our regression analysis, larger the farther to the right the sounds were delivered with regard to the computer screen location, supporting the view that auditory spatial attention is distributed in a gradient fashion from peripheral auditory space [17-18]. These results are in agreement with a series of studies on involuntary orienting of attention in the visual modality, showing that pop-out or prime stimuli occurring in the right visual hemifield have larger disturbing effects than those occurring in the left hemifield [19-21]. In addition, they also match with MMN data showing an advantage for processing auditory spatial information in the right compared to the left hemispace [22, 23]. Taking together, our results support the view that the involvement of left and right brain regions in the control of automatic attention on the right hemispace provides a rightward bias for the behavioral influence of unexpected stimuli in right side of the environment [24].

The only remarkable effect on the electrophysiological data was that the novelty-P3 was larger for novel sounds originating from sound source locations near by the computer screen than for remote locations. Several studies have shown the sensitivity of the novelty-P3 to attentional manipulations [5,8,15,25], and one may therefore argue that novel sound occurring closer to the attended extrapersonal space, i.e., by the computer screen, were expected to elicit larger responses than those occurring far away from the attentional set. On the other hand, the lack of relationship between the amplitude of the novety-P3 and the observed behavioral disruption of visual-task performance, give support to recent views that challenge an explicit relationship between the novelty-P3 and the orienting response [3].

Conclusion

The results obtained showed that the distracting effects of novel sounds observed in a condition where the sounds were presented through headphones disappeared when the sounds occurred at the same location of the visual targets. Moreover these distracting effects were of increasing magnitude as the angular distance between the sound source and the visual location increased, all in all supporting the role of shifting spatial attention in the well-characterized auditory-visual distraction paradigm.

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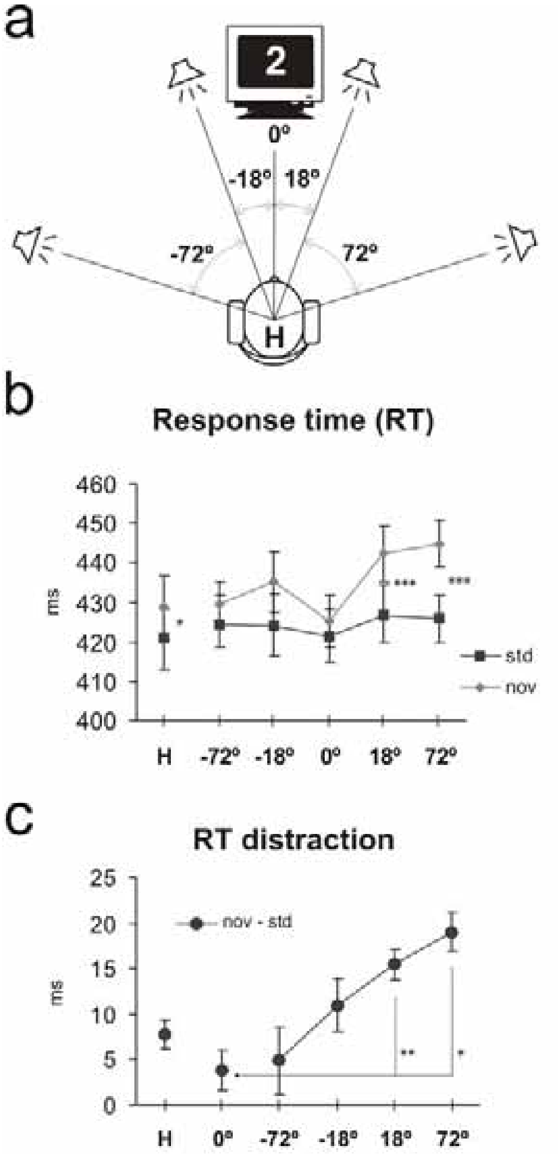

Figure 1. **a)** Outline of the experimental setting. Subjects sat 115 cm in front of a computer screen, and the sounds were presented, in different source location conditions, from headphones (H) or from loudspeakers located at 72º and 18º degrees of either side, and from a central location, i.e., by the computer screen (0º). **b)** Response time (RT) for standard (std) and novel (nov) trials in each location condition. **c)** Behavioral distraction(novel RT *minus* standard RT) as a function of location. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

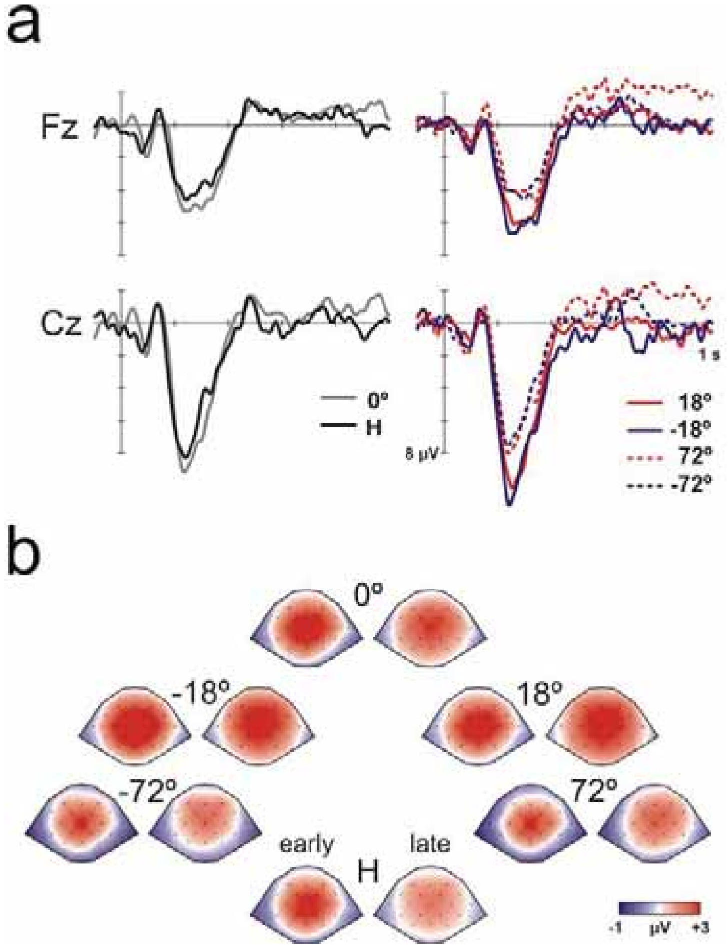

Figure 2. **a)** Difference waveforms obtained by subtracting the novel *minus* de standard ERPs at Fz and Cz. **b)** Scalp distribution maps of the two phases of the novelty-P3 (early: 200-260 ms; late: 285-345 ms) for all source location conditions.

4.3. Study III

Corral, M.J., Berti, S., Jacobsen, T., Widmann, A., Yago, E., Schröger, E., & Escera, C. *(submitted).* Distraction effects with different distractor-to-target intervals: a combined behavioral and event-related brain potential study.

Distraction effects with different distractor-to-target intervals: a combined behavioral and event-related brain potential study

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Abstract

In order to evaluate whether the temporal distance between the task-irrelevant change and the task-relevant information is critical for distraction and whether the RON component indicate a pure signal of reorientation to the task independently to deviance onset, slight pitch changes were introduced in an auditory duration discrimination task while the target onset remained constant. Impaired performance was observed after each deviance onset. However, the pattern of distraction was different as a function of the deviance onset (at 50 or 150 ms) and the type of target processing (short or long stimuli). The RON component was not strongly synchronized to the target onset. The present results contribute to the mental chronometry of auditory distraction by showing that task-irrelevant information affects different stages of target processing and the reorienting of attention to the task is not totally independence of the distractor processing.

Descriptors: human, audition, mismatch negativity (MMN), P3a, reorienting negativity (RON), deviant asynchrony, impulsive style, reflexive style, slow responses, inaccurate responses.

Introduction

In everyday live, our senses are constantly stimulated by information. The adaptive control of behavior requires the integration and coordination of relevant information for our task at hand and the flexibility to react to unexpected new events. Driving a bike requires focus on the way and being able to detect unexpected changes around, for instance the sudden appearing of a child. The ability to respond to changes is maintained by the capability of the sensory systems to detect irregularities without focused attention which, subsequently, may result in the allocation of attention onto new information. However, it is still unclear under what circumstances a switch of attention after the detection of a change is accomplished.

In a series of studies the potential of physical changes to catch attention was tested by so called distraction paradigms demonstrating response times prolongation on a primary task by changes of a task irrelevant stimulus feature (Berti & Schroger, 2003; Escera, Alho, Winkler, & Naatanen, 1998; Escera, Corral, & Yago, 2002; Escera, Yago, Corral, Corbera, & Nuñez, 2003; Schroger & Wolff, 1998a,b; Schroger, Giard, & Wolff, 2000). The advantage of this distraction logic is that the processing of a non-attended physical information could be tested. These studies established that the behavioral distraction effects depend on the size (Berti, Roeber, & Schroger, 2004), the unpredictability (Munka & Berti, 2006; Sussman, Winkler, & Schroger, 2003), and the channel proximity of the change to the task-relevant information (Schroger & Wolff, 1998a). That is, large and unpredictable distractors such as a telephone ring may obviously yield larger distraction than small distractors, which are physically similar to standard auditory background, or than predictable stimuli (e.g., visually cued ones). On the other hand, there is no systematic investigation how a distractor interferes to cause impaired performance. In detail, the question is whether the task-irrelevant stimulus may affect to any stage of the task-relevant processing or, whether there is a particular vulnerable temporal window between the distractor and the target stimulus which determines more distraction. In the present study we investigated this question by manipulating the onset of the deviant stimulus information without changing other aspects of the stimuli and the task itself.

In a previous study, Schröger (1996) showed impoverished performance (hit rate decrease and response time increase) when the task-irrelevant stimulus change was presented at 200 ms from the task-relevant tones, whereas no detrimental performance was found when the interval was enlarged to 560 ms. Later, Escera, Yago, & Alho, 2001 also used two different asynchronies between the task-irrelevant sound and the subsequent imperative visual stimulus. Participants were slower to classify the visual stimulus when it was preceded by a slightly higher deviant tone or a novel environmental sound than when the visual target was preceded by a repetitive standard tone. However, no performance differences were found irrespective of whether the asynchrony between the task-irrelevant sound and the task-relevant visual stimuli was of 245 or 355 ms. Moreover, a negative component related to reorienting of attention to towards main task performance after distraction (RON) appeared synchronized to the task-relevant information.

Different temporal distances between distractor and target onset has been manipulated in an auditory duration discrimination task, where distractor onset coincided with the stimulus onset and the temporal difference between the short and the long stimuli determines target onset. For example, when participants are to classify short stimulus of 200 ms and long stimulus of 400 ms, the distractor (task-irrelevant change) begins with stimulus onset, whereas the task-relevant target onset occurs 200 ms later (when the stimulus should finished, if it was a short stimulus). With this paradigm, it has been shown that asynchronies between deviance onset and target onset of 200 ms (Roeber, Berti, & Schoger, 2003; Roeber, Widmann *et al.*, 2003; Schroger & Wolff, 1998b; Schroger *et al.*, 2000) and 100 ms (Schroger & Wolff, 1998a) are effective enough to cause behavioral distraction. Moreover, Rinne, Sarkka, Degerman, Schroger, & Alho (2006) showed that task-irrelevant decrements or increments of intensity when participants had to discriminate between two equiprobable sounds which differed in pitch, that is, when the distance between the task-relevant and the task-irrelevant feature was of 0 ms, also caused distraction. In addition, (Roeber, Widmann *et al.*, 2003) found slower responses when infrequent long stimuli (400 ms) appeared in a sequence of repeated short stimuli (200 ms) and participants had to discriminate the localization of the sound (front or left), that is, when the task-irrelevant feature came 200 ms after the task-relevant information. So it seems that task-irrelevant changes presented from -355 ms to 200 ms relative to the target onset could impair performance.

The present study addressed two specific questions. First, whether the occurrences of the auditory change at different asynchronies from the target feature onset could affect the magnitude of distraction. Second, whether the reorienting of attention indexed by RON is insensitive to the deviance onset, as in the previous study of Escera, Yago, & Alho, 2001. For that purpose, participants were instructed to respond to short (200 ms) and long stimulus (400 ms) and ignore all other aspects of stimulation. Most of the tones (p=0.88) had the same pitch from the beginning to the end (standard tones, STD) and in a small set of stimuli (p=0.12) slight task-irrelevant pitch changes were introduced (deviant stimuli, DEV). Two time points (fig. 1) were selected maintaining a similar distance between them around 100 ms as the previous study (Escera, Yago, & Alho, 2001). One pitch deviance was presented early, at 50 ms from stimulus onset (early-DEV). The other pitch deviance was presented later, at 150 ms from stimulus onset (late-DEV). Because the short stimuli were of 200 ms and the long stimuli of 400 ms, the discrimination point between them occurred at 200 ms from stimulus onset (point when the short stimulus finished and the long stimulus continued). So, target onset remained constant through deviant stimuli. Whether a temporal window that determines more distraction exists, different behavioral responses should be recorded between conditions. Moreover, whether RON shows the reorienting of attention to the relevant information, it should be peaked at the same time window between deviant conditions, because for both deviant conditions target onset began at the same time.

Methods

Participants

Twelve healthy students of the University of Leipzig (18-25 years; mean age 21 ys; 2 males) participated in the study for either course credit or payment (12 €). All of them were right-handed and none reported auditory dysfunction. One further participant and the long late-DEV ERP condition of another participant were discarded due to technical problems. Informed consent was obtained from each participant, after the nature of the study was explained to them.

Stimuli

Short (200 ms) and long (400 ms) stimuli were presented with equal probability of appearance (p=0.5). The pitch of the stimuli was the same, from the beginning to its end, for standard stimuli (p=0.88), or changed, at some point from sound onset, for the deviant stimuli (p=0.12). That is, standard stimuli (STD) were short or long sinusoidal tones of 1000 Hz, with equal probability of appearance (p=0.44 each one). In turn, deviant stimuli had a first segment of the same pitch as the standard stimuli (1000 Hz), and a second segment of slightly higher pitch (1100 Hz). The transition between the standard and the deviant pitch was carried out over a window of 20 ms centered at the point of change. As shown in Fig. 1, the duration of the initial segment was of 50 ms or 150 ms from stimulus onset. That is to say, for the early deviant stimulus (early-DEV), there was 150 ms of pitch change before target onset (i.e., discrimination point between short and long stimulus 200 ms from stimulus onset), while for the late deviant stimulus (late-DEV), there was 50 ms of pitch change before target onset. As the standard stimuli, both type of the deviant stimuli could be short or long in duration (i.e., 200 or 400 ms), and had equal probability of appearance (p=0.03 each one). All stimuli were delivered binaurally through headphones at intensity of 75 dB SPL and with a rise and fall time of 5 ms.

Procedure

Participants were instructed to press, as fast and as accurately as possible, one response button for the short stimuli and another response button for the long stimuli. Since only the stimulus duration information was relevant for the task, participants were also instructed to concentrate on stimulus duration and to ignore all other aspects of stimulation (e.g., pitch). The task was administered in 12 blocks of 200 auditory stimuli delivered each, at a constant stimulus-onset-asynchrony (SOA) of 1300 ms. Standard and the two types of deviant stimuli were presented within the same block in random order, with the only restriction that at least the first four stimuli of each block were standard stimuli, and that two deviant stimuli never appeared consecutively. Before the experimental session, participants received one practice block with only standard tones, and all of them reached a hit rate level of at least 85%. To avoid tiredness, participants had a short rest period after each block. In order to reduce eye-blinks and movements during the EEG recording, participants were instructed to focus on a central fixation point.

EEG-recording

The experiment was conducted in a dimly lit, electrically and acoustically shielded room. The electroencephalogram (EEG) was continuously digitized at a rate of 500 Hz (bandpass 0.05-100 Hz) by SynAmps amplifier (NeuroScan Inc., Herndon, Va., USA) from 20 scalp Ag/AgCl electrodes positioned according to the 10-20 system (Fp1, Fp2, F7, F3, Fz, F4, F8, T5, T3, C3, Cz, C4, T4, T6, P3, Pz, P4, O1, Oz, and O2). The electrodes were mounted in an elastic cap (Easy Cap FMS, Munich, Germany). Two additional electrodes were placed on left (M1) and right (M2) mastoids. The electro-occulogram (EOG) was recorded with electrodes attached to the left canthus and below the left eye. The reference electrode was attached to the tip of the nose.

Data analysis

Mean response times (RT), hit rate (HR), error rate (ER) and miss rate (MR) were calculated for the standard and the two types of deviant sounds, as well as for short and long stimuli, separately. Only responses between 300 and 1200 ms after stimulus onset were included in the computation of RT, HR and ER. RTs were calculated for hit trials only, with respect to the onset of the duration difference between the short and long stimulus, i.e., taking the zero time at 200 ms from stimulus onset. No button press or a response before 300 ms from stimulus onset computed in the MR. Distraction effects caused by deviant stimuli were analyzed by means of analysis of variance (ANOVA) for repeated measures with type of auditory stimulus (STD, early-DEV, and late-DEV) and stimulus duration (short, long) as within-subject factors, performed on the mean RT, HR, ER and MR. Post-hoc analysis of the magnitude of the distraction as a function of the type of deviant stimuli was based on non-pooled contrasts.

ERPs were averaged off-line for each auditory stimulus type separately over an epoch of 1000 ms which included a pre-auditory stimulus baseline of 200 ms. Artifact rejection was performed to exclude trials with extreme EOG activity. Standard deviation was calculated within a slide window of 200 ms along all the EEG. Intervals exceed 50 μV in the horizontal and 40 μV in the vertical EOG from the standard deviation, as well as, the first four epochs of each block, were automatically excluded from averaging. Individual ERPs were band-pass filtered between 1 and 30 Hz.

Target (N2 and P3b) and difference wave (MMN, P3a and RON) ERP components were analyzed. Mean amplitude to N2 and P3b for the short and long standard stimulus was compared by *t*-test analysis.

