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Research Report

An electrophysiological study of haptic roughness: Effects of levels of texture and stimulus uncertainty in the P300

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ABSTRACT

This study investigated the neural mechanisms implicated in tactile perception using a discrimination task. We also investigated the influence of the type of presentation on the subject's uncertainty. The stimuli varied across four levels of roughness and were presented using a pure/mixed block design. We used an oddball paradigm with three target stimuli varying in the level of roughness, and a smooth surface as the non-target. Stimuli were presented using a specific-purpose device. We analyzed the modulation of the P300 amplitude elicited by targets and non-targets in both presentation conditions. The results showed that the P300 waveform was modulated by roughness, as well as by the order of stimuli presentation. The P300 amplitude was more sensitive to roughness when stimuli were presented in mixed blocks (higher uncertainty). The results are discussed in the context of the attention resources allocation theory applied to tactile modality.

1. Introduction

Research on touch has interested neuroscientists and psychologists for many years, but the field has developed dramatically over the last decade (Ballesteros and Heller, 2008). Touch enables us to extract accurate information about objects, including their identity (Ballesteros and Reales, 2004; Klatzky et al., 1987; Reales and Ballesteros, 1999), symmetry/asymmetry (Ballesteros et al., 1998; Ballesteros and Reales, 2004), and material properties such as texture and hardness (Klatzky et al., 1987). Several studies have shown that it is relatively easy for human haptic perceivers to detect stimuli varying in roughness (*e.g.*, Ballesteros et al., 2005; Bergman-Tiest and Kappers, 2007; Hollins and Risner, 2000; Taylor and Lederman, 1975). A number of psychophysical (Lawrence et al., 2007) and neurophysiological studies have investigated

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the peripheral (Johnson et al., 2002) and cortical (Kitada et al., 2005) correlates of tactile roughness perception. Concerning the temporal course of brain activity related to these mechanisms, several studies have investigated the neural correlates of roughness perception and attention to stimuli presented to touch (Brázdil et al., 2003; Huang et al., 2005; Kida et al., 2004b, 2012; Rektor et al., 2007). However, less attention has been paid to investigate whether the presentation order affects the perceptual discrimination of these stimuli.

Texture is a more salient property for touch than shape or size (Klatzky et al., 1987). Research has shown that spatial information is central for coarse textures, suggesting the importance of spatial code in roughness perception (Lederman and Taylor, 1972; Blake et al., 1997). However, vibrotaction (movement-induced vibration) is important in the perception of smooth textures. A single parameter, groove width, predicts the variance in estimates of perceived roughness (Lawrence et al., 2007). In a previous study, we investigated the extent to which two tactile stimuli varying in roughness (peak-to-peak spacing of triangular grating) and movement speed (the time available for tactile contact with the surface) modulated earlier stages of brain activation using a dynamic passive task (Ballesteros et al., 2009). According to Chapman (2009; p. 32) "*A special type of dynamic passive touch, often used in experimental situations, is to displace surfaces, mounted on a drum or a moveable platform, over a single region of skin*". The results of our study showed a biphasic N100-P200 deflection that occurred significantly earlier for the smoother than for the rougher texture (28 ms and 17 ms from stimulus onset, respectively). However, only at the slowest presentation speed (12 cm/s) was the N100 component significantly more negative than that of the rougher texture. We also found that the N100 component was related to the activation produced at the somatosensory cortex, while the P200 was related to the posterior cingulate cortex, suggesting that both areas are involved in roughness perception by touch. However, as the experiment did not require participants to produce an active response, the ERPs elicited were interpreted as being related to the physical attributes of the stimuli (bottom-up processing), as well as to the perceiver's ability to detect different levels of roughness by touch.