Mean amplitude to the P3b component for the deviant stimulus was analyzed by means of an ANOVA for repeated measures with deviant type (early-DEV, late-DEV) and stimulus duration (short, long) as within-subject factors. Moreover, P3b scalp distribution was analyzed on the ERP-normalized amplitudes (McCarthy & Wood, 1985) at F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4 and T6, by an ANOVA with target type (short STD, long STD, short early-DEV, long early-DEV, short late-DEV, long late-DEV), frontality (frontal, central, parietal) and laterality (left, central, rigth) as factors. Difference waveforms were calculated by subtracting ERPs elicited by standard stimuli from those elicited by deviant stimuli of the same duration. Mean amplitude of MMN at Fz was analyzed by means of an ANOVA with deviant type (early-DEV, late-DEV) and stimulus duration (short, long) as factors. Scalp distribution of P3a and RON was analyzed by an ANOVA with deviance onset (early-DEV, late-DEV), stimulus duration (short, long), frontality (frontal, central, parietal) and laterality (left, central, rigth) as factors. Peak-latencies over Fz of MMN, P3a and RON were analyzed independent ANOVAs with deviance onset (early-DEV, late-DEV), stimulus duration (short, long) as factors.

The temporal window for all the components analyzed (in parenthesis, the relevant electrode to select on visual inspection the largest peak to center the latency window) was taken from the stimulus onset to the individual target ERP components (N2 and P3b), and from the deviance onset to the difference waveform components (MMN, P3a and RON). The interval analyzed for N2 (Cz) was 345−395 ms for all the targets. P3b (Pz) was analyzed in the following temporal windows: 495−595 ms for the standard, 565−665 ms for the early-DEV, and 630−730 ms for the late-DEV stimuli. MMN (Fz), P3a (Fz, Cz, Pz) and RON (Fz, Cz, Pz) components were analyzed for the early-DEV condition at 150−200 ms, 230−330 ms, 380−530 ms, respectively, and for the late-DEV condition at 145−295 ms, 230−330 ms, 355−505 ms, respectively. ANOVAs were carried out with the Greenhouse-Geisser correction. When appropriated, we reported the *F* value, the uncorrected degrees of freedom, probability level following correction and the η^2 effect size index.

Results

Performance

Across stimulus duration and stimulus types, participants had an overall high performance level of about 92% classifying short and long stimuli. The stimulus duration factor (short, long) did not reach significant differences in hit rate (HR) [$F(1,11) = 4.43$, $p = 0.059$, $\eta^2 = 0.29$] or error rate (ER) [$F(1,11) = 4.30$, $p = 0.062$, $\eta^2 = 0.28$], although response time (RT) was clearly prolonged for the long than for the short stimuli [$F(1,11) = 90.92$, $p < 0.001$, $\eta^2 = 0.89$] (Fig. 2). Miss responses did not yield significant differences for any factor or interaction.

Stimulus type factor (STD, early-DEV, late-DEV) was significant for HR [$F(2,22) = 17.39$, $p = 0.001$, $\varepsilon = 0.58$, $\eta^2 = 0.61$], ER [$F(2,22) = 17.45$, $p = 0.001$, $\varepsilon = 0.56$, $\eta^2 = 0.61$], and RT [$F(2,22) = 61.93$, $p < 0.001$, $\varepsilon = 0.83$, $\eta^2 = 0.85$]. Post-hoc comparisons based on non-pooled contrast revealed that participants were more inaccurate and slower for the deviant than for the standard stimuli [stimulus type (STD, early-DEV): HR, $F(1,11) = 18.71$, $p = 0.001$, $\eta^2 = 0.63$; ER, $F(1,11) = 18.46$, $p = 0.001$, $\eta^2 = 0.63$; RT, $F(1,11) = 48.00$, $p < 0.001$, $\eta^2 = 0.81$; stimulus type (STD, late-DEV): HR, $F(1,11) = 14.73$, $p =$

0.003, $\eta^2 = 0.57$; ER, $F(1,11) = 15.18$, $p = 0.002$, $\eta^2 = 0.58$; RT, $F(1,11) = 101.93$, $p < 0.001$, $\eta^2 = 0.90$]. Moreover, post-hoc comparisons between deviant stimuli yielded a distraction trade-off effect. Participants were faster [RT, $F(1,11) = 13.92$, $p = 0.003$; $\eta^2 = 0.56$] but more inaccurate [HR, $F(1,11) = 15.73$, $p = 0.002$, $\eta^2 = 0.59$; ER, $F(1,11) = 16.16$, $p < 0.002$, $\eta^2 = 0.60$] for the early-DEV than for the late-DEV stimuli.

No significant interactions between stimulus duration and stimulus type were observed in HR or ER, though a significant interaction was found for RT [$F(2,22) = 17.07$, $p < 0.001$, $\varepsilon = 0.92$, $\eta^2 = 0.61$]. *T*-test comparisons revealed that participants were slower for the long than for the short standard [$t(11) = -4.57$, $p = 0.001$], the early-DEV [$t(11) = -5.88$, $p < 0.001$] and the late-DEV [$t(11) = -9.32$, $p < 0.001$] stimuli.

A specific analysis for the short stimuli did not show significant differences to the stimulus type factor in HR or ER. However, there was a significant difference for the stimulus type factor in RT [$F(2,22) = 10.69$, $p = 0.001$, $\varepsilon = 0.86$, $\eta^2 = 0.49$]. *T*-test comparisons revealed that participants were slower for the short deviant stimuli than for the short standard tones [STD, early-DEV: $t(11) = -3.12$, $p = 0.010$; STD, late-DEV: $t(11) = -5.38$, $p < 0.001$], but not between short deviant stimuli.

On the other hand, the same specific analysis for the long stimuli showed significant differences for the stimulus type factor in HR [$F(2,22) = 8.67$, $p = 0.012$, $\varepsilon = 0.53$, $\eta^2 = 0.44$], ER [$F(2,22) = 9.25$, $p = 0.010$, $\varepsilon = 0.53$, $\eta^2 = 0.46$], and RT [$F(2,22) = 66.28$, $p < 0.001$, $\varepsilon = 0.77$, $\eta^2 = 0.86$] and whatever it was the *t*-test comparison (*t* values rage from -9.95 to 3.25, all $p \leq 0.025$).

Event-related brain potentials

Target ERPs

Fig. 3 shows the grand-average ERPs for all the targets. No significant differences between the short and the long standard tones were found for the N2 mean amplitude at Cz or Fz. P3b mean amplitude at Pz was larger for the short than for the long standard tone [$t(10) = 2.96$, $p = 0.014$]. Because deviant stimuli were also targets, P3b component were elicited in these trials. An ANOVA with deviant type (early-DEV, late-DEV) and stimulus duration (short, long) as factors did not reveal significant differences over the P3b mean amplitude at Pz for any factor or interaction.

As showed in the right part of Fig. 3, similar scalp distributions were found to P3b for all stimulus targets except for the short standard one. An ANOVA with target type (short STD, long STD, short early-DEV, long early-DEV, short late-DEV, long late-DEV), frontality (frontal, central, parietal) and laterality (5 levels) as factors over the normalized P3b mean amplitudes yielded a significant interaction between the target type x frontality x laterality [$F(40,400) = 3.18$, $p = 0.011$, $\varepsilon = 0.12$, $\eta^2 = 0.24$]. Post-hoc comparison between the short STD P3b and the rest of the targets yielded a significant target type factor (F values raging 5.27 and 9.47, all $p \leq 0.045$). An ANOVA only for frontal leads (F7, F3, Fz, F4, F8) also revealed a significant difference to target type factor [$F(5,50) = 6.63$, $p = 0.002$, $\varepsilon = 0.58$, $\eta^2 = 0.40$]. Post-hoc comparisons between the short STD P3b and the rest of the targets again yielded a significant effect of the target type factor (F values raging 7.67 and 18.50, all $p \leq 0.020$), which indicated lager central positivity for the short standard than for the remaining targets.

Difference waveforms

Both deviance onsets elicited a similar pattern of deflections peaked at different latencies (Fig. 4). The first negative deflection showed one small first peak, followed by a larger negativity. The first peak was elicited about 120 ms from the change onsets, so probably indicated the N1 to the pitch change from 1000 to 1100 Hz. The second peak was generated around 175 ms from each deviance onset, so presumable involve the change detector mechanism indexed by MMN. Once corrected the temporal distance between deviance onsets (i.e., 100 ms), an ANOVA with deviance onset (early-DEV, late-DEV) and stimulus duration (short, long) as factors over the peak latencies did not yield statistically significant differences for the MMN component. However, the deviance onset factor was significant for the latencies of P3a [$F(1,10) = 16.79$, $p = 0.002$, $\eta^2 = 0.63$] and RON [$F(1,10) = 12.33$, $p = 0.006$, $\eta^2 = 0.55$] components, indicating that P3a and RON components emerged 30 ms and 40 ms, respectively, earlier for the late-DEV condition than for the early-DEV condition. Also, the interaction deviance onset x stimulus duration was significant for the RON component [$F(1,10) = 8.62$, $p = 0.015$, $\eta^2 = 0.46$]. The same analysis for the RON peak-latency from target onset (without deviance temporal correction) yielded analogous statistical results. *T*-test comparison showed that short and long early-DEV conditions differed significantly [$t(11) = -3.54$, $p = 0.005$], but not the short and the long late-DEV nor the short early-DEV and the short late-DEV conditions.

Although, MMN appeared at different time windows from the target onset (30 ms for the early-DEV condition and 125 ms for the late-DEV condition), an ANOVA over its mean amplitude with deviance onset (early-DEV, late-DEV), stimulus duration (short, long) and frontal electrodes (F7, F3, Fz, F4, F8) did no yield significant difference for any factor or interaction.

P3a normalized-mean amplitude analyzed by means of an ANOVA with deviance onset, stimulus duration, frontality and laterality as factors yielded significant differences for the deviance onset factor [$F(1,10) = 9.06$, $p = 0.013$, $\eta^2 = 0.47$] and the deviance onset x stimulus duration interaction [$F(1,10) = 6.53$, $p = 0.029$, $\eta^2 = 0.39$]. Analogous analysis only for early-DEV conditions did not revealed significant differences or interactions, while late-DEV conditions yielded significant difference between the short and the long deviance onset [$F(1,10) = 6.70$, $p = 0.027$, $\eta^2 = 0.40$]. The same analysis only for short deviance onsets showed a significant interaction between deviance onset x laterality factors [$F(4,44) = 4.72$, $p = 0.032$, $\varepsilon = 0.38$, $\eta^2 = 0.30$], whereas long deviance onsets yielded a significant difference for deviance onset factor [$F(1,10) = 9.42$, $p = 0.012$, $\eta^2 = 0.48$].

The statistical analysis of RON by means of a four-way repeated measures ANOVA yielded significant effects of the deviance onset factor [$F(1,10) = 6.87$, $p = 0.026$, $\eta^2 = 0.41$] and deviance onset x stimulus duration [$F(1,10) = 7.18$, $p = 0.023$, $\eta^2 = 0.42$], stimulus duration x laterality [$F(4,40) = 3.70$, $p = 0.031$, $\varepsilon = 0.63$, $\eta^2 = 0.27$] and deviance onset x frontality x laterality [$F(8,80) = 4.55$, $p = 0.007$, $\varepsilon = 0.41$, $\eta^2 = 0.31$] interactions. Analysis only for the early-DEV condition showed the interaction stimulus duration x laterality significant [$F(4,44) = 3.40$, $p = 0.028$, $\varepsilon = 0.77$, $\eta^2 = 0.24$], while short and long late-DEV conditions did not reveal significant differences or interactions for the main factors. The same analysis only for short deviance onsets showed a significant interaction between deviance onset x frontality x laterality factors [$F(8,88) = 4.62$, $p = 0.012$, $\varepsilon = 0.33$, $\eta^2 = 0.30$], whereas long deviance onsets yielded a significant difference for deviance onset factor [$F(1,10) = 8.41$, $p = 0.016$, $\eta^2 = 0.46$] and the deviance onset x frontality interaction [$F(1,10) = 5.54$, $p = 0.029$, $\varepsilon = 0.43$, $\eta^2 = 0.36$].

Discussion

The main question of the present study was whether the onset of an unexpected (and irrelevant) change of the stimulation may disrupt the processing of task-relevant information. In addition to other studies, we embedded this change within the task-relevant stimulus at different points in time relative to the onset of the relevant or target information to test the effect of the deviant-to-target interval on distraction. In general, all participants were able to perform the task with high efficiency, as indicated by the overall hit rate of above 90%. More important, the RT data demonstrated that the processing of task-relevant information is vulnerable irrespective of the deviant-to-target interval. This is in line with different other studies demonstrating distractibility within a time-window of -355 to 200 ms relative to target onset. In addition with theses findings our study shows that distractibility is also possible during the processing of task relevant stimulus. This is supported by the ERP results showing the elicitation of distraction potentials, namely MMN, P3a, and RON in both types of deviant stimuli. However, beside this clear cut result of general distractibility in every phase of task-related information there are remarkable differences not only in the processing of the deviant information but also in the processing of the target information. On one hand, all parameters of distraction (RT prolongation, P3a and RON) show remarkable differences between deviant stimuli with an early and a late pitch change. On the other hand, even processing of standard stimuli differs between short and long stimuli. These different effects of the manipulation of deviant and target information interact in the parameters of distraction. We, therefore, start with the discussion of the effects of the target information.

In general, participants were slower in pressing the response button for the long stimuli than for the short stimuli. Obviously, the short stimuli have a sharp offset that could serve as a cue in order to respond. Mean RT from stimulus offset was on average about 328 ms for the short and 157 ms for the long stimulus. Because 157 ms does not seem enough to prepare and execute a response, the long stimulus response should be prepared some time before. One possible explanation for the delay (30 ms) in responding to the long in comparison to the short stimuli could be due to the time needed by participants to realize that the long stimuli was exceeding the critical duration of 200 ms. Furthermore, in order to resolve the task it could be just necessary activate an internal template of the short duration. This explanation is supported by the different scalp distribution of P3b found for the short standard tone in comparison to the rest of the targets. If P3b reflects the match between stimulus and voluntary maintained attentional trace (Naatanen, 1992), it could interpret that participants held in mind the “short standard template” in order to discriminate short and long stimuli. When the presented target was a short standard tone, it matched with the neural trace saved in working memory and the associated response was triggered faster. However, whether the ongoing stimulus did not match with the neural trace saved, then the prepared response had been stopped and a switch response for the long stimuli was required, resulting in a delay response time. Actually, frontal leads showed significant different activity for all the targets that were not short standard tones, that is, for long and deviant stimuli. This topographic difference could be interpreted as a result of a context update triggered by all the targets that they were not match with the short standard tone memory trace.

Moreover, the occurrence of a task-irrelevant pitch change in the short deviant stimuli did not cause hit rate decrease or error rate increase. Participants classified without difference the short standard and the short deviant stimuli. If we assume that HR and ER are measures of stimulus classification processing, it seems clear that unexpected pitch changes were not able to affect this target processing stage. The switch of attention indexed by P3a peaked from the target onset was around 150 ms for the early-DEV condition and around 225 ms for the late-DEV condition. It could be possible for the early-DEV condition the classification was still not ready, while for the late-DEV condition was advanced or already made. This could explain the underlying slight lateralized activity for the late-DEV than the early-DEV condition in the P3a window. However, although HR or ER was not affected by the task-irrelevant changes, RT was slower for the short deviant than for the short standard stimuli. Specifically, the delay was 40 ms which coincided with the temporal window that covered P3a, so it could be possible P3a generation was the cause of the delay and responses were postponed until its end.

A different pattern of results was obtained for the long stimuli. The occurrence of a task-irrelevant pitch change caused hit rate decreased, error rate increase and slower response time to the long deviant in comparison to the long standard and the short deviant stimuli. Maybe because of the long stimulus processing was delayed in comparison to the standard stimuli, or because a switch response should be produced, or both, an inaccurate and slower performance was registered. Interesting, there was a trade-off between response time and response accuracy of pitch change effects in the two long deviant stimuli. The long early-DEV stimulus resulted in more inaccurate responses (decreased hit rate caused by an increased error rate) than when the change occurred closer to discrimination point, i.e., the late-DEV stimulus. Whereas, the response time increase was smaller for the long late-DEV stimulus than for the long early-DEV stimulus. In this way, it appears that a task-irrelevant pitch change occurring 150 ms before target onset yielded an impaired impulsive response (fast but inaccurate), while the same task-irrelevant change occurring 100 ms later, i.e., 50 ms before target onset, resulted in a impaired reflective response (slow but accurate).

Again, a look at the underlying neuroelectric brain activity may help to elucidate these results. The P3a scalp distributions for long stimuli clearly showed that the underlying processing was significant different between deviance onsets. Short and long early-DEV conditions did not show significant differences, which it could mean that similar switches of attention was triggered to the temporal window of 150 ms from the target onset. Actually, the statistical analyses did not reveal significant interaction between stimulus type and stimulus duration in HR or ER, which it meant that similar stimulus classification was obtained between short and long early-DEV stimulus. However, the scalp distribution of P3a to the long late-DEV condition clearly differed from the rest of conditions. The P3a component for the late-DEV condition peaked around 225 from the target onset, which it could be explain that the classification process was presumably quite advance yielding better rate that the long early-DEV stimulus. Moreover, although P3a peaked at the same temporal window to the short and the long late-DEV conditions, presumably the underlying stimulus processing should be delay for the long stimulus in comparison to the short stimulus. It could explain the different scalp distributions found between the short and the long late-DEV conditions. Also, the slower RT to the long late-DEV than the short late-DEV stimuli could due that the P3a affected different stages of the response processing, a latter in the case of the short and earlier in the cause of the long stimuli.

Therefore, the present results suggest that distraction it is not only observed when the processing of the task-relevant object just started (i.e., early-DEV stimulus), but also when it has been processed even during 150 ms (i.e., late-DEV stimulus), all in all suggesting that the different auditory features are processed and controlled independently from each other, and supporting the hypothesis of feature specific distraction (Jankowiak & Berti, 2007). In this line, one may argue that task-irrelevant and task-relevant features are processed in parallel until the orienting of attention, indexed by P3a, is triggered. At this point of time, the behavior effects will depend on the ongoing processing. This explanation could also help to elucidate the results obtained by (Roeber, Widmann *et al.*, 2003). In their data, when the distractor preceded the target onset for 200 ms, P3a peaked before response time and clear distraction was observed. However, when the distractor appeared 200 ms after the target onset, P3a peaked after the response time and no impaired performance was observed. Also, the hypothesis of auditory independent features fits well with the different behavioral patterns produced by novel stimuli observed in several previous studies. Opposite to what occurs with deviant sounds, novel sounds do not usually lead to hit rate decrements but to large response time increases (Escera *et al.*, 1998; Escera, Yago, &

Alho, 2001). As Parmentier *et al.* (2008) have shown in the auditory-visual paradigm, the slower response times to the visual target preceded by a novel sound, in comparison to a standard tone, are not due to a detrimental visual analysis nor categorical processing of the target stimuli, but just to the time involved in recapturing attention from auditory novel processing to visual target processing. It seems that novel task-irrelevant sounds produce a complete reallocation of attentional resources and once the relevance of the novelty has been evaluated, attention could return back to target processing, which results in preserved hit rate but delayed response times. On the other hand, deviant stimuli allow parallel processing of the task-relevant and task-irrelevant information affecting different behavioral responses that reflect impaired stages from the target processing.

On the contrary to a previous study (Escera, Yago, & Alho, 2001), RON component did not appear completely synchronized to the target onset. One possible explanation could due that in Escera, Yago, & Alho (2001) no significant distraction effects were observed between asynchronies. Actually, in the present study, short deviant stimuli which also no differed in RT, either did not reach significant difference in the RON peak-latency. It could mean that when distractor affects to the target processing in a similar way, the orienting of attention can be accomplished in a the same temporal window. However, whether the distractor affects different stages from the target processing, then the reorienting of attention to the task-relevant information will be also accomplished in different way from the impaired stage.

In summary, the present study suggests, first, that classifying short stimuli, of 200 ms, and long stimuli, of 400 ms, take account different target processing. Second, the unexpected occurrence of a task-irrelevant pitch change during this stimulus duration classification impaired performance. Third, the behavioral effects of task-irrelevant pitch changes depend on the impaired stage of the ongoing target processing. Fourth, the orienting of task-relevant information indexed by RON depended on the impaired stage of the target processing caused by the distractor.

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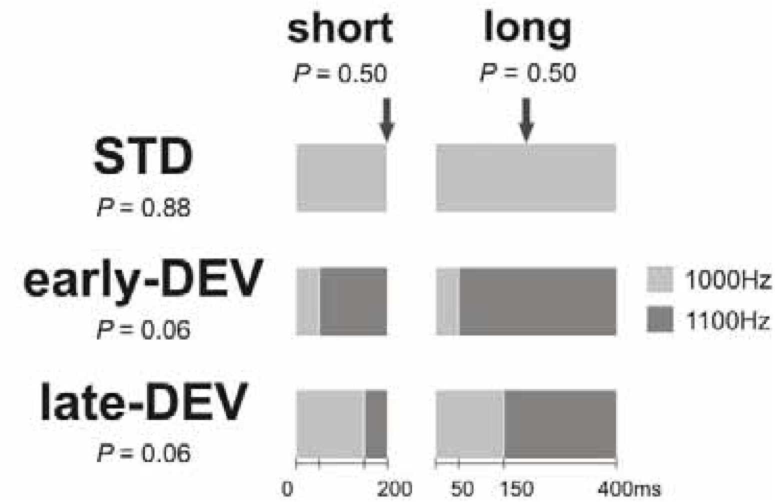

Figure 1. Illustration of the stimuli. All stimuli were targets, with most of them (88%) with the same pitch during their whole length (standards tones, STD), and some of them (12%) including a pitch change (deviant stimuli) at 50 ms (early-DEV) or at 150 ms (late-DEV) from stimulus onset. Arrow indicated the target onset.

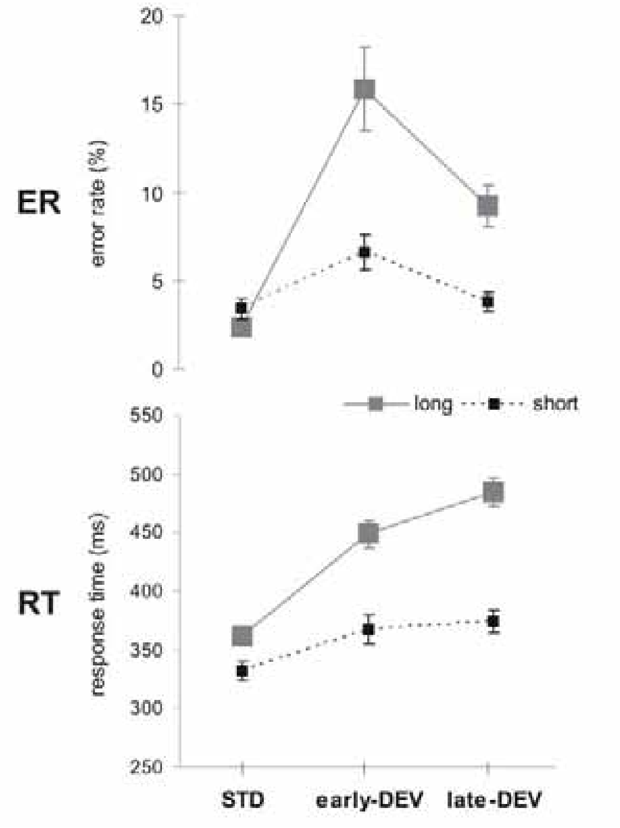

Figure 2. Mean error rate (ER) and response time (RT) for standard tones (STD) and deviant stimuli (early-DEV or late-DEV), for short (black) and long (grey) stimuli. Bars indicate the standard error of the mean. Because hit rate and error rate analysis showed analogous results, just ER has been plotted.

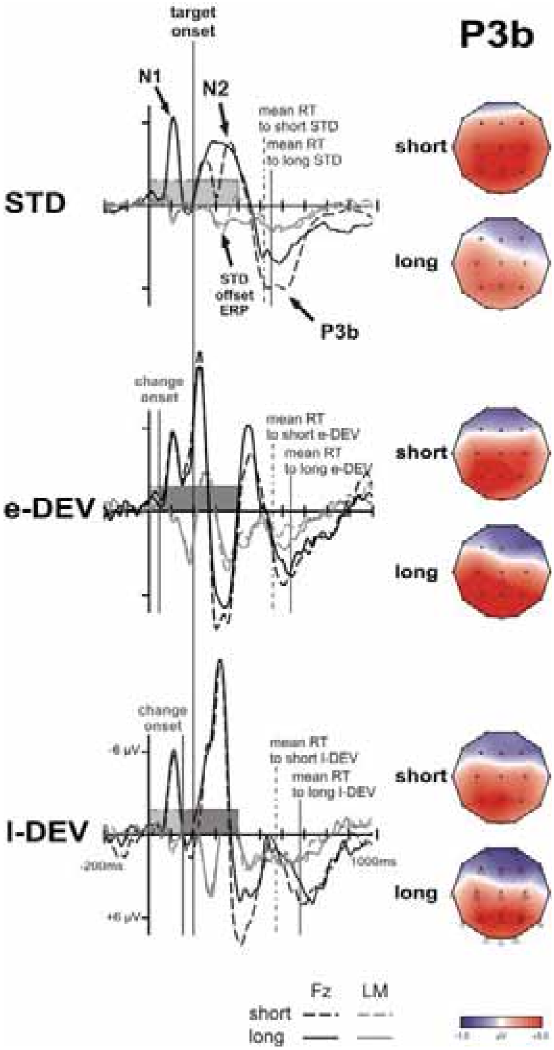

Figure 3. Left, grand-average ERPs elicited to frequent standard (STD) and to infrequent deviant, early-DEV (e-DEV) and late-DEV (l-DEV) for short (dot line) and long stimuli (plain line). Note that the orienting of attention indexed by P3a peaked at different temporal window of the target stimulus processing. Specifically, when the distractor feature occurred far away from the target onset (e-DEV), the P3a overlapped the N2 standard window, whereas when the distractor feature occurred closer to target onset (l-DEV), the P3a peaked over the raising slope of the standard N2 ERP and shortly preceding the target feature P3b window. Right, scalp isopotential maps around 10 ms of the P3b peak for each target.

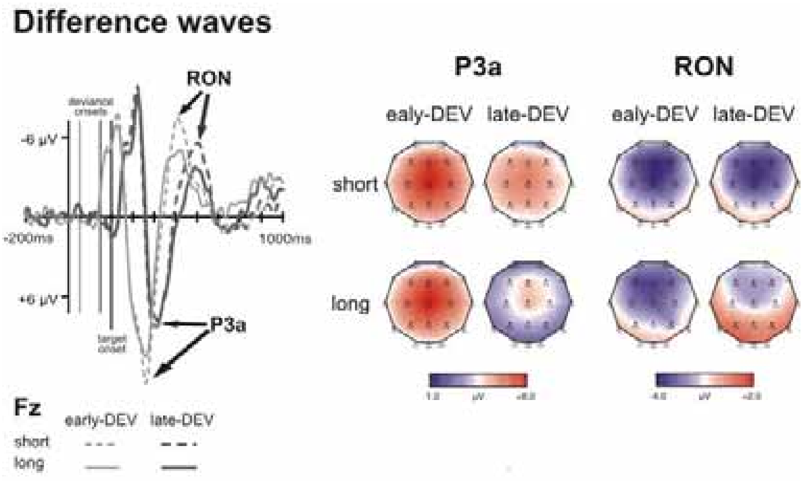

Figure 4. Left, grand-average difference waveforms obtained by subtracting the ERPs elicited by the standard stimuli from those elicited to the deviant stimuli at Fz. Right, scalp isopotential maps of the P3a and RON component around the analyzed peak-latency window.

5. General discussion

Participants classified odd/even or short/long stimuli with an overall hit rate of above 85%. However, random changes embedded in the repetitive stream of auditory stimulation impaired performance. Responses were from 10 ms to 72 ms slower when they were preceded by a sound change than when they were preceded by a repetitive sound, a phenomenon referred to as distraction.

Different types of changes to the physical features of the sound were able to cause distraction. Slight modifications of intensity (7% softer), duration (75% shorter) or pitch (17% higher) regarding the standard stimulation produced similar hit rate decreases (5.2%), error rate increases (5.6%) and slower response times (24 ms) with regard to the first study. Moreover, slight pitch changes (10% higher) in the third study and complex (with a broad spectral range) novel environmental sounds in the second study produced slower responses (72 ms and 10 ms, respectively). Therefore, the brain system seems to detect slight or large task-irrelevant changes that break the preceding regularity. The evaluation of these unexpected irruptions presumably reallocated the attentional resources from the task-relevant to the task-irrelevant information, and impaired performance, as reflected by the behavioral results.

The distraction pattern obtained for slight changes (deviant stimuli: first and third study) and novel sounds (second study) also differed. Hit and error rates were affected in the case of deviant stimuli, but not for novel sounds, as has been reported before (Escera *et al.*, 1998, 2001). If we assume that the classification of the stimulus is related to hit and error rate measures, it seems that novel sounds did not interfere with the first stages of the target processing. Actually, using novel sounds as task-irrelevant stimuli, Parmentier *et al.* (2008) showed that increasing the difficulty of the stimulus identification or the categorical processing of the target had no impact on the magnitude of the distraction. Only when a recapture signal was presented before the target was the distraction abolished. The authors interpreted that the slower responses produced by novel sounds (in the absence of recapture signal) were not due to any interference in the target processing, but to the moving of attention from the task-irrelevant to task-relevant information.

The next open question was to determine what kind of shifts could have been involved in these effects. Task-relevant information was visual and was presented circa 1 m from the participant's eyes. Task-irrelevant information was auditory and presented via headphones placed on the participant's head. So, at least two kinds of shifts could be involved: one between sensory modalities (from auditory to visual), and another between spatial locations (from headphones to the screen).

The second study has helped to elucidate this question. In this study, the spatial distance between the task-relevant and the task-irrelevant channels was manipulated, while the two types of sensory modality remained constant. The results revealed that when task-relevant and task-irrelevant information shared the same location, the distraction was extinguished. However, in the rest of the conditions, where task-relevant and task-irrelevant were presented at different locations, distraction did not follow a pattern that was exactly proportional to distance. Novel sounds presented from the right hemispace of the participant caused distraction, while novel sounds occurring at homologous locations on the left hemispace did not impair performance. These results were in agreement with a series of studies on involuntary orienting of attention in the visual modality, which showed larger disturbing effects to pop-out or prime stimuli occurring in the right visual than in the left visual hemifield (Castro-Barros *et al.*, 2008; Pollmann, 1996, 2000). In addition, the magnetic counterpart of the MMN elicited by location deviant stimuli showed that the right but not the left lateralized deviants elicited equally short mismatch latencies in the two cerebral hemispheres, suggesting an advantage for processing auditory spatial information in the right hemispace than in the left one (Kaiser *et al.*, 2000). Taking all these findings together, a rightward bias for the behavioral influence of unexpected stimuli in the right side of the environment it seems plausible (Mesulam, 1990). Therefore, the spatial location of the auditory task-irrelevant and visual task-relevant stimuli becomes fundamental to the attention system, supporting the notion that the distraction effects of novel sounds could be caused by a spatial shifting of attention.

Besides affecting response time, slight deviant sounds also produced hit rate decreases and error rate increases (first and third study). Actually, the third study showed that responses to the long stimuli produced more errors when the deviance onset was far away from the target onset (150 ms) than when it was nearby (50 ms). Again, if we assume that stimulus classification could be involved in the hit rate and error rate measures, it appears that slight deviant changes could be able to affect the first stages of the target processing. Moreover, the opposite pattern of results to the response time for the long stimuli was recorded. When the temporal distance between deviance and target onset was longer (150 ms), faster responses were recorded, while for the shorter distance responses were slower. So, in this case the response time was more affected when the hit rate and error rate were more preserved. These apparently contradictory results make sense if we assume that task-relevant (duration) and task-irrelevant (pitch) features are processed in parallel at the first stages. Therefore, when the distance between the deviance and the target onset was shorter, the classification processing was presumably more advanced, yielding better hit and error rates, but impairing the later stage of the target processing associated with the response processing (causing slower response times). However, when the distance between the deviance and target onset was longer, the classification processing could not be finished; this would have influenced hit or error rate measures, but would have had a lesser effect on response time.

Another result that supports this view is the difference in distracting effects found for the two types of targets used in the auditory-auditory distraction paradigm. While the long stimuli yielded the behavioral results discussed above, short stimuli did not show any statistically significant differences in hit or error rates for any deviance onset. However, the response time to short stimuli was faster in general than to long stimuli, which may indicate a different underlying cognitive processing for resolving the two types of target. So, if classifying short and long stimuli requires different target processing, it seems plausible that a deviant feature occurring in two different temporal windows could also affect different stages of the target processing for short and long stimuli, which would be reflected by different distracting effects, precisely the outcome shown here. Because responses to short stimuli were faster, deviance onset further away or closer to the target onset was not able to affect the classification stimulus processing. However, short deviant stimuli caused similarly slower responses for both deviance onsets, suggesting that when the target processing was faster, the deviant feature affected a similar stage of the target processing.

In summary, while the distracting effects observed by novel sounds were due to a total allocation of attentional resources before the target processing, slight deviant changes seem to allow a parallel processing of the task-relevant and task-irrelevant features. One could argue that the asynchrony used in the second study between the novel sounds and the visual stimuli was too long (300 ms) to impair the classification stage of the processing.

However, deviant stimuli were presented with the same asynchrony in the first study and, even so, hit rate and error rate appeared affected. Therefore, although we cannot conclusively rule out the possibility that novel sounds presented in short asynchronies as those of the third study could impair classification measures, at present it seems that novel sounds recapture attentional resources in a different way from deviant sounds.

The electrophysiological activity recorded during the presentation of these stimuli also helped to elucidate the distraction effects. The difference waves obtained from the subtraction of the standard ERPs from the deviant ERPs allowed us to isolate the neural activity due to distraction. All the types of slight deviant changes (first and third study) elicited a first negative component around 150-200 ms identified as MMN, which corroborates its role as an early automatic call for focal attention. In the case of novel sounds with a rich frequency range, its elicitation was subordinate the N1 component, which is usually triggered by abrupt changes in the background stimulation. Obviously, the scalp distribution of MMN varied for each type of change (pitch, duration or intensity) suggesting that specific neural populations were involved in the detection of different auditory features, in agreement with previous studies (Giard *et al.*, 1994).

Following the MMN, a positive component called P3a was elicited for novel (second study) and slight pitch changes (third study). Two results from the present thesis have broadened our understanding of P3a. First, its amplitude is sensitive to the spatial location between task-relevant and task-relevant information (second study). That is, P3a amplitude was larger at closer locations between novel sound distractors and visual targets. Second, its scalp distribution and its temporal peak were affected by the ongoing stage of target processing (third study). P3a was elicited faster when the task-irrelevant and task-relevant were closer (50 ms) than when it was far away (150 ms). Also, P3a presented a large central positivity distribution when it was elicited during the first stages of the target processing. In summary, P3a generation was sensitive to the spatial location of the unexpected changes and the underlying ongoing cognitive processing; this latter finding is also in agreement with previous and related studies (Dominguez-Borras *et al.*, 2008a; San Miguel *et al.*, 2008a).

Finally, the reorienting negativity (RON) following the P3a ERP component on distraction context was not absolutely independent on the deviance onset (third study). In a previous study, Escera *et al.* (2001) observed that RON peaked to a similar time window to different distractor-to-target asynchronies (245 and 355 ms). Their results confirmed the role of RON as index of the attentional allocation to the processing of the relevant information after a momentary distraction (Schroger and Wolf, 1998b). Nevertheless, the shorter distractor-to-target asynchronies (150 and 50 ms) used in the third study of the present thesis did not confirm this result on the auditory-auditory paradigm. A possible explanation could be that the intervals used by Escera *et al.* (2001) allowed the orientation of attention on a similar time window. Actually, no behavioral differences between the two types of asynchronies were observed. However, when the asynchrony between the distractor and the target was shorter (third study), significant behavioral differences were obtained. Therefore, returning to primary task performance after impairing the classification or response stage of target processing should exhibit a different cognitive process, as shown by the temporal and scalp distribution of RON results.

While the present thesis has resolved some issues on the brain's control of attention, new questions have emerged. Further investigation should explore the attentional mechanisms activated by novel sounds using shorter distractor-to-target intervals. If novel sounds do not really allow parallel processing, hit and error rate measures would still be unaffected. Also, an independent analysis of the types of target in the auditory-visual paradigm could reveal deviant and target processing interaction. If classifying one type of target differs from the others, specific patterns of behavioral and electrophysiological measures of distraction should also be found.