The present study was specifically designed to investigate how attention modulates the perception of tactile stimuli varying in roughness. Tactile attention is necessary for the selection of specific sensory inputs at certain body locations (Kitada et al., 2005; Müller and Giabbiconi, 2008). Tactile stimulation and the spatial and non-spatial representations of stimuli perceived by touch are largely processed in primary somatosensory areas (Foster and Eimer, 2004; Harrington and Hunter Downs III, 2001), engaging attention at very early stages of information processing. A number of studies using magneto-electrical approaches have mainly focused on controlled processing (Josiassen et al., 1990; Kida et al., 2004a; Mima et al., 1998; Nakajima and Imamura, 2000; Tomberg, 1999). In these studies, electrical stimulation was applied to different fingers or to the median nerve at the wrist to elicit vibrotactile perception. The results provided evidence of early and late Somatosensorial Event-Related Potential components (SERPs), revealing some sort of neural modulation in the somatosensory cortex depending on whether attention was directed to different physical features (stimulus-driven processing) or to the psychological properties of the task (*e.g.*, keeping attention focused on the task demands, Kida et al., 2004a).

Early SERPs in somatosensory processing have previously been studied (Desmedt and Tomberg, 1989; Josiassen et al., 1990; Kida et al., 2004a; Mima et al., 1998). However, little tactile research has been conducted on late SERPs, such as the P300 component. The amplitude of P300 is related to the amount of attentional resources allocated to stimulus perception, object evaluation, object categorization and memory updating (Kramer and Strayer, 1988; Polich, 2003; Ruchkin et al., 1988). Other studies have related P300 amplitude to the level of arousal, which governs the amount of attention necessary to perform the task, as well as to response preparation (Kahneman, 1973; Polich, 2007). Therefore, this ERP deflection is considered as an endogenous upstream-sensitive component (Donchin et al., 1978). However, some experimental manipulations suggest that the P300 also has an exogenous component, as it depends on the physical features of the stimuli. For example, Nakajima and Imamura (2000) observed that the P300 component increased as a function of stimulus intensity and the level of attention directed to the tactile targets. Both the P300 and N200 components have mostly been elicited using the oddball paradigm (Squires et al., 1975; see also Näätänen and Picton, 1986; Hoffman, 1990). The P300 amplitude depends on the probability of targets (the odd stimulus to be attended to) and non-targets (Picton, 1992) in the oddball task. The context-updating P300 hypothesis (Donchin and Coles, 1988) proposes that the P300 can be interpreted as a cognitive routine supporting the formulation of an internal environmental model in which a stimulus is evaluated. Taking this view, we can manipulate such models or psychological states by presenting stimuli in different types of sequence, varying uncertainty and inter-trial variability (Los, 1996).

In discrimination tasks, the somatosensory P300 component is elicited in a distributed network of brain areas involved in perception (somatosensory system), attention, and memory (association cortical areas). See Nakajima and Imamura (2000) and Polich (2007). In an early study, Bruyant et al. (1993) investigated the P300 component using a tactile paradigm in which target electric shocks were presented to the attended or the unattended hand, whilst frequent non-target stimuli were presented to the other hand. The P300 component was elicited even when the target stimulus was presented to the unattended hand, reflecting some sort of automatic processing of the target stimuli. These findings suggest that brain activity is modulated by attention, but that this modulation also depends on experimental conditions or contextual features.

The way in which the tactile stimuli are presented (passive touch *vs.* dynamic passive touch) is also relevant in modulating perception and attention. As reviewed above, much of our knowledge on tactile perception has been obtained in passive touch studies. However, little effort has been devoted to investigating how attention drives neural activity when the perceiver is performing a task involving dynamic passive touch. In this case, both vibration and mechanical depression of the skin activate the full range of mechanoreceptors (Greenspan and Bolanowsky, 1996). In an early study, Desmedt (1977) showed that the application of mechanical stimulation to the index fingertip while participants identified the orientation of a ridge evoked a prolonged positive potential (the P300 component) over the right temporal cortex. The author concluded that this lateral positivity was related to tactile scanning and completion of the perceptual decision.

1.1. *The current study*

In this study, we recorded electrophysiological data while participants experienced moving textured surfaces under their index fingertip (dynamic passive touch). Although roughness can be detected by a simple static contact, it is generally acknowledged that tactile perception is better with dynamic than static tactile stimulation (Morley et al., 1983). Two main questions were addressed in the present study. (1) Is the P300 component sensitive to the level of roughness (exogenous or stimulus-driven component)? (2) Is the P300 waveform modulated differentially in pure and mixed block conditions (endogenous component)?