On the other hand, many studies in the spatial cross-modal attentional literature (Eimer & Schroger, 1998; Eimer, 1999; Spence & Read, 2003) have shown a P3a-like positivity when the target stimulus appeared in an unexpected location. Closer investigations involving distraction and spatial attention studies could help to elucidate the cognitive role of P3a in attention. And, because the distraction potential (DP) has been recorded in the absence of behavioral distraction (condition 0º in the third study, Munka & Berti, 2006; Polo *et al.* 2003), new studies should continue to review the underlying cognitive process of its components as has recently been suggested (Barcelo *et al.*, 2006; Berti, 2008a).

6. Conclusions

The present thesis investigated the electrophysiological indexes of the detection and processing of auditory distractors. The resulting conclusions can be summarized as follows:

- Across all the studies, slightly deviant and novel sounds embedded in a repetitive stream of auditory stimulation caused distraction (slower response times). The distraction pattern of slightly deviant and novel sounds differed from each other. Slightly deviant and target features could be processed in parallel, which affected the classification processing (i.e., reductions in hit rate and error rate) and delay response time. In turn, novel sounds seem to produce a total reallocation of attentional sources before the beginning of the target processing, delaying the response time, but with no impairment in any stage of the target processing.

- The results of the second study showed that spatial location of the sounds was a relevant factor for distraction. When task-irrelevant stimuli were situated in the right hemifield far away from the task-relevant stimulus, distraction was observed. However, when the task-irrelevant and task-relevant stimulus shared the same location or when the task-irrelevant stimulus was situated in the left hemifield, distraction was abolished.

- When the target processing was long-lasting (long stimuli), the manipulation of the temporal distance between the distractor and the target onset in the third study also became a relevant parameter for the pattern of distraction. Impaired impulsive response style was observed in the case of the longest interval (150 ms) between the distractor and the target feature, while impaired reflexive response style was obtained in the case of the shortest interval (50 ms).

- The elicitation of mismatch negativity (MMN) for pitch, duration and intensity changes in the first study confirmed its role as a genuine change detector mechanism.
- The attentional switch from the task-relevant to the task-irrelevant information identified in the ERP components as P3a was sensitive to the distractor location in the second study. Larger mean amplitude was found in the case of closer locations between the task-irrelevant and the task-relevant information. So the attentional switch indexed by P3a could indeed be a switch of the attentional resources between spatial locations.
- The cognitive processing of the return to primary task performance after a momentary distraction indicated by the reorienting negativity (RON) depends, according to the third study, on the impaired stage of the distractor to the ongoing target processing.

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Appendixes

Catalan summary of the thesis

Resum de la tesi

Títol

Indicadors electrofisiològics de la detecció i el processament de distractors auditius

Introducció

A la vida diària, els nostres sentits estan contínuament bombardejats per informació procedent de diferents modalitats i localitzacions. Per aconseguir concentrar-nos en les nostres tasques necessitem la capacitat de seleccionar els estímuls rellevants d'entre tota la informació que ens envolta. Tot i així, un bloqueig total de qualsevol estímul irrellevant resultaria inadaptatiu per la incapacitat de poder reaccionar a canvis potencialment importants com, per exemple, la percepció del plor d'un nadó quan ens trobem en espais diferents de la casa, o la ruptura d'un vidre prop nostre. Estudis recents han investigat com el sistema nerviós porta a terme la selecció de la informació rellevant per la tasca en curs, alhora que permet l'avaluació de possibles canvis auditius en l'entorn.

Paradigmes de distracció auditiva

Diversos paradigmes han intentat recrear al laboratori la interferència provocada per canvis en l'entorn acústic. Una de les possibles tasques encomanda als participants consisteix en classificar estímuls auditius, curts o llargs (Schroger & Wolff, 1998a), o bé, estímuls visuals, parells o senars (Escera, Alho, Winkler, & Naatanen, 1998). Aquests estímuls rellevants són precedits per una estimulació auditiva constant. De forma infreqüent i inesperada l'estimulació constant és reemplaçada per un altre tipus de so. Anomenem estímuls auditius discrepants quan es modifica lleugerament alguna característica física respecte l'estimulació auditiva precedent, com pot ser la freqüència, la intensitat o la durada. En canvi, quan l'estimulació constant és reemplaçada per estímuls únics o totalment diferents, com pot ser el so d'un telèfon o el caure d'unes claus, parlem d'estímuls innovadors (Escera *et al.*, 1998). Ambdós tipus de canvis provoquen respostes lleugerament més lentes (de l'ordre de milisegons), fenomen identificat com a distracció.

Factors que influeixen en la distracció auditiva

Dos dels paràmetres coneguts que afecten la distracció són la magnitud del canvi (Berti, Roeber, & Schroger, 2004) i la seva predrictibilitat (Sussman, Winkler, & Schroger, 2003). És a dir, grans i impredictibles canvis, tal com el so d'un telèfon, òbviament produeixen major distracció, que canvis molt similars a l'estimulació precedent o que poden ser previstos per altres estímuls (Escera *et al.*, 1998; Escera, Yago, & Alho, 2001). La magnitud de la distracció s'ha observat proporcional al canvi de to entre l'estímul repetitiu i l'estímul discrepant (Berti *et al.*, 2004; Jaaskelainen, Schroger, & Naatanen, 1999; Schroger, 1996). Seguint la mateixa línia, estímuls innovadors susceptibles de ser reconeguts, com per exemple, el timbre del telèfon o el soroll d'una perforadora al carrer, generen respostes més lentes que estímuls innovadors (sons complexes amb un ample espectre de freqüència) difícilment associats a cap element conegut (Escera, Yago, Corral, Corbera, & Nunez, 2003). La predictibilitat dels estímuls discrepants ha estat estudiat per Sussman *et al.* (2003). En aquesta investigació, cada so estava precedit per un estímul visual. Dues condicions van ser presentades. En la condició previsible, l'estímul visual indicava la freqüència del so. En la condició imprevisible, l'estímul visual es presentava aleatòriament emparellat amb la freqüència del so, sense proporcionar cap informació sobre la freqüència de l'estímul subseqüent. Els estímuls discrepants de la condició impredictible van provocar distracció, però els estímuls discrepants de les series predictibles no.

Causa en la distracció auditiva

Per quin motiu els canvis en l'entorn acústic provoquen un pitjor rendiment de la tasca en curs? Una possible explicació rau en que part dels recursos atencionals destinats a l'execució de la tasca encomada s'utilitzin per l'avaluació del nou estímul. Però, en quin moment el canvi irromp en el processament dels estímuls rellevants? Alho, Escera, Diaz, Yago, & Serra, (1997) van observar que el potencial evocat N1 de l'estímul visual rellevant es veia atenuat quan era precedit per un estímul discrepant, en comparació a quan era precedit per un estímul repetitiu. Aquest resultat va suggerir als autors que el distractor era capaç d'interrompre una fase primerenca del processament de l'estímul rellevant. Més tard, Parmentier, Elford, Escera, Andres, & San Miguel, (2008) van voler corroborar aquest resultat en el cas d'estímuls innovadors. La magnitud de la distracció no es va veure afectada ni per la dificultat de discriminació visual de l'estímul rellevant, ni per l'augment de categories a l'hora de classificar els estímuls rellevants per la tasca. Només en una condició en la qual es presentava un estímul captador de l'atenció, just abans de l'aparició de l'estímul rellevant, va ser capaç d'anular la distracció conductual. Per tant, la distracció en el cas d'estímuls auditius no semblava estar causada per una interferència en etapes primerenques o tardanes del processament de l'estímul rellevant, sinó pel moviment de l'atenció del distractor (estímul innovador) fins l'estímul rellevant. La següent qüestió oberta a preguntar-se és de quina naturalesa resulta aquest moviment. Els resultats de la present tesi (estudi segon) permetran resoldre si es tracta d'un moviment en l'espai (de la localització en la què es presenten els distractors –a través dels auriculars– fins a la pantalla per on es presenten els estímuls visuals rellevants –situada aproximadament a un metre del participant), o bé, si el moviment es tracta de traspassar els recursos atencionals destinats a la modalitat visual (rellevant) cap a la modalitat auditiva (irrellevant).

Finestral temporal vulnerable a la distracció auditiva

Schröger (1996) va observar un empitjorament de les respostes conductuals (decrement del nombre de respostes correctes i augment del temps de resposta) quan el distractor es presentava 200 ms abans de l'estímul rellevant, però no, quan es presentava a 560 ms. Posteriorment, Escera *et al.* (2001) va utilitzar també dues asincronies entre l'estímul distractor i l'estímul rellevant: a 245 ms i a 355 ms. Ambdós intervals van provocar respostes més lentes, encara que no van mostrar diferència significativa ni quan el distractor es tractava d'un estímul discrepant, ni quan es tractava d'un estímul innovador. Altres estudis han registrat distracció conductual utilitzat intervals de 200 ms (Roeber, Berti, & Schroger, 2003; Roeber, Widmann, & Schroger, 2003; Schroger & Wolff, 1998b; Schroger, Giard, & Wolff, 2000), 100 ms (Schroger & Wolff, 1998a) o, fins i tot, quan l'estímul distractor i l'estímul discrepant es presentaven a l'hora (Rinne, Sarkka, Degerman, Schroger, & Alho, 2006). Un dels altres objectius de la present tesi (tercer estudi) és esbrinar si la distància temporal entre el distractor i l'estímul rellevant resulta decisòria per la magnitud de la distracció.

Electrofisiologia de la distracció auditiva

Els potencials evocats registrats durant l'execució de les tasques de distracció permeten investigar la dinàmica espacial i temporal de les xarxes neuronals implicades en el control de l'atenció. El potencial evocat típic en aquesta situacions mostra una complexa morfologia formada per l'activitat associada a l'estímul distractor i l'estímul rellevant. La resta aritmètica entre el potencial evocat davant de l'estímul distractor i el potencial evocat davant l'estímul repetitiu permet aïllar l'activitat cerebral relacionada amb la distracció conductual. Mitjançant aquesta simple operació, el potencial evocat resultant mostra típicament tres components que han estat relacionats amb diferents fases neurofisilògiques de la distracció. Primer, un component negatiu que apareix al voltant dels 150-200 ms des de l'aparició del distractor i que ha estat relacionat amb la detecció automàtica del canvi. Aquest component primerenc rep el nom de potencial de disparitat (*mismatch negativity, MMN*, en terminologia anglosaxona). Segon, una deflexió positiva que segueix al potencial de disparitat i que ha estat relacionada amb l'orientació efectiva de l'atenció cap al canvi, batejada amb el nom de P3a. Finalment, un component negatiu, identificat en terminologia anglosaxona com a *reorienting negativity (RON)*, implicat amb la reorientació de l'atenció cap a l'estímul rellevant després d'una distracció momentània. Tot i així, alguns treballs mostren l'aparició d'aquests components en absència de distracció conductual (Munka & Berti, 2006; Polo *et al.*, 2003), pel que una revisió independent per cada un d'ells pot ajudar a descriure més acuradament els processos cognitius subjacents a la seva generació.

La detecció del canvi i el potencial de disparitat *(MMN)*

La detecció automàtica d'estímuls potencialment rellevants que ocorren fora del focus d'atenció ha estat relacionada amb, almenys, dos mecanismes cerebrals. Un dels mecanismes és activat per inicis o acabaments inesperats d'estímuls, com per exemple, la llum d'un llamp, l'alarma d'una sirena o el cessament del funcionament del motor de la nevera després de tot un dia en marxa. Un altre mecanisme diferent és activat quan un estímul en particular trenca amb la petja neural de la constant estimulació auditiva precedent. Un exemple típic de l'activació d'aquest mecanisme l'han utilitzat durant anys les emissores de ràdio per anunciar les notícies: una sèrie de tons constants finalitza amb un to més agut o més llarg.

El primer mecanisme està basat en la reacció neurofisiològica als momentanis increments o decrements d'energia física i ha estat associat amb el component auditiu N1 (Naatanen & Picton, 1987). El segon mecanisme implica una avaluació constant de l'entorn acústic capaç de detectar qualsevol canvi que trenqui amb la regularitat precedent, i ha estat relacionat amb el potencial de disparitat (Naatanen, 1990, 2007; Schroger, 2007; Winkler, 2007). Un ampli nombre de treballs han indicat que tant el component N1, com el potencial de disparitat, tenen les seves fonts generadores al *planum temporale* de l'escorça auditiva (Alho, 1995; Alho *et al.*, 1998; Escera, Alho, Schroger, & Winkler, 2000; Naatanen & Picton, 1987), amb contribucions de regions prefrontals (veure Giard *et al.*, 1994 per N1; Deouell, 2007, pel potencial de disparitat).

Tot i així, la majoria d'estudis acostumen a utilitzar com a distractors un canvi en el to de l'estimulació. Per tant, no és possible descartar totalment que la resposta cerebral associada a la detecció del canvi no estigui provocada per la resposta específica de neurones sensibles a una determinada freqüència (Jacobsen & Schroger, 2001; Yago, Escera, Alho, & Giard, 2001). Estudis subseqüents, entre ells el primer estudi de la present tesi, han demostrat que, efectivament, el detector de canvis associat al potencial de disparitat també és sensible a modificacions en la durada (Escera, Corral, & Yago, 2002; Roeber *et al.*, 2003), la intensitat (Escera *et al.*, 2002; Rinne *et al.*, 2006), i la localització del so (Roeber *et al.*, 2003), corroborant el paper del potencial de disparitat en la detecció automàtica del canvi en general.

El canvi atencional i P3a

El component P3a ha estat considerat per la literatura psicofisiològica com un indicador de l'orientació de l'atenció cap el canvi (Friedman, Cycowicz, & Gaeta, 2001; Knight, 1984; Squires, Squires, & Hillyard, 1975) i la seva amplitud s'ha relacionat amb el nivell de distracció conductual. Treballs recent, però, han trobat diferències en la magnitud de la distracció en absència de la generació del component P3a (Rinne *et al.*, 2006), i a la inversa, generació del component P3a en absència de distracció conductual (Munka & Berti, 2006; Polo *et al.*, 2003). A més a més, mentre MMN i N1 semblen ser mecanismes que operen automàticament, P3a ha resultat altament dependent de factors moduladors superiors *(top-down)*. Per tant, en contrast amb la més estesa interpretació de P3a com una resposta d'orientació de l'atenció, o un índex de distractibilitat conductual, la seva generació podria, més aviat, resultar un signe d'avaluació de la novetat contextual, reflectint una reconfiguració de la xarxa neuronal per tal d'actuar en conseqüència davant el canvi (Barcelo, Escera, Corral, & Perianez, 2006).

La reorientació de l'atenció i *RON*

Tant important com la flexibilitat en dirigir l'atenció cap a canvis inesperats és el retorn de la mateixa atenció cap el focus d'interès.

Aquest procés cognitiu s'ha estat identificat en els potencials evocats amb un component negatiu que apareix després de la generació de P3a i s'ha anomenat RON (de l'anglès, *reorienting negativity*; Escera *et al.*, 2001; Schroger & Wolff, 1998b). Va ser descobert per Schroger & Wolff (1998b) quan en els seus registres una ona negativa (posteriorment batejada com a RON) apareixia només després d'estímuls discrepants que provocaven distracció, però no quan els mateixos estímuls havien de ser identificats activament o ignorats passivament pels participants. Més tard, Escera *et al.* (2001) va argumentar que si realment el component RON indicava l'orientació de l'atenció, la seva generació hauria de veure's sincronitzada amb l'estímul rellevant, però no amb l'inici de l'estímul discrepant o innovador. En el seu treball, els autors van manipular l'interval temporal entre la presentació de l'estímul distractor i l'estímul rellevant i, efectivament, la generació de RON es va veure sincronitzada amb l'inici de l'estímul rellevant, independent de l'inici de l'estímul distractor. Un dels altres objectius de la present tesi (tercer estudi) serà corroborar aquesta troballa per intervals més propers i, quan l'estímul distractor i rellevant comparteixen la mateixa modalitat (auditiva).

Resultats

Els resultats presentats a continuació han estat extrets dels tres estudis que conformen la present tesi. En el primer dels estudis (Escera *et al.*, 2002) l'objectiu va ser estudiar la implicació del potencial de disparitat per canvis que no fossin exclusivament en la freqüència, és a dir, per canvis també en la intensitat i la durada. En el segon dels estudis (Corral & Escera, *enviat per publicació*) es va explorar si en el moviment atencional provocat per estímuls innovadors era degut a un moviment en l'espai, o bé, si es tractava d'un moviment dels recursos atencionals entre les modalitats sensorials implicades (visual –rellevant, auditiva –irrellevant). En el tercer dels estudis (Corral, Berti, Jacobsen, Widmann, Yago, Schroger & Escera, *enviat per publicació*) es va manipular l'interval de presentació del distractor i l'estímul rellevant per tal d'estudiar la seva implicació en la magnitud de la distracció, alhora que corroborar el paper del component RON en la reorientació de l'atenció.

Els resultats dels tres estudis van demostrar que tant petits canvis (estímuls discrepants; primer i tercer estudi), com grans canvis (estímuls innovadors; segon estudi), respecte l'estimulació precedent, van provocar respostes més lentes. A més a més, la utilització d'estímuls discrepants com a distractors va disminuir el nombre de respostes correctes i va augmentar el nombre d'errors.

En concret, el resultat més destacat del primer estudi va ser que tant canvis en la freqüència, com canvis en la intensitat i la durada, van generar el potencial de disparitat. La seva distribució topogràfica va ser específica per cada tipus de canvi.
Pel que fa al segon estudi, la distancia espacial entre el distractor i l'estímul rellevant va resultar decisiva per la distracció conductual. En la condició en la què l'estímul distractor i l'estímul rellevant compartien la mateixa localització, o l'estímul distractor es presentava en l'hemicamp esquerra, la distracció conductual va desaparèixer. En canvi, quan el distractor es presentava en l'hemicamp dret (en anàlogues posicions que a l'hemicamp esquerra), o a través dels auriculars (situats a un 1.15 m de distància dels estímuls rellevants, com a la resta de condicions), es va observar distracció conductual. A més a més, el registre electrofisiòlogic per cada una de les condicions

va mostrar que l'amplitud de P3a es feia més gran conforme s'escurçava la distància entre el distractor i l'estímul rellevant.

El tercer estudi va presentar patrons de distracció en funció de cada un dels dos tipus d'estímuls rellevants. Quan l'estímul rellevant va ser contestat ràpidament pels participants, canvis en la freqüència inserits en l'estímul en diferents moments van provocar respostes lentes similars i no van afectar ni el nombre de respostes correctes, ni el nombre d'errors. En canvi, en el cas en què l'estímul rellevant era respost més lentament, els mateixos canvis de freqüència inserits, van provocar diferents patrons de distracció. Quan la distància temporal entre el distractor i la característica rellevant era llarga (150 ms) les respostes van ser més ràpides però menys acurades (estil impulsiu), que quan la distància temporal era curta (50 ms), condició en la què es van presentar respostes més acurades però més lentes (estil reflexiu).

Discussió

Canvis inesperats en l'entorn auditiu provoquen un empitjorament del rendiment de la tasca en curs (demora en el temps de resposta). El patró d'afectació va ser diferent entre els estímuls discrepants (lleugerament diferents a l'estimulació precedent) i els estímuls innovadors (totalment diferents a l'estimulació precedent). El nombre de respostes correctes i el nombre d'errors es va veure afectat en el cas d'estímuls discrepants (estudi primer i tercer), però no en el cas d'estímuls innovadors (segon estudi). A més a més, el tipus d'estímul rellevant, així com el moment d'aparició d'un canvi de freqüència inserit en l'estímul discrepant, van resultar paràmetres influents en el patró de distracció (tercer estudi). Quan l'estímul rellevant podia ser resolt i contestat ràpidament, el canvi presentat en dos intervals temporals diferents no va afectar la demora de la resposta. En canvi, quan el processament de l'estímul rellevant consumia més temps o, si més no, era contestat més lentament, canvis presentats en diferents intervals van provocar més o menys afectació a les mesures de classificació de l'estímul (nombre de respostes correctes i nombre d'errors) o la selecció/execució de la resposta (temps de reacció). Així doncs, petits canvis en l'estimulació precedent poden afectar diferents fases del processament de l'estímul rellevant en funció de la seva naturalesa i el moment de la seva presentació.

D'altra banda, els estímuls innovadors no presenten cap afectació de les mesures relacionades amb la classificació de l'estímul rellevant. De fet, Parmentier *et al*. (2008) van suggerir que la demora provocada pels estímuls innovadors era deguda a un moviment dels recursos atencionals des de l'estímul distractor fins a l'estímul rellevant, abans de l'inici d'aquest. Els resultats del segon estudi posen de manifest que aquest moviment, més que ser degut a la diferència entre modalitats, és el resultat de moure els recursos atencionals en l'espai (de la localització on es troba l'estímul rellevant, a la localització del distractor). Tot i així, la distracció no va ser directament proporcional a la distància i el factor hemicamp va resultar important. Els distractors presentats per l'hemicamp dret, o a través dels auriculars, van provocar distracció; en canvi, els distractors que compartien la mateixa localització que l'estímul rellevant, o eren presentats per l'hemicamp esquerra en posicions homòlogues a l'hemicamp dret, no.

L'activitat electrofisiològica enregistrada en els tres estudis va permetre identificar els tres components associats a la distracció conductual (potencial de disparitat, P3a i RON). El primer estudi va demostrar que el potencial de disparitat es va generar no només per canvis en la freqüència, sinó també, per canvis en la durada o la intensitat de l'estimulació precedent, fet que corrobora el seu paper com a mecanisme detector automàtic del canvi. El segon estudi va observar que l'amplitud de P3a va ser sensible a la distància entre el distractor i l'estímul rellevant, motiu pel què el canvi atencional associat a P3a podria ser, de fet, un canvi en la localització espacial dels recursos atencionals. Finalment, el tercer estudi va analitzar la finestra temporal del component RON, demostrant que la seva generació depèn del moment d'afectació del distractor sobre l'estímul rellevant, és a dir, que la reorientació de l'atenció cap a la tasca depèn la fase del processament de l'estímul rellevant que afecta el distractor.

Conclusions

La present tesi ha investigat els indicadors electrofisiològics de la detecció i el processament de distractors auditius. A continuació es presenten les conclusions obtingudes:

- El tres estudis mostren que canvis inesperats en l'entorn poden provocar distracció, el què permet validar el paradigma com a eina eficaç per l'exploració de l'atenció.

- Els resultats obtinguts del primer i tercer estudi assenyalen que els canvis lleugerament diferents de l'estimulació precedent poden processar-se paral·lelament amb les característiques rellevants per la tasca, afectant així diferents fases del processament de l'estímul rellevant en funció del moment d'aparició del distractor. Contràriament, quan el canvi resulta totalment diferent a l'estimulació precedent, els recursos atencionals es dirigeixen completament a l'avaluació de l'estímul innovador, demorant el processament de l'estímul rellevant, però no afectant cap de les seves fases.

- La manipulació de la localització del distractor en el segon estudi va resultar un factor important per la distracció. Quan el distractor es presenta en la mateixa posició que l'estímul rellevant, o per l'hemicamp esquerra del participant, la distracció va quedar abolida. En canvi, distractors presentats per l'hemicamp dret, o pels auriculars, van mostrar distracció.

- El potencial de disparitat registrat en el primer estudi es va presentar davant canvis en la freqüència, la durada i la intensitat, resultats que corroboren el seu paper com a mecanisme automàtic en la detecció del canvi.

- En el segon estudi, el canvi atencional associat a P3a va ser sensible a la distància espacial entre el distractor i l'estímul rellevant, suggerint que el canvi d'atenció de l'estímul rellevant a l'estímul distractor, en realitat, impliqui un canvi dels recursos atencionals en l'espai.

- El procés cognitiu de reorientació de l'atenció cap a la tasca principal, després d'una distracció momentània, analitzat en el tercer estudi, va resultar dependent de la fase del processament de l'estímul rellevant afectat pel distractor.

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Role of Mismatch Negativity and Novelty-P3 in Involuntary Auditory Attention

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Abstract. It has been proposed that the functional role of the mismatch negativity (MMN) generating process is to issue a call for focal attention toward any auditory change violating the preceding acoustic regularity. This paper reviews the evidence supporting such a functional role and outlines a model of how the attentional system controls the flow of bottom-up auditory information with regard to ongoing-task demands to organize goal-oriented behavior. Specifically, the data obtained in auditory-auditory and auditory-visual distraction paradigms demonstrated that the unexpected occurrence of deviant auditory stimuli or novel sounds captures attention involuntarily, as they distract current task performance. These data indicate that such a process of distraction takes place in three successive stages associated, respectively, to MMN, P3a/novelty-P3, and reorienting negativity (RON), and that the latter two are modulated by the demands of the task at hand.

Keywords: evoked potentials, audition, involuntary attention, orienting response, stimulus-driven attention, top-down modulation

Shortly after the discovery of the mismatch negativity (MMN) phenomenon in 1978 by Näätänen and colleagues (Näätänen, Gaillard, & Mäntysalo, 1978), as an event-related brain potential (ERP) elicited to auditory stimuli deviating from a repeating sound, Näätänen and Michie (1979) proposed that the underlying generating process would be implicated in issuing a call for focal attention upon the detection of an unexpected auditory change in the acoustic environment. This proposal was further elaborated in subsequent theoretical papers (Näätänen, 1990, 1992), but had to wait for about 20 years to find the appropriate empirical support. A study by Erich Schröger which appeared in 1996 (Schröger, 1996), was the first to demonstrate that the occurrence of an MMN-eliciting tone, deviating in frequency from the standard stimuli in the unattended channel of a selective attention task, impoverished behavioral performance to a subsequent target occurring in the attended channel. Moreover, this effect was restricted to a short latency window between the unattended deviant and the attended target, i.e., 200 ms, but disappeared when this interval was extended to 560 ms. Furthermore, the magnitude of the effect was related to the magnitude of the deviant-standard frequency difference, i.e., the behavioral cost was larger for larger deviants. All in all, this pattern of results strongly pointed out to a role of the MMN-generating process in involuntary attention.

Two years later, Schröger and Wolff (1998a) and Escera and colleagues (Escera, Alho, Winkler, & Näätänen, 1998) published studies that, using different but related experimental approaches, provided strong support for the role of the MMN underlying process in involuntary attention. In their designs, subjects were instructed to classify auditory (Schröger & Wolff, 1998a) or visual (Escera et al., 1998) stimuli while ignoring concurrent, task-irrelevant auditory information. Systematically, the occurrence of MMN-eliciting, stimulus changes in the task-irrelevant auditory channel decreased hit rate and prolonged response times in the auditory or visual classification task, i.e., "distracted" current task performance. Moreover, this "distracted" performance was accompanied by a pattern of brain responses, later named the distraction potential (DP) by Escera and Corral (2003), which included the MMN, the P3a or novelty-P3 (depending of the type of auditory distracter stimuli used), and a new ERP component discovered by Schröger and Wolff (1998b) in this context of behavioral distraction, named reorienting negativity (RON).

Subsequent studies using similar distraction paradigms extended these findings and provided the building blocks for a model of involuntary attention. The present review extends our previous ones (Escera, Alho, Schröger, & Winkler, 2000; Escera & Corral, 2003) and aims at summarizing these involuntary attention studies, with an emphasis on those using the auditory-visual distraction paradigm. We also aim at outlining a neurocognitive model on how the attentional system controls the flow of bottom-up auditory information in the context of the ongoing-task demands to organize goal-oriented behavior.

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Auditory Distraction

In the auditory-auditory version of the distraction paradigms, subjects are instructed to concentrate on a particular dimension of the auditory stimuli, i.e., duration, while ignoring any other aspect of the auditory input, i.e., a task-irrelevant and rare change, say, in frequency. The sequence is arranged so that, in random order, half of stimuli have a particular duration, while the other half are longer; the subject is instructed to press the corresponding response button according to stimulus duration. In a few of the trials, the standard frequency is slightly increased or decreased, and this task-irrelevant frequency change, which elicits a distinct MMN, yields also a behavioral cost in the duration discrimination task: Subjects respond more slowly and make more errors in these "deviant" trials (Schröger & Wolff, 1998a,b; Schröger, Giard, & Wolff, 2000). Subsequent studies have shown that the magnitude of the distracting effects was proportional to the frequency difference between the deviant and the standard tones (Berti, Roeber, & Schröger, 2004; Jääskeläinen, Schröger, & Näätänen, 1999), as previously observed by Schröger (1996), and that

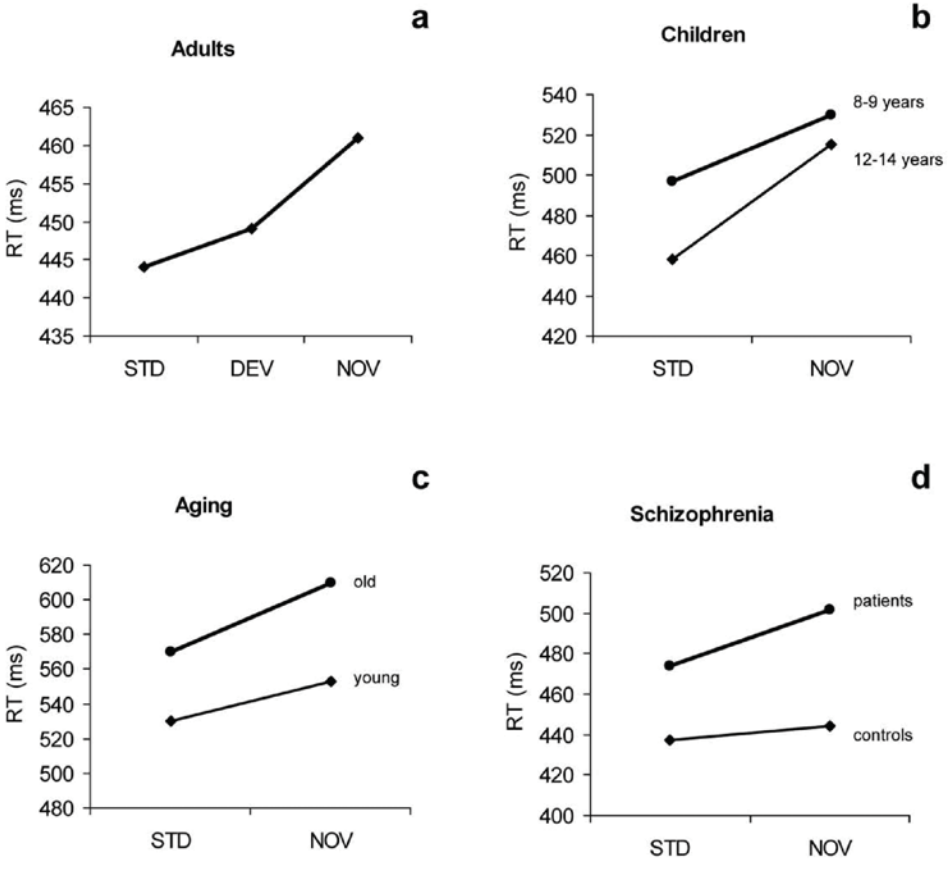

Figure 1. Behavioral examples of auditory distraction obtained with the auditory-visual distraction paradigm. Auditory distraction is observed as an enlargement of response time (RT) in trials containing a distracting sound, i.e., a deviant tone (DEV) or a novel sound (NOV), compared to RT in standard trials (STD). (a) Distraction caused by deviant tones and novel sounds in healthy adults (adapted from Escera et al., 1998). (b) Distraction caused by novel sounds in children (adapted from Gumenyuk et al., 2004). (c) Distraction caused by novel sounds in young and old adults: notice the larger distraction in the older (adapted from Andrés et al., 2006). (d) Increased distraction in schizophrenic patients (adapted from Cortiñas et al., submitted).

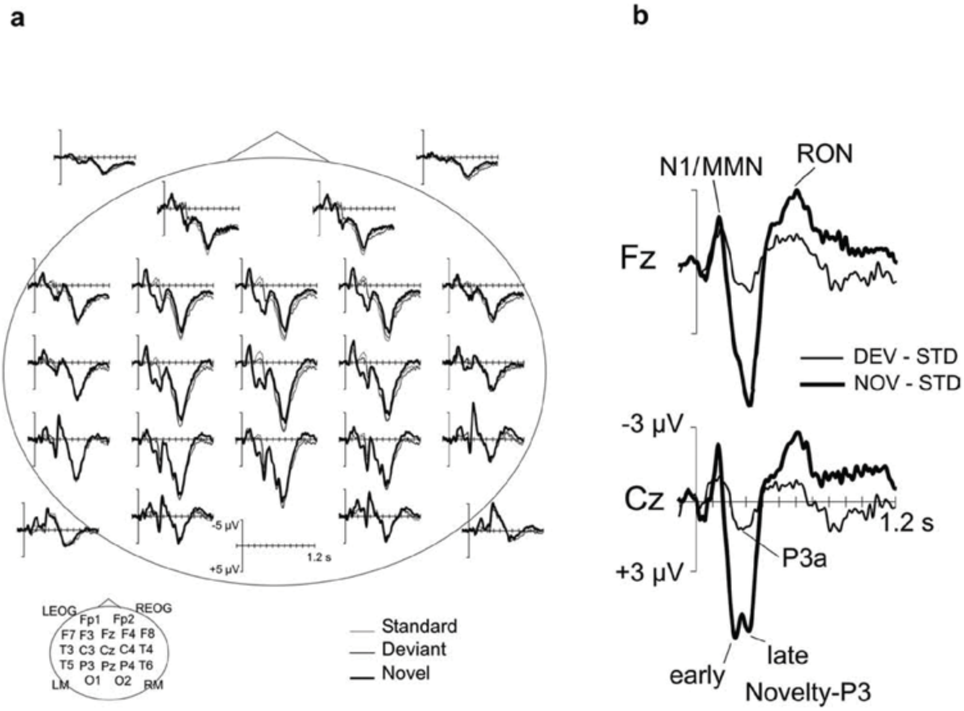

Figure 2. The distraction potential (DP). (a) Event-related brain potentials elicited to standard, deviant, and novel trials during visual task performance while ignoring the auditory stimulation. (b) Subtraction waveforms (distracting, i.e., deviant and novel, minus standard trials) revealing DP. The DP appears as a three-phasic waveform disclosing the contribution of MMN, N1-enhancement, P3a/novelty-P3, and RON. Data in the figure are taken from Escera et al. (2001).

similar behavioral and electrophysiological effects could be elicited using intensity (Rinne, Särkkä, Degerman, Schröger, Alho, 2006), and location and duration deviances (Roeber, Widmann, & Schröger, 2003). Moreover, the paradigm provides reliable and replicable behavioral and electrophysiological results (Schröger et al., 2000), and it has proved to be suitable to study involuntary attention in children (Wetzel, Widmann, Berti, & Schröger, 2006; Wetzel & Schröger, 2007a,b), and with a modified version using animal sounds instead of pure tones, even in children as young as 5 or 6 years of age (Wetzel, Berti, Widmann, & Schröger , 2004).

In the auditory-visual version of the distraction paradigm, subjects are instructed to classify visual stimuli into two particular categories, as quickly and accurately as possible, and to ignore concomitant auditory stimuli, which are presented one at a time preceding the visual stimulus, usually with a stimulus-onset asynchrony (SOA) of 300 ms, onset-to-onset. These task-irrelevant sounds are manipulated conveniently, so that the "standard" stimulus (occurring in 80% of the cases) is occasionally and randomly replaced by a "distracter," i.e., a stimulus slightly higher/lower ("deviant") in frequency or by a unique environmental ("novel") sound (i.e., telephone ringing, a glass breaking, or the one produced by a drilling device). In the original version of the task, subjects were instructed to classify digits into odd and even categories (Alho, Escera, Díaz, Yago, & Serra, 1997; Escera et al., 1998; Escera, Yago, & Alho, 2001; Escera, Corral, & Yago, 2002; Escera, Yago, Corral, Corbera, & Nuñez, 2003; Jääskeläinen, Alho, Escera, Winkler, Sillanaukee, & Näätänen, 1996; Yago, Escera, Alho, & Giard, 2001a; Yago, Escera, Alho, Giard, & Serra-Grabulosa, 2003), but in subsequent versions of the auditory-visual distraction paradigm, the task was modified to classify digits vs. letters (Polo, Escera, Yago, Alho, Gual, & Grau, 2003), or to decide whether the present digit was bigger or smaller than 5 (SanMiguel, Escera, Erhard, Fehr, & Herrmann, in prep.).