To test whether the P300 component is sensitive to the deployment of attention when a specific tactile attribute is attended to, we used an oddball paradigm. In this experiment, we presented four levels of roughness to the perceiver's fingertip using a specific-purpose device, the *Tactile spinning wheel,* described in more detail in Reales et al. (2010). One of the stimuli was a completely smooth surface and this was always the unattended texture. The other three stimuli varied in the level of roughness and were always the attended textures. We hypothesized that the ability to perceive and evaluate tactile roughness would mainly be based on physical properties and could be revealed by changes in P300 amplitude. Therefore, we expected that the amplitude of the P300 component would be related to the physical differences between targets and non-targets. Accordingly, we predicted that the easier the discrimination between the targets and the non-targets, and the smaller the attentional demands, the larger the P300 amplitude would be (Polich, 2007).

To answer the second question, we used two types of stimulus presentation: (a) the three levels of roughness were presented separately (pure block presentation); and (b) levels of roughness were randomly intermixed (mixed presentation). The pure block condition consisted of blocks of trials that included only one of the three textured stimuli (the target) intermixed with the completely smooth texture as the non-target stimuli. By contrast, the mixed condition consisted of presenting all three target stimuli randomly intermixed with instances of the non-target stimulus. We assumed that the two types of presentation would induce different degrees of stimulus uncertainty and preparedness for action (Los, 1996). In pure block conditions, participants can deal more effectively (*i.e.* with less uncertainty, more readiness) with forthcoming events than in mixed block conditions. In fact, Anselme (2010) referred to anticipation and attention as a set of cognitive processes that allow participants to extract roughness information by reducing the uncertainty of the occurrence of relevant events. We hypothesized that extracting roughness information from tactile stimuli presented in mixed blocks would require more attentional effort than when the same stimuli were presented separately in the pure block condition. We reasoned that the different level of uncertainty derived from the two stimulus presentation conditions might have a differential effect on elicitation of the P300 (Sutton et al., 1965). Moreover, we expected to find an interaction between roughness and presentation condition. Since these conditions differ in the level of uncertainty, we hypothesized that roughness processing would be enhanced in the mixed condition as compared with the pure condition (Fitzgerald and Picton, 1983).

2. Results

2.1. *Behavioral results*

Accuracy in counting the number of non-flat stimuli in the pure and the mixed conditions were 95% and 77%, respectively. Although accuracy was higher in the pure condition than in the mixed condition, the difference was not statistically significant ($t_{24}=1.7$; $p=.1$) due to the large variance of the mixed condition. Accuracy for each of the three targets could not be measured separately in this condition. However, lower accuracy in the mixed condition than in the pure condition could be explained mainly by a lower ability to discriminate rough0 from rough1.

2.2. *Event-related potentials overview*

Fig. 3 displays the grand averages of the event-related potentials (ERPs) at the most representative electrodes for the four levels of roughness under the pure condition. The earlier components were not very prominent compared to the larger P300-like waveform.

The P300 amplitude was greater for rough2 and rough3 than for the non-target stimulus (rough0), while positive deflections for rough2 and rough3 were similar across all

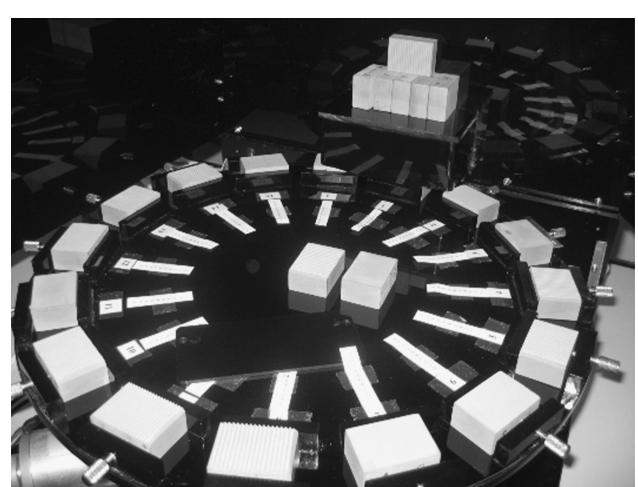

Fig. 1 – An overhead view of the *Spinning Wheel* for presenting tactile stimuli to the index fingertip.