The auditory-visual distraction paradigm was also tested to work with tasks using more complex visual stimuli and decisions, such as classifying drawings into animate (animals) or inanimate (objects) categories (Gumenyuk, Korzyukov, Alho, Escera, & Näätänen, 2004), or in deciding whether the color of a figure (a face) was the same or different from that of its surrounding frame (Domínguez-Borràs, Trautmann, Fehr, Ehrard, & Herrmann, & Escera, submitted-a), or even whether two natural pictures presented simultaneously were equal or different (Domínguez-Borràs, Garcia-Garcia, & Escera, submitted-b). In all the tasks described thus far, the unexpected occurrence of a distracting sound – either deviant or novel – preceding the visual stimulus causes a delay in the subjects' responses (Figure 1), "distracting" current task performance. This distraction effect is larger in novel than in deviant trials (Escera et al., 1998, 2001), and for meaningful than for nonmeaningful novel sounds (Escera et al., 2003). As with the auditory-auditory distraction paradigm, the distraction effects can be also observed with tones deviating in other features than frequency, such as tone duration or intensity (Escera et al., 2002). In some studies, the response time increase in deviant trials was accompanied by a hit rate decrease caused by an error rate increase (Alho et al., 1997; Jääskeläinen et al., 1996; Escera et al., 1998, 2001, 2002).

The auditory-visual distraction paradigm has been shown to provide sizeable distracting effects in subjects over 8 years of age (Gumenyuk et al., 2001, 2004), in healthy elderly (Andrés, Parmentier, & Escera, 2006), and also in a range of clinical populations, including ADHD (Gumneyuk et al., 2005) and dyslectic (Corbera et al., in prep.) children as well as closed-head-injured patients (Polo, Newton, Rogers, Escera, & Butler, 2002), chronic alcoholics (Polo et al., 2003), and schizophrenics (Cortiñas, Corral, Garrido, Garolera, Pajares, & Escera, submitted). Moreover, these clinical studies allowed to demonstrate increased distractibility in most of patient groups (ADHD, dyslexia, schizophrenia), and even among normal aging persons (Andrés et al., 2006).

The Distraction Potential

Recording of ERPs during performance of the distraction paradigms described above allows investigation of the spatio-temporal dynamics of activation of the cerebral network underlying involuntary attention control. The typical ERP recorded in this scenario shows a complex morphology, both for the standard and the distracting trials, since it includes both auditory and visual responses (Figure 2a). However, a simple arithmetic computation, i.e., the subtraction of the responses elicited to standard trials from those elicited to the distracting ones, isolates the neuroelectric activation underlying behavioral distraction; for convenience, Escera and Corral (2003) termed this activation pattern the distraction potential (DP). The DP shows a characteristic triphasic shape, starting with a negative wave followed by a positive one, and ending with a final phase of a more or less sustained negative potential (Figure 2b). Each of these waveforms provides a neurophysiological index of what are considered the three main processes involved in involuntary attention control (Escera et al., 2000):

1) the mechanism of attention capture, associated to the mismatch negativity (MMN) and/or to the N1 ERP,
2) the orientation of attention, associated with the P3a or novelty-P3, and
3) the reorientation of attention toward main task performance after a momentary distraction, associated with the so-called reorienting negativity (RON).

However, the precise relationship between these neurophysiological phenomena and the cognitive process attributed to them is not completely clear and is discussed below.

In order to capture attention, at least two cerebral mechanisms operate within the auditory modality (Näätänen, 1990). One mechanism is based on a neurophysiological reaction to transient increment/decrements in stimulus energy and has been associated with the auditory N1 (Näätänen & Picton, 1987), or at least with some of its components (Giard, Perrin, Echallier, Thévenet, Froment, & Pernier, 1994; Escera et al., 1998). The second mechanism relies on the dynamic modeling of regularity in the acoustic environment, and on the detection of any stimulus change that does not fit in with a neural trace of such regularity. This is, therefore a "change-detector" mechanism, which has been associated to the generation of MMN (Näätänen, 1990, 2007; Schröger, 2007; Winkler, 2007), and can best be isolated by using slightly different distracter stimuli with regard to the repetitive stimulation (see an extended discussion on this issue in Schröger & Wolff, 1998a).

The behavioral data obtained with the auditory-auditory (Rinne et al., 2006) and auditory-visual distraction paradigms support the existence of these two attention capture mechanisms. Specifically, the distracting effects observed with this later paradigm in novel and deviant trials display a distinct pattern. Indeed, whereas novel sounds cause a large delay in the response time to visual stimuli (about 25 ms), compared to standard trials, deviant sounds cause only a small response time increase (about 5 ms), but a noticeable increment in the number of erroneous classifications, as mentioned above. ERP recordings also show this differential effect, with a clear MMN generated to deviant distractors and a combined N1-enhancement/MMN elicited to novel distractors (Alho et al., 1998; Escera et al., 1998). A large body of evidence indicates that both the MMN and the N1 are generated within the planum temporale of the auditory cortex (Alho, 1995; Alho et al., 1998; Escera et al., 2000; Näätänen & Picton, 1987), with additional contributions from prefrontal regions (see Giard et al., 1994, for the N1; and Deouell, 2007, for the MMN).

The P3a waveform, generated with large amplitude to novel stimuli and therefore called novelty-P3 (see Simons, Graham, Miles, & Chen, 2001, for a discussion on whether the P3a and novelty-P3 can be considered the same ERP component), in the psychophysiological literature has been

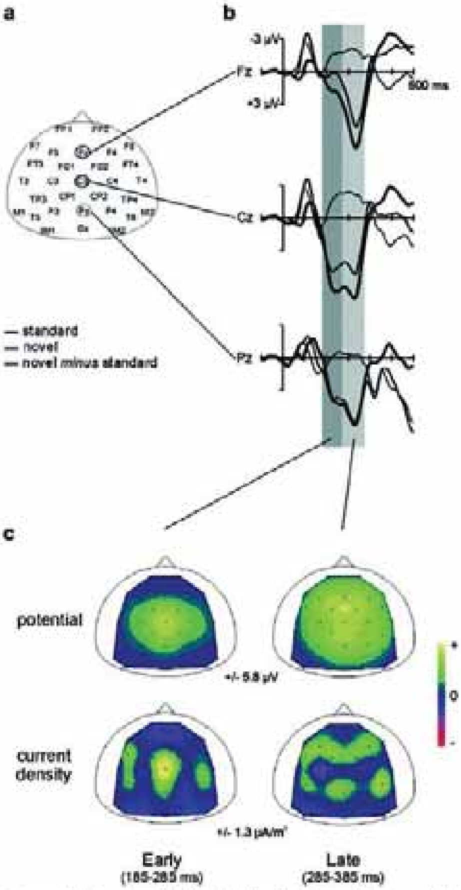

Figure 3. The novelty-P3. (a) The 30 electrode set used in the EEG recordings. (b) ERP at Fz, Cz, and Pz electrodes to standard and novel stimuli, and the corresponding difference waves. Gray shadows show the two phases of the novelty-P3, with latency ranges of 185–285 ms (dark gray) and 285–385 ms (light gray). (c) Scalp potential (SP) and current density (SCD) distributions of the two phases of the novelty-P3. The SCD analyses revealed positive currents over central, bilateral temporoparietal, and left frontotemporal areas during the early novelty-P3, and over superior parietal, bilateral temporoparietal, and frontal areas during the late novelty-P3. Adapted from Yago et al. (2003).

taken as a cerebral signature of the orienting response (Friedman, Cycowicz, & Gaeta, 2001; Knight, 1984; Squires, Squires, & Hillyard, 1975). Studies using the auditory-visual distraction paradigm have shown that novelty-P3 generation is accomplished in two consecutive phases, each of them involving a different scalp distribution and a different sensitivity to attentional manipulations (Escera et al., 1998, 2001). The first novelty-P3 phase, with peak latency between 220 and 320 ms, has a centrally distributed topography and appears independent of attentional manipulations (Escera et al., 1998; SanMiguel, Corral, & Escera, in press; Domínguez-Borràs et al., in press; see, however, Domínguez-Borràs, Garcia-Garcia, & Escera, submitted-b). On the other hand, the second phase of the novelty-P3, occurring between 300 and 400 ms, has a right frontal scalp distribution and appears highly sensitive to attentional manipulations as it increases in amplitude, for instance, when subjects can monitor the sounds, i.e., in the auditory-visual paradigm, compared to a condition of passive listening (Escera et al., 1998; 2003; see the elaborated discussion below). The scalp-current density (SCD) analysis of the novelty-P3 recorded in the auditory-visual distraction paradigm has, in agreement with previous results (Herrmann & Knight, 2001), shown that novelty-P3 generation encompasses at least five different cerebral regions (Figure 3), engaged in clear spatiotemporal orchestration (Yago et al., 2003). This study suggested that the anterior cingulated cortex activated first (circa 160 ms), followed by the simultaneous activation of the bilateral temporoparietal and the left frontotemporal cortices (around 200 ms), finishing with activation of the superior parietal cortex and prefrontal regions (at 300 ms).

Equally as important as the flexibility to direct attention toward unexpected potentially relevant events outside the focus of attention is the ability to return attention back to original task performance after a momentary distraction. It has been proposed that this attentional process is associated with the generation of another ERP component recorded in distraction tasks, the so-called reorienting negativity (RON) (Escera et al., 2001; Schröger & Wolff, 1998b). In fact, Schröger and Wolff (1998b) in their recordings found a negative waveform, subsequent to P3a, only when their subjects carried out a task where the deviant stimuli acted as behavioral distractors, but not when the subjects were asked to actively discriminate these stimuli, or when they were instructed to completely ignore the auditory stimulation and to concentrate on an unrelated visual task. Moreover, Escera et al. (2001) argued that, to indicate the process of reorienting attention back toward main task performance, RON should be time-locked to target stimuli in the task and not to distracting ones. In their experiment using the auditory-visual distraction paradigm, the asynchrony between the distracter and the visual target was manipulated to 245 or 355 ms, under different conditions. Their results showed that RON peak latency was about 345 ms from visual target onset, regardless of distracter-target asynchrony (Figure 4). These results strongly suggest that RON generation reflects the process of returning attention back to primary task performance after a momentary distraction.

On the other hand, Escera et al. (2001) observed that RON actually had two different phases or subcomponents (Figure 4) which were dissociated on the basis of their dif-

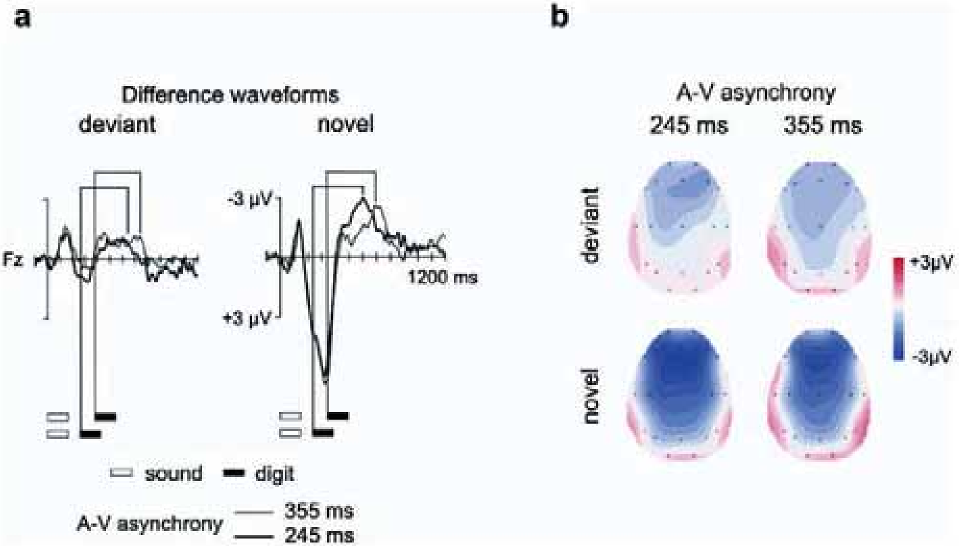

Figure 4. The reorienting negativity (RON) elicited in distracting trials, (a) as seen in difference waveforms at Fz. RON peaks at 345 ms from visual stimulus onset irrespective of distracter asynchrony. Notice, however, that RON might have two different subcomponents as suggested by the double-peaked negativity elicited in the deviant and novel trials of the 245 ms asynchrony (later confirmed by Munka & Berti, 2006). (b) The scalp distribution of RON obtained in deviant and novel trials for the two conditions of distracter-target asynchrony. Adapted from Escera et al. (2001).

ferent scalp distribution, and that the late subcomponent was the one time-locked to task-relevant aspects of stimulation, i.e., the visual stimulus. The existence of two RON subcomponents was confirmed in a recent study using the auditory-visual distraction paradigm by Munka and Berti (2006). These authors found that an early RON component was elicited when the discrimination task had a working memory component, i.e., consisting of making a semantic judgment on the visual stimuli (in fact, a classical odd/even classification). However, when the decision was based on a physical feature of the stimuli (size or color, in different experiments), only a late RON subcomponent could be observed.

What Is Being Distracted?

A critical issue to gaining insight into the neural mechanisms of involuntary attention toward unexpected deviant or novel sounds would be to establish what the cognitive process (or processes) is during visual task performance which are affected by the occurrence of the distracting sounds. Indeed, processing of distracting sounds could interfere with any of the several processes related to task performance, such as identification of the visual stimulus, its classification, response selection, or response execution, to mention only a few. In an early study, Alho et al. (1997) observed that the visual N1 elicited to the visual target was attenuated when the preceding sound was a deviant one, suggesting that its occurrence attracted attention involuntarily to the auditory modality, leaving fewer resources available to analyze the visual target in extraestriate visual areas, where this component is generated (Mangun & Hillyard, 1991; Heinze et al., 1994). These data clearly suggest interference on visual stimulus identification.

Parmentier, Elford, Escera, Andrés, and SanMiguel (2008) went a step beyond by addressing the auditory-distracter/visual-target interaction. These authors argued that the interference of the distracting sound could occur either during visual stimulus identification or during response selection. To test these alternative suggestions, they devised an experiment in which visual stimulus discriminability was manipulated by adding a white noise mask to the visual target, or by making response selection more difficult as there were four possible response categories instead of the usual two. Their results showed that, whereas making both visual discrimination or response selection more difficult enlarged the time necessary to perform the task, the distracting effects of novel sounds were of equivalent size to

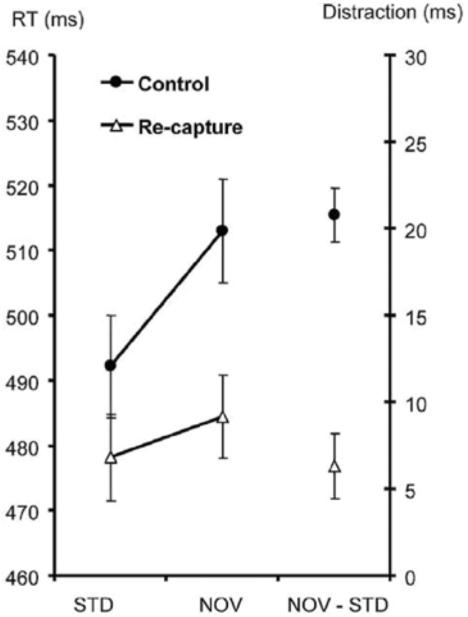

Figure 5. The cognitive locus of distraction. When a visual stimulus is quickly flashed within the interval between the distracting sound and the imperative visual stimulus, the distracting effects of the sound are abolished (adapted from Parmentier et al., 2008).

those observed in the respective control conditions (i.e., with no visual masking and with two response categories, respectively). The authors suggested that the distracting effect of the novel sounds should occur *before* the presentation of the imperative visual stimulus, and that the behavioral cost observed in the distracting trials would be due to the time necessary to move attention from the auditory modality, where it would get engaged by the novel sound, toward the visual modality upon the appearance of a visual target.

To confirm this hypothesis, in a subsequent experiment Parmentier and colleagues (Parmentier et al., 2008) quickly flashed (50 ms) a shrinking cross in the time period between the auditory, task-irrelevant stimulus and the visual target, in what they called a "re-capture" (of attention) condition. The results were clear cut: Whereas the effects of novel sounds on visual task discrimination in a control condition were as described previously, i.e., a significant response-time increase of about 25 ms, these distracting effects were abolished in the re-capture condition (Figure 5). These results demonstrated, according to the authors, that the unexpected task-irrelevant change in the auditory background engaged, and retained, attention in the auditory modality, and that the response time increase observed in the distracting trials would reflect the time necessary to move attention back, from the auditory to the visual modality upon the occurrence of a fresh sensory event in the task-relevant modality, i.e., vision.

Although appealing, however, the results obtained by Parmentier et al. (2008) cannot fully disregard the possibility that the distraction effects observed with the auditory-visual distraction paradigm resulted from the time necessary to move attention between spatial locations instead of sensory modalities. In fact, it should be borne in mind that the visual stimuli are presented in a screen located in front of the subject's head (usually, 100 cm), whereas the sounds are played binaurally through headphones. A preliminary study using loudspeakers placed beside the screen instead of headphones – but reproducing all remaining methodological details – failed to observe any distracting effects of novel sounds (Annett Schirmer, personal communication, January 2006). This negative result was replicated in a more recent and systematic study by Corral and Escera (in prep.), who varied systematically the location of the sounds presented in an auditory-visual distraction paradigm. In their experiments, the sequence of sounds (including both the standard and novel ones) was presented in separated conditions, binaurally through headphones or by means of loudspeakers located at 72° left, 18° left, 18° right, 72° right, and 0° from the computer screen on which the visual stimuli were being displayed. As observed in many previous experiments using the auditory-visual distraction paradigm, novel sounds occurring within the headphones sequence distracted subject's performance, i.e., significantly increased response time. Interestingly, novel sounds occurring in any lateral location, except the 72° left one, also distracted subject's performance in the visual task. However, as in the preliminary observation by Schirmer, the novel sounds occurring by the computer screen (0° location) failed to elicit any response time increase, compared to standard trials, in response to visual targets. This pattern of results challenges the interpretation of Parmentier et al. (2008) discussed above and strongly supports a role of spatial attention in explaining the distracting effects observed in the auditory-visual distraction paradigm.