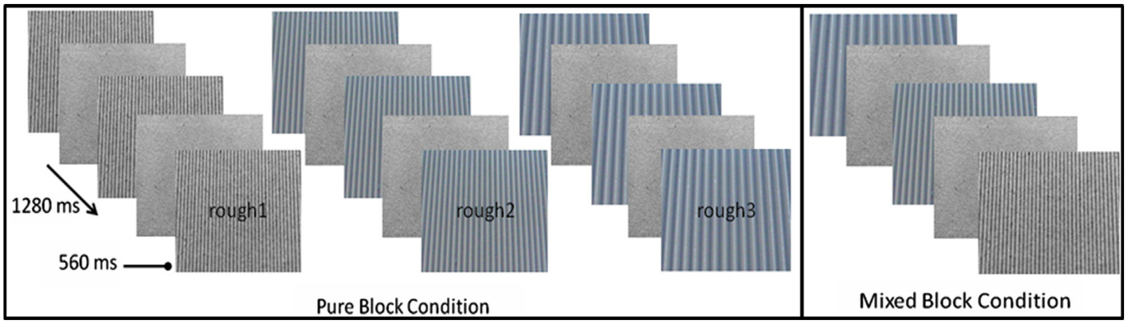

Fig. 2 – Schematic representation of the experimental conditions showing the three levels of roughness and the two presentation conditions.

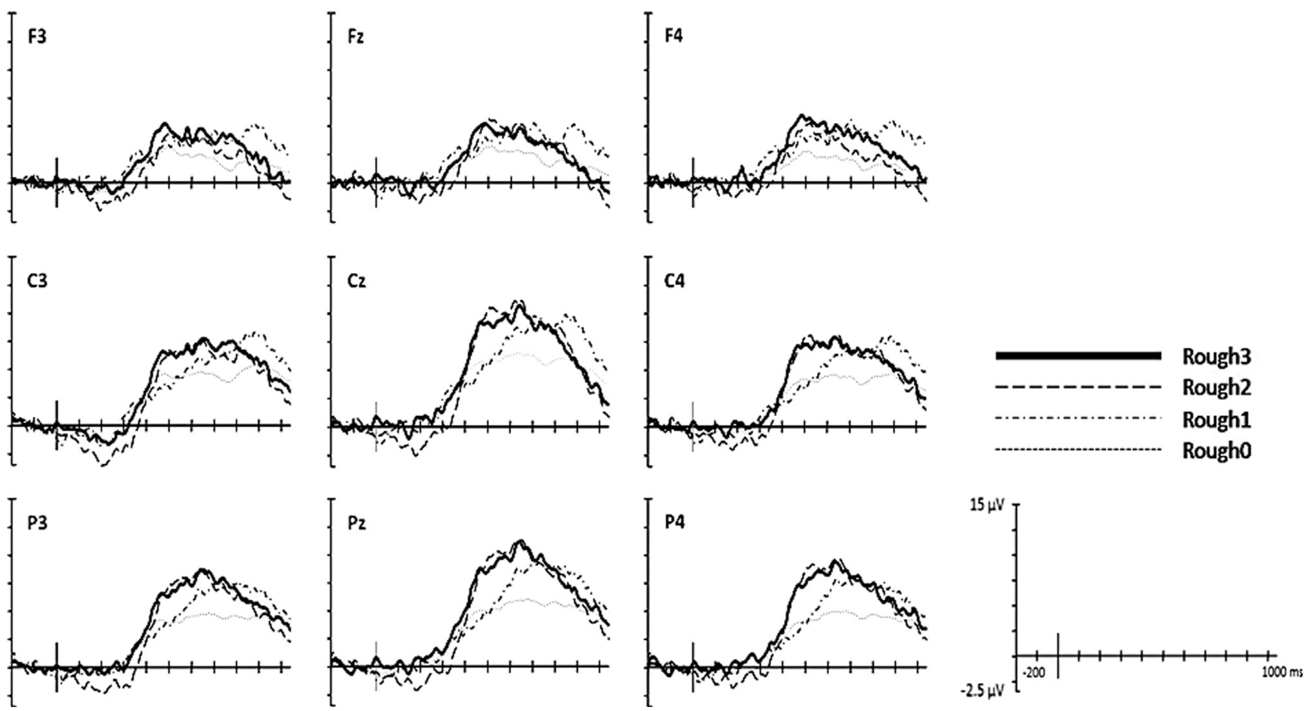

Fig. 3 – Grand averages of the event-related potentials (ERPs) corresponding to the four levels of roughness in the pure blocked condition at the most representative electrodes.

electrodes. It is noteworthy that the ERP waveforms corresponding to rough0 and rough1 were parallel shortly after stimulus onset, but a few milliseconds later the waveform corresponding to rough1 began to diverge from the one corresponding to rough0.

Fig. 4 displays the grand averages corresponding to the mixed condition, showing that the roughness condition produced similar but more sharply defined ERP patterns compared to the pure condition. An overall negative deflection was observed at stimulus onset. Later, the P300 amplitude appeared greater for rough3 than for rough2, particularly at midparietal electrodes. Rough1 and rough0 stimuli also showed small differences in amplitude from the beginning of the P300. This pattern of results was not found in the pure condition.

This bird's eye view shows that the P300 component varies as a function of the discriminability of the target depending on whether the levels of the independent variable (roughness levels) were presented separately (pure block condition) or randomly intermixed (mixed condition).

2.3. *Statistical results*

Table 1 shows a summary of the significant results obtained in the present study. As mentioned above, separate $2 \times 4 \times 3 \times 3$ mixed ANOVAs were conducted for each time window, with Presentation condition as the between-subjects factor, and Roughness, Anterior/posterior axis, and Laterality as within-subjects factors. The analysis revealed a main effect of Roughness ($4.3 < Fs_{(2, 48)} < 18.0$; $.0001 < ps < .01$) in the 400–1000 ms time interval, the P300 latencies. *Post-hoc* analyses revealed differences between targets and non-targets. Regardless of the presentation condition, the P300 component elicited by rough1 and rough0 stimuli did not differ significantly in amplitude in the 400–600 ms time interval. However, in the 600–1000 ms time interval, rough1 evoked a