Top-Down Modulation of Auditory Distraction

A major milestone in MMN theory is that the underlying process and the associated neural response is automatic, i.e., does not depend on the direction of attention (Näätänen, Paavilainen, Rinne, & Alho, 2007). Although this notion has been challenged by several empirical papers and has been object of an intense debate (see Sussman, 2007, for a comprehensive discussion), it is widely accepted that change detection in the auditory modality can be considered attention-independent. Nevertheless, it is a common experience that the effects of an unexpected novel (or rare) sound in everyday life depends to a large extent on the ongoing activities: In general, highly demanding activities prevent distraction, whereas distractibility is enhanced during nonmotivating or nondemanding tasks. Experimental support for the common observation that distraction depends on top-down factors comes from studies of visual attention. These studies have shown, for instance, that when the location of a subsequent irrelevant stimulus is known beforehand, subjects could "block" that spatial location in a way that the ability of a distracter to attract attention involuntarily disappeared (Atchely, Kramer, & Hollstrom, 2000; Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Yantis & Egeth, 1999; Yantis & Jonides, 1990). These and related observations led to the proposal that attention capture is not entirely determined by distracter properties, but rather by the *relationship* of these properties with those of the relevant stimuli (Folk et al., 1992). This "contingent-orienting" view of involuntary attention postulates, therefore, that the current "cognitive set" determines the attentional configuration in a top-down fashion, and that the occurrence of a distracter in the sensory environment will capture attention automatically, in a bottom-up manner, inasmuch as it fits with the attentional configuration (Pashler, Johnston, & Ruthruff, 2001). According to this theory, the occurrence of deviant, or novel, sounds in the distraction paradigms reviewed above should have an impact on subject's performance and related brain responses, depending on the task assigned to them.

In fact, these "contingent-orienting" effects have been observed in the distraction paradigms described above, suggesting that they provide a suitable framework to study the neural mechanisms subserving the interaction between the top-down and bottom-up forms of attention control. In their seminal paper, Escera et al. (1998) already observed that, compared to a passive condition in which the subjects were instructed to read a book and to ignore the auditory sequence, the same novel sounds in the exactly same auditory sequence embedded in an auditory-visual distraction paradigm elicited a novelty-P3 of a much larger second phase, while the early one remained unaffected, suggesting a top-down modulation of the novelty-P3. A similar effect was further suggested by Escera et al. (2003), who found that meaningful novel distracters led to larger novelty-P3, compared to nonmeaningful ones, only when they were contingent to, i.e., occurred in a temporal relationship with, the visual task-relevant stimuli.

Moreover, in a study by Berti and Schröger (2003), using the auditory-auditory distraction paradigm, the distraction effects of deviant tones were largely reduced when the subjects performed a task that had a working memory component, i.e., withholding the response to the present stimulus until the subsequent trial (i.e., a 1-back task). These behavioral results were accompanied by an attenuation of the P3a and RON, whereas the MMN remained the same in the working memory and the corresponding control conditions. These results, involving

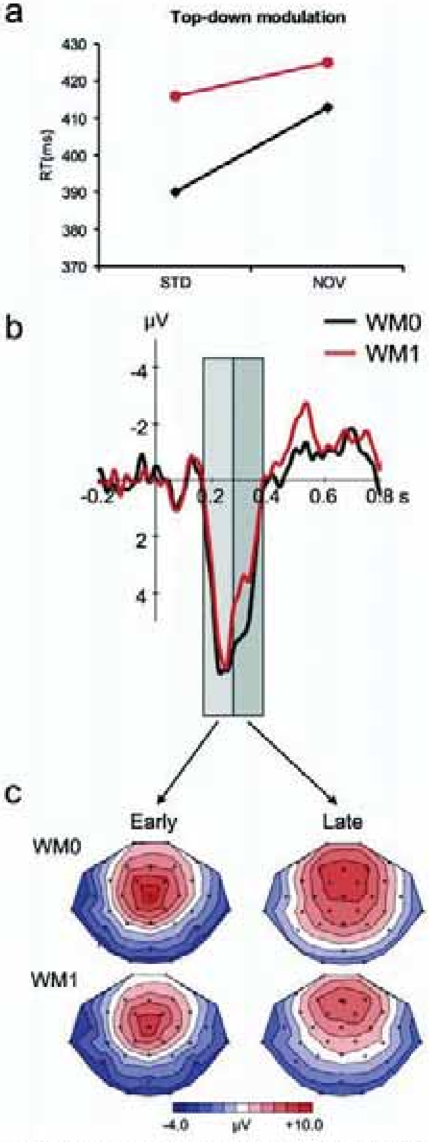

Figure 6. The top-down modulation of auditory distraction. When the visual task is made more difficult, for instance by imposing a load into working memory, involuntary attention toward distracting sounds in attenuated. This attenuation appears as a reduction in the behavioral distracting effects of the distracting sounds (a), and also as an attenuation of the late subcomponent of the novelty-P3 (b), also observed in the scalp-distribution maps (c) (adapted from SanMiguel et al., in press).

working memory manipulation, have recently been confirmed in a study using the auditory-visual distraction paradigm (SanMiguel, Corral, & Escera, in press). There, subjects were instructed to compare, in one condition involving a working memory load, the left-most digit of a two-digit number with the one of the same position displayed in the previous trial. The control condition was to decide whether the two digits were the same or different. As in the Berti and Schröger study, SanMiguel et al. (in press) observed a reduced distraction under working memory load and a reduced late-phase of novelty-P3 (Figure 6), while the early novelty-P3 and the N1-enhancement/MMN remained unaffected. Interestingly, and in contrast to Berti and Schröger's observations, RON was enhanced under the working memory load condition (SanMiguel et al., in press). Nevertheless, working memory load manipulation might result also in an increase of the distraction effects by deviant tones, as shown using the auditory-auditory distraction paradigm (Muller-Gass & Schröger, 2007). As discussed by these authors, the interaction between working memory and involuntary attention might depend on the channel separation between the distracting and target features of the stimuli (Lavie, 2005).

Another way of influencing involuntary attention through top-down factors would be by making the occurrence of the distracting sounds predictable. Such a scenario is similar to that used in the seminal experiments in the visual modality that lead to the formulation of the "contingent-orienting" view of involuntary attention outlined above. This was the rationale of an experiment by Sussman, Winkler, and Schröger (2003), who presented a visual cue preceding every sound of an auditory-auditory distraction paradigm. In a predictable condition, the visual stimuli indicated the pitch of the tone; in the unpredictable, the visual stimuli were randomly paired with the sounds, but did not provide any information on their pitch. Deviant tones occurring in the unpredictable condition elicited clear behavioral and a full "distraction potential." However, deviant tones in the predictable series failed to enlarge response time and also elicited an ERP that had comparable MMN to that observed in the unpredictable condition, but that clearly lacked the P3a and RON components (see also Wetzel & Schröger, 2007a, for similar results in children). Nevertheless, implicit predictability, i.e., sequences with regularly occurring standard and deviant tones seems not to be sufficient to prevent from behavioral and electrophysiological signs distraction (Jankowiak & Berti, 2007).

Still another particular circumstance in which top-down modulation is expected to exert a large influence on stimulus-driven brain responses is under emotional activation. A large body of evidence has shown that emotional stimuli have a privileged position in the environment, eliciting stronger and faster attention capture than nonemotional stimuli (Öhman, Flykt, & Esteves, 2001; Richards & Blanchette, 2004). Similarly, emotional context has been reported to enhance the processing of concomitant sensory inputs, as indexed for instance, by startle reflex potentiation (Stanley & Knight, 2004; Amrhein, Mühlberger, Pauli, & Wiedemann, 2004; Bradley, Codispoti, & Lang, 2006) or sensory gating suppression (Yamashita, Okamoto, Morinobu, Yamawaki, & Kähkönen, 2004). This results in adaptive and evolutionary advantages: The consequences of reacting slowly to emotionally salient information could be more dramatic than the consequences of a similar reaction to neutral events. In the recent study mentioned above, Domínguez-Borràs et al. (in press) asked their subjects to decide whether the two pictures on the screen, arranged in an auditory-visual distraction sequence, were similar or different. Half of the pictures were of neutral emotional content, whereas the other half displayed affective images of a negative emotional valence, such as mutilations or destruction. Results were remarkable: The effects of novel sounds on visual-task performance and brain responses were magnified when the visual stimuli were of a negative emotional valence, i.e., their distracting effects were larger – and the late novelty-P3 was also enlarged, compared to the neutral condition.

Furthermore, a subsequent study using improved experimental design, Domínguez-Borràs et al. (submitted-b) replicated a similar increased distractibility under negative emotional load. In this case, however, the emotional context effects on novelty processing were already observable at the stage of the early novelty-P3. This contrasts with the previous studies showing top-down modulation on the late novelty-P3 (Domínguez-Borràs et al., in press; Escera et al., 1998; SanMiguel et al., 2008), but might be explained by the central role emotions play in regulating behavior. In fact, a related study by Domínguez-Borràs et al. (submitted-a), designed to measure brain activation with functional magnetic resonance imaging, yielded data that might help to explain the effects of emotion on the early novelty-P3. In their study using another variant of the visual task – a color decision on the color of a face and its surrounding frame (see section one) – subjects were largely distracted when the face portrayed a negative emotion (fear, anger) compared to neutral ones. Novel sounds, both in the neutral and negative conditions, activated the superior and medial temporal gyrus, as observed in previous studies (Downar, Crawley, Mikulis, & Davis, 2000; Opitz, Mecklinger, Friederici, von Cramon, 1999). However, a comparison of novelty activation in negative vs. neutral conditions resulted in increased activation in superior temporal gyrus in the negative condition, indicating gating of novelty processing in this cerebral region under emotional load. Interestingly, the brain regions that showed this emotional modulation are similar to those described as contributing to the early phase of the novelty-P3 (Alho et al., 1998; Yago et al., 2003), so that these findings provide support to the observation of enhanced early novelty-P3 by Domínguez-Borràs et al. (submitted-b).

Role of Mismatch Negativity and Novelty-P3 in Auditory Distraction

The studies reviewed in the preceding sections demonstrated that the occurrence of an unpredictable deviant or novel sound in the acoustic environment attracts attention involuntarily, and that this involuntary attention switch has specific behavioral consequences on current task-performance, i.e., impoverishes it, which is accompanied by a specific pattern of brain responses, the "distraction potential." These studies used two versions of an auditory distraction paradigm, one using auditory and one using visual stimuli as targets, and in both cases have allowed to demonstrate that involuntary attention is contingent upon the demands of the task at hand, i.e., that the brain response to distracting sounds and their behavioral consequences are modulated by top-down factors. Although the two paradigms yield comparable results, i.e., deviant tones occurring in either of them result in delayed response time to subsequent targets, there are remarkable differences among them. First, the response time increase in the auditory-auditory distraction paradigm for deviant trials is about 50 ms, whereas it is only 10% thereof in the auditory-visual one, in both cases for a "standard" response time of circa 0.5 s. Second, the response time increase in the auditory-auditory distraction paradigm is always paralleled by a hit rate decrease, though this hit rate decrement is not always obtained with the auditory-visual distraction paradigm. And third, whereas there is a parallel increase of behavioral distraction and its accompanying electrophysiological signs in the auditory-auditory behavioral paradigm with increasing distracter salience (i.e., the deviant-standard difference; Berti et al., 2004; Jääskeläinen et al., 1999; Rinne et al., 2006), such a parallelism is not present in the auditory-visual distraction paradigm (Yago, Corral, & Escera, 2001b). Of course, a major difference between these two paradigms is that distracting information is carried by the same object or perceptual group in the auditory-auditory distraction paradigm, whereas distracting and target features are presented with a large channel separation, i.e., in different sensory modalities, in the auditory-visual distraction paradigm (see Escera et al., 2000, for further discussion). Nevertheless, these two paradigms provide a useful tool to investigate the mechanisms of involuntary attention and their particularities in children (Gumenyuk et al., 2001, 2004; Wetzel et al., 2004, 2006; Wetzel & Schröger, 2007a, b), aging (Andrés et al., 2006; Horváth, Czigler, Birkás, Winkler, & Gervai, in press; Mager, Falkenstein, Störmer, Brand, Müller-Spahn, & Bullinger, 2005) and clinical populations or drug conditions (Corbera, & Escera, in prep.; Cortiñas et al., 2008; Gumenyuk et al., 2005; Jääskeläinen et al., 1996, 1999; Knott et al., 2006; Polo et al., 2002, 2003).

As described above, a distracting sound elicits a distinct pattern of event-related brain responses, the DP, which is composed of three distinct waveforms (early negativity, positivity, and late sustained negativity), each of which reflect different ERP components. Early negativity reflects activation of the MMN generating process: a change-detector mechanism of rare sounds, or/and the activation of fresh neuronal elements upon the detection of new transient features of the stimulation; this later mechanism is associated with the auditory N1 or at least with some of its components (Näätänen & Picton, 1987; Escera et al 1998; Giard et al., 1994). Interestingly, both the MMN and the N1-enhancement recorded during distraction appear to be insensitive to top-down modulation, irrespective of the effects of the task at hand on distraction and brain responses subsequent to these two components. This suggests that transients/change detection is a fundamental property of the attentional system, one that operates automatically to prevent that any potential novel event in the acoustic environment to go unnoticed.

On the other hand, whereas the MMN and N1 mechanisms seem to operate automatically, the subsequent brain response, the P3a or novelty-P3 reflecting according to the most accepted view the orienting of attention toward unexpected deviant or novel sounds (Escera et al., 1998; 2000; Friedmann et al., 2001; Herrmann & Knight, 2001; Knight, 1984), is largely dependent on top-down factors. The studies reviewed above showed that the P3a elicited by deviant tones in the auditory-auditory distraction paradigm, as well as the novelty-P3 elicited by novel sounds in the auditory-visual distraction paradigm, can increase or reduce its amplitude, in parallel with effects of similar direction at behavioral level, i.e., enhanced or reduced distractibility, depending on the task at hand. This would support the P3a/novelty P3 as scalp signature of the involuntary orienting of attention; or, what is the same, one may take the occurrence of a distinct P3a as the probe that an effective orienting of attention toward distracting stimuli has taken place. This interpretation has been, however, recently challenged by a study of Rinne et al. (2006), who found that behavioral distraction increased as a function of intensity decrements in the absence of any P3a elicitation, contrasting with the results obtained for intensity increments, where behavioral distraction increments as a function on intensity increments were paralleled by a similar increase in P3a amplitude (see, however, Muller-Gass, Macdonald, Schröger, Sculthorpe, & Campbell, 2007, for P3a elicited to intensity decrements). These results call for a reconsideration of the role attributed to P3a generation in involuntary attention models. This is not the only case in which P3a/behavioral-distraction dissociations have been observed using the auditory distraction paradigms. Using the visual version, Munka and Berti (2006) observed the opposite phenomenon: generation of P3a in the absence of any signs of behavioral distraction. Similar results were also obtained by Yago et al. (2001b), who, in a study manipulating parametrically the deviant-standard frequency difference, found that the P3a (and also MMN and RON) increased linearly as a function of change magnitude, whereas no behavioral effects were observed except for the condition of 10% of change. These authors even reported a facilitation effect for a condition with 5% of frequency change. A further dissociation was observed by Polo et al. (2003), where larger (late) novelty-P3s were observed in a group of chronic alcoholics, compared to matched controls, in the absence of any differences in behavioral distraction. As suggested by Rinne et al. (2006), one possible explanation for the lack of relationship between P3a elicitation and behavioral distractibility might have to do with the fact that two different brain mechanisms control automatically for detecting rare events in the acoustic environment, as largely discussed above, and that P3a generation might not constitute a general index of attention switching, but one related to attention switch triggered solely by the N1 mechanism.

Although interesting, the proposal by Rinne et al. (2006) is seriously challenged by two recent studies using the auditory-auditory distraction paradigm. In these studies, behavioral distraction effects, accompanied by the corresponding distraction potential were obtained in conditions in which the N1 mechanism for attention capture hardly can have been activated. In one of these studies, subjects were to discriminate the duration (short, long) of a second tone of a pair of tones while ignoring their corresponding frequencies. The second tone was 26% higher in frequency in the standard trials, but this relationship was reversed in the deviant ones, and the particular frequencies of the pairs varied randomly from 600 to 1200 Hz in steps of 10 Hz (Schröger, Bendixen, Trujillo-Barreto, & Roeber, 2007). In another study of the same group, Bendixen, Roeber, and Schröger (2006) presented their participants with sequences of short and long tones arranged in random order with any of eight different frequency values. The frequencies values were, unnoticed to the participants, arranged with an internal regularity that dynamically changed along the course of the experiment. In both cases, the violation of the abstract rule governing the frequency relationship of the standard pairs (Schröger et al., 2007), or the implicit acoustic regularity of the auditory sequence (Bendixen et al., 2007), elicited clear behavioral distraction and a clear distraction potential, including P3a. Remarkably, the lack of any specific physical feature defining the deviant events in these studies would have hardly activated a transient detector mechanism associated to N1. Rather, the attention capture mechanism involved in these experiments is that related to the dynamic modeling of regularity in audition, associated to MMN generation (Bendixen et al., 2007; Schröger et al., 2007; Winkler, 2007), suggesting that P3a elicitation and its association to behavioral distraction is independent of the N1 mechanism.

In summary, the studies reviewed support the role of the MMN generating process in drawing attention toward unexpected violations of the implicit regularity of the acoustic scene. Such a process would operate automatically, i.e., unaffected by top-down factors, and would complement another mechanism for attention capture, that related to energy transient detection, associated to N1 generation. In contrast with the most extended view on the P3a, however, it is proposed that, rather than reflecting orientation of attention per se, the P3a/novelty-P3 signifies the evaluation of the contextual novelty of unexpected sounds. Furthermore, it reflects the reconfiguration of a cerebral network involved in updating task set information for goal-directed action selection (Barceló, Escera, Corral, & Periáñez, 2006).

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The Distraction Potential (DP), an Electrophysiological Tracer of Involuntary Attention Control and its Dysfunction

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Abstract

Attention involves both top-down and bottom-up processes. Top-down processes refer to those driven by the subject's intentions, plans and motivations. Bottom-up processes refer instead to those processes governed mainly by environmental conditions. The present text addresses this later type of attentional processes, as reflected in behavioural and event-related brain potential (ERP) indices. An auditory-visual distraction paradigm has been designed, allowing the recording of the neuroelectric concomitants of the activation of the cerebral network of involuntary attention during behavioural distraction. Subjects are instructed to respond to visual stimuli (i.e., press one response button to letters, and another response button to numbers) while ignoring the shortly preceding, task-irrelevant sounds. When these sounds are deviant or novel with regard to the repetitive auditory stimulation, behavioural distraction, i.e., prolonged reaction time and increased number of errors, is observed. In the ERPs, a triphasic neuroelectric response, the "distraction potential" (DP) is elicited, characterized by the N1/MMN, the P3a and the RON components, signalling, respectively, detection of sound change, orienting of attention and reorienting of attention after temporary distraction. In different conditions of brain damage, such as in alcoholism or after closed head injury, these ERP components reveal cerebral dysfunction of the involuntary attention network even in the absence of

behavioural concomitants, providing an objective tool to assess deficits in the involuntary control of attention.

Introduction

To manage oneself in a challenging environment fulfilled with thousands of stimuli requires an extraordinary ability to select the crucial and to reject the irrelevant. This ability is called attention, and permits us for example to concentrate in the reading of a text in a noisy environment, such as the campus cafeteria, or to listen to a specific instrument of a philharmonic orchestra while playing Symphony #9 (d minor) by Beethoven. This form of attention, which receives the name of voluntary or selective, is complemented with the other face of attention, similarly critical from an adaptive point of view, that is in charge of bringing to the focus of conscious evaluation stimuli initially not attend for their analysis in depth. This other form of attention, the so-called exogenous or involuntary, is responsible for the orienting response, and in general for avoiding that stimuli of vital importance for an adaptive behavioural from remaining unnoticed.

We have developed in the laboratory a simple behavioural "distraction" task that allows to investigate the cerebral mechanisms underlying the exogenous control of attention. Shortly, subjects are instructed to concentrate in the performance of a simple visual task (for example, to classify letters and numbers by pressing the corresponding response buttons) while ignoring the occurrence of irrelevant sounds that are presented one third of second before each visual stimulus. These irrelevant sounds are manipulated conveniently, in such a way that occasionally and with random order, the "standard" stimulus (occurring in 80 % of the cases) is replaced by a "distractor", i.e., a stimulus slightly higher in frequency (deviant) or by an environmental (novel) sound (as for example, a telephone ring, a glass breaking, the tinkle of some keys or that produced by a drilling device). We have observed consistently in several independent experiments that the distracting sounds increase the response time and the number of incorrect choices in the visual classification task, revealing behavioural distraction in the performance of such visual task (*Figure 1*) [1, 4, 6, 7, 17, 22, 23, 24; see review in reference 5].

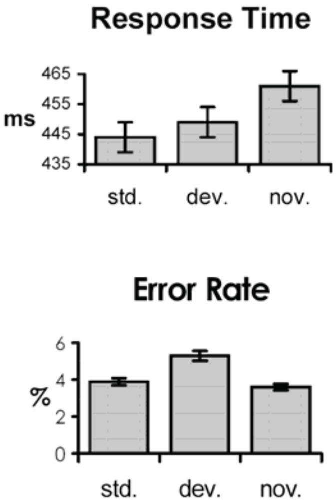

Figure 1: Mean response time (top) and error rate (bottom) to visual stimuli occurring after standard tones (std.), deviant tones (dev.), or novel sounds (nov.) in the distraction paradigm. The bars indicate the standard error of mean. Adapted from [4].

The concomitant recording of event-related brain potentials (ERPs) during the execution of the distraction task allows us to investigate the spatio-temporal dynamics of activation of the cerebral network underlying the exogenous control of attention. The typical ERP recorded in this scenario shows a complex morphology, both for the standard and the distracting trials. This is caused by the overlapping of the neuroelectric responses related to the processing of the physical features of the auditory stimulus, its distracting features, the visual stimulus and the neuroelectric activity associated to the cognitive processing involved in the task being carried out by the subject with regard to the target stimulus (*Figure 2a*). However, a simple arithmetic computation, i.e., the subtraction of the response elicited to the standard trial from that elicited to the distracting trial, allows us to isolate the neuroelectric activation underlying behavioural distraction; for reasons of convenience, we have termed to this activation *distraction potential* (DP). The distraction potential shows a characteristic tri-phasic shape, with an initial negative wave, followed by a positive wave and a final phase with a more or less sustained negative wave (*Figure 2b*). Each of these phases provides a marker for one of the three main processes involved in the involuntary control of attention: (1) the mechanism of attention capture, associated with the *mismatch negativity* (MMN) and/or with the N1 ERP components, (2) the orienting of attention, associated with the P3a or novelty-P3, and (3) the reorienting of attention towards the main task after a momentary distraction, associate with the so-called *reorienting negativity* (RON). These mechanisms and their electrophysiological concomitants are discussed briefly in the following paragraphs.

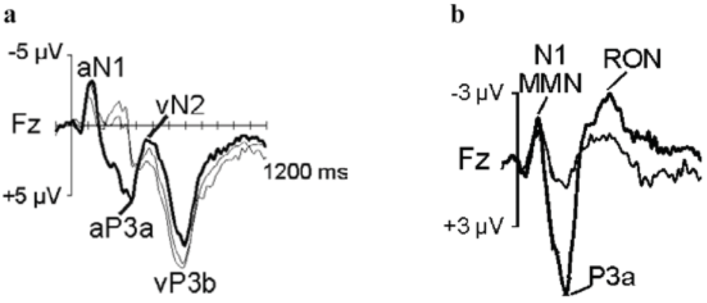

Figure 2: (a) ERPs in the auditory-visual distraction task. Standard (thin), deviant (medium) and novel (thick) trials. The auditory components are labelled as aN1 and aP3a, and those elicited to the visual stimuli as vN2 and vP3b. *(b)* The *distraction potential* (DP), obtained by subtracting the potential elicited to the standard trial from that in the deviant (fine line) or novel (thick line) trials. The distraction potential is characterized by a tri-phasic response including: MMN/N1, P3a and RON ERP components. Adapted from [7].

It has been proposed that there are at least two cerebral mechanisms responsible for directing the focus of attention towards environmental unattended events of potential relevance for competent behaviour [13]. One of them, phylogenetically more ancient, is based on a neurophysiological reaction to transient increment/decrements in the stimulating energy, and operates similarly in the auditory, visual and somatosensory modalities. This mechanism has been associated with the auditory N1 ERP component [15], and is activated, in our distraction paradigm, by the novel stimuli, yielding to an increase in novel-N1 amplitude when compared to the standard N1 (*Figure 2*). The second mechanism is based on the analysis of the implicit regularity of the incoming auditory information, and in the building and maintenance of a neural representation of its features, to react neurophysiologically to any subtle change in the auditory input. This mechanism activates a change-detector process which leads to the generation of the MMN [14, 16, 17], and can be best identified by using distractor stimuli of slight difference with regard to the repetitive stimulation (*Figures 2b* and *3*). In our distraction paradigm, the behavioural data confirm the existence of these two attention capture mechanisms, since the distracting effects are different for novel and deviant sounds. Indeed, whereas novel sounds cause a large (about 25 ms) delay in the response time in the visual discrimination task, deviant sounds cause only a small response time increase (about 5 ms), but a noticeable increment in the number of erroneous classifications as well [1, 4, 7; see *Figure 1*]. ERP recordings show also this differential effect, with a clear MMN generated to deviant distractors and a combined MMN/N1 response elicited to novel distractors [2, 4].

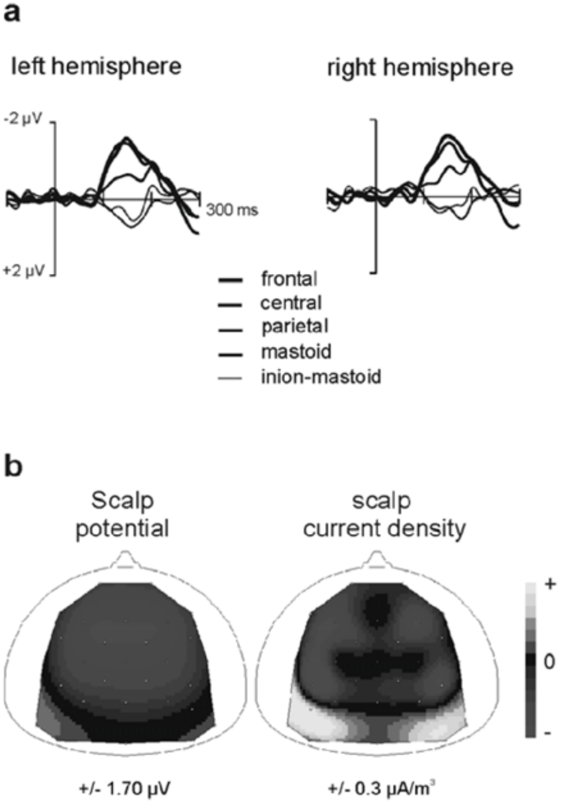

Figure 3. (a) The MMN elicited to frequency deviant stimuli in the distracting paradigm. It appears as a negative-polarity component with a polarity reversal at sites below the Sylvian Fissure (i.e., mastoid, inion-mastoid). *(b)* Scalp distribution of the MMN potential (left) and the corresponding scalp current density map (right). Adapted from [22].

The P3a ERP component, generated with large amplitude to novel stimuli and therefore called “novelty-P3”, has been considered in the psychophysiological literature as a cerebral sign of the orienting response [8, 12, 13]. In our studies, we have observed that novelty-P3 generation is accomplished in two different phases, each of them involving a different scalp distribution, a different latency, and a different sensitivity to attentional manipulations [4, 7]. The first P3a phase, with a peak latency between 220 and 320 ms, has a central bilateral scalp distribution and appears independent of attentional manipulations. On the other hand, the second phase of the novelty-P3, occurring between 300 and 400 ms, has a right frontal scalp distribution, and appears highly sensitive to attentional manipulations: when the subjects can monitor covertly the distracting sounds its amplitude is considerably larger [4]. Recently, we have shown, in agreement with previous results described in the literature [9], that novelty-P3 generation encompasses at least five different cerebral regions (*Figure 4*), engaged in clear spatiotemporal orchestration [24]. As early as 160 ms from novel sound onset, the first contribution to novelty-P3 appears to be the anterior cingulate gyrus; over 200 ms from novel sound onset, a simultaneous activation of the bilateral temporoparietal region and the left frontotemporal cortex is observed; finally, approximately after 300 ms from novel sound onset the superior parietal cortex and prefrontal regions are activated [24].

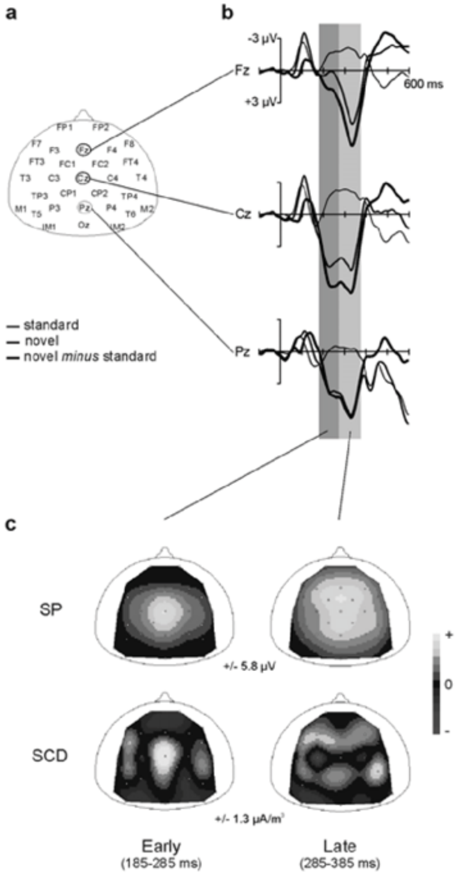

Figure 4: The novelty-P3, *(a)* Distribution over the scalp of the 30 electrodes used in the EEG recordings. *(b)* ERP at midline electrodes elicited to standard and novel stimuli, and the corresponding difference waves. Gray shadows show the two phases of the novelty-P3, in the respective latency ranges of 185-285 ms (dark gray) and 285-385 ms (light gray). *(c)* Scalp potential (SP) and current density (SCD) distributions of the two phases of the nP3. The SCD analyses revealed positive currents over central, bilateral temporoparietal and left frontotemporal areas during the early novelty-P3a, and over superior parietal, bilateral temporoparietal and frontal areas during the late novelty-P3. Adapted from [24].

As important as the flexibility to direct attention towards unexpected potentially relevant events, is the ability to return attention back to original task performance after a momentary distraction. It has been proposed that this attentional process is associate with the generation of another ERP component recorded in distraction tasks, the so-called *reorienting negativity* (RON) [3, 20, 21]. These authors found in their recordings a negative wave, subsequent to P3a, only when the subjects carried out a task where the deviant stimuli acted as distractors, but not when they were asked to discriminate actively these stimuli or when they were instructed to ignore completely the auditory stimulation and to concentrate in an unrelated visual task not concomitant to the sounds. We argued that, to indicate the process of reorienting of attention back towards the main task, RON should be time-locked to the target stimuli in the task, and not with the distractor stimuli. In our experiment, we manipulated the asynchrony between the distractor stimuli and the visual target stimuli, and we observed that the RON latency was of 345 ms, independently of the asynchrony between the auditory distractor and the visual target, which were in different conditions of 245 or 355 ms (*Figure 5*) [7]. Therefore, these data suggest that RON may constitute, indeed, a neurophysiological scalp marker of the process of returning attention back to primary task performance after a momentary distraction.

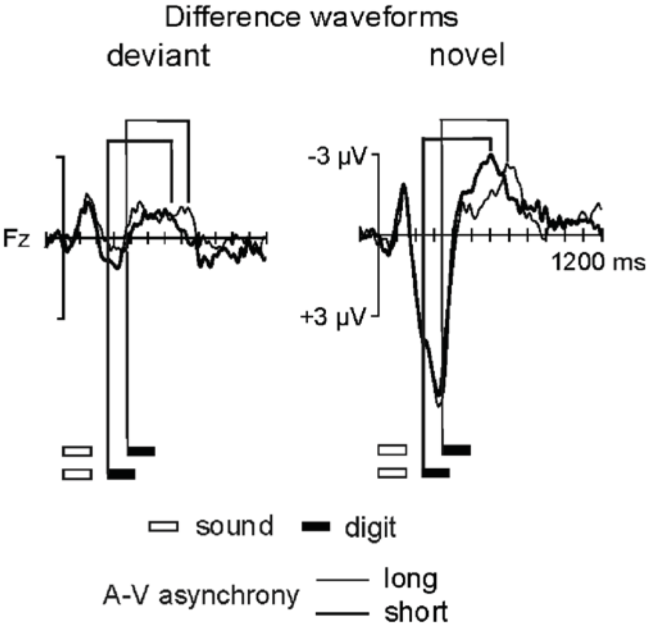

Figure 5: The reorienting negativity (RON) elicited in distracting trials, as seen in difference waveforms at Fz. RON peaks at 345 ms from visual stimulus onset irrespective of distractor asynchrony (short = 245 ms; long = 355 ms). Adapted from [7].

In several recent studies of our laboratory we have been able to show the utility of the distraction potential to reveal attentional impairments in closed head injury patients [10, 18] and chronic alcoholics [17], in the absence of behavioural deficits or evident neuropsychological or neuroradiological signs.

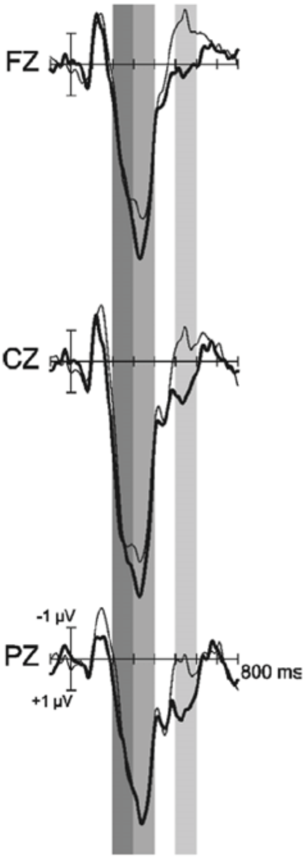

Figure 6: The distraction potential in alcoholic (thick line) and control subjects (thin line). Grey shadows show the early (200 to 300 ms, dark grey) and late (300 to 400 ms, medium grey) phases of the novelty-P3, and RON (500 to 600 ms, light grey). Adapted from [17].

In one of these studies, we compared the results obtained in a sample of detoxified male alcoholic subjects (N = 17, average age: 40 years) and their respective healthy controls (N = 14), matched by age and socio-economic level, during the execution of our distraction task [17]. Both groups showed similar performance in the distraction task, i.e., a similar amount of response time increase in distracting trials, suggesting intact mechanisms of the exogenous control of attention. However, the distraction potential revealed some noticeable anomalies in the exogenous control of attention in the patients, that would confirm their complains of increased subjective distraction and difficulty of concentration. Indeed, in comparison with control subjects, alcoholic patients showed a clearly enhanced novelty-P3 amplitude, particularly over the left fronto-temporal cortex, and a total lack of RON (Figure 6). In agreement with the conceptual framework on the generation of these ERP components, outlined in the present review, these results suggest an exaggerated orienting of attention towards the task-irrelevant novel sounds in alcoholics, as well as a difficulty to reorient attention back towards the main task after a momentary distraction, in agreement with their subjective complains. However, it is possible that in controlled situations, such as those of laboratory testing, they may compensate those deficits to perform in the visual task as control subjects, but nevertheless failing in the executive control of attention in natural conditions, where irrelevant stimuli occur considerably more frequently. In summary, a new distraction paradigm allows to evaluate the neuroelectric activation of the cerebral network involved in the exogenous control of attention, through the distraction potential (DP), which includes the MMN/N1, the P3a and the RON ERP components, in combination with behavioural measures of distraction. A powerful appeal of this new neuroelectric approach to the cerebral activation of attention is that it can disclose neurofunctional impairment even the absence of behavioural concomitants, thus providing indices of neurological dysfunction in cases in which neuroradiological or neuropsychological tests cannot objectify the patient's subjective complaints. Future research in these directions will confirm the power of such a new approach to the cognitive and clinical neuroscience of attention.

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