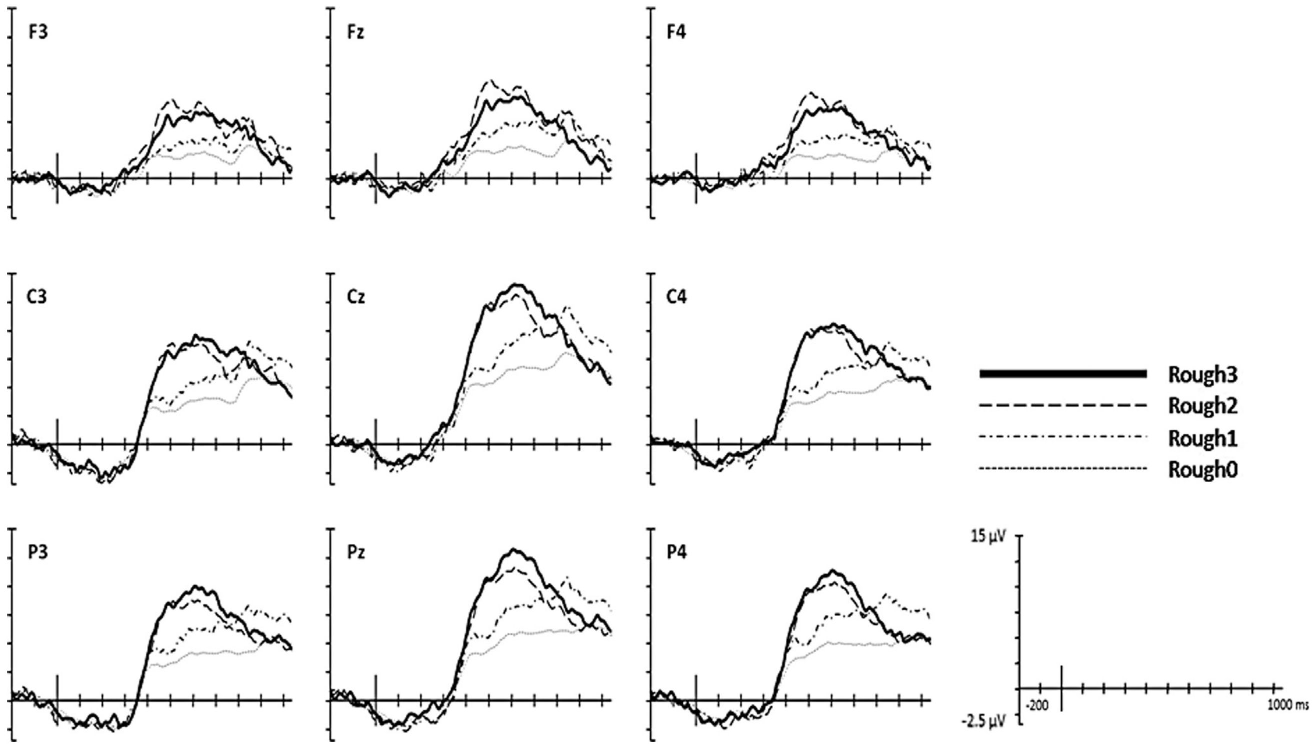

Fig. 4 – Grand averages of the event-related potentials (ERPs) corresponding to the four levels of roughness in the mixed blocked condition at the most representative electrodes.

Table 1 – ANOVA results for the time windows from 100 to 1000 ms corresponding to Roughness, Anterior–Posterior Axis, Laterality and the interaction between Roughness, Anterior–Posterior Axis and Presentation conditions.

Time window (ms)	Roughness			Anterior–Posterior Axis			Laterality			Roughness × Anterior–posterior axis × presentation condition		
	F	P	η^2	F	P	η^2	F	P	η^2	F	P	η^2
100–200		Ns		10.8	.001	.31	11.7	<.0001	.33			
200–300		Ns		4.8	<.05	.17	26.5	<.0001	.52			
300–400		Ns			Ns		30.1	<.0001	.56	2.5	<.05	.09
400–500	12.2	<.0001	0.33	33.5	<.0001	.58	37.3	<.0001	.60	4.1	.001	.15
500–600	16.3	<.0001	0.40	66.7	<.0001	.73	51.0	<.0001	.68	3.5	<.01	.13
600–700	18.03	<.0001	0.43	112.8	<.0001	.82	61.4	<.0001	.72	2.5	<.05	.09
700–800	9.7	<.0001	.29	112.8	<.0001	.82	48.2	<.0001	.67	2.6	.06	.08
800–900	4.7	.005	.16	74.1	<.0001	.75	29.3	<.0001	.55	4.6	<.0001	.16
900–1000	4.3	<.01	.15	72.9	<.0001	.75	7.1	<.001	.23	3.4	<.005	.12

significantly larger P300 component than rough0, the non-target stimuli ($7.7 < Fs_{(1, 25)} < 23.5$; $.001 < ps < .01$). This component was also significantly larger for rough2 and rough3 targets compared to rough0 non-targets in the 400–900 ms time interval ($4.7 < Fs_{(1, 25)} < 78.8$; $.001 < ps < .05$, and $4.8 < Fs_{(1, 25)} < 61.9$; $.001 < ps < .01$, respectively). The P300 component was significantly larger for rough2 and rough3 than for rough1 ($8.2 < Fs_{(1, 25)} < 29.8$; $.001 < ps < .01$; and $7.4 < Fs_{(1, 25)} < 14.2$; $.001 < ps < .01$) in the 400–700 ms time interval. Interestingly, in the 900–1000 ms time window, the P300 was significantly more positive going in rough1 than in rough2 and rough3 [$F_{(1, 25)} = 7.6$; $p = .01$; $F_{(1, 25)} = 7.1$; $p = .01$].

A main effect of Anterior–Posterior axis was also highly significant ($4.8 < Fs_{(2, 48)} < 112.8$; $.0001 < ps < .05$), meaning that later effects on P300 amplitude were maximal at centro-parietal sites. The analysis also revealed a main effect of Laterality, meaning that P300 was highly significant at midline sites ($7.1 < Fs_{(2, 48)} < 61.4$; $.0001 < ps < .01$) throughout all time windows. Importantly, the main effect of Presentation was not significant.

At the 100–300 ms time windows, we found a significant two-way interaction between Presentation conditions and Anterior–Posterior Axis ($F_{(2, 48)} \approx 4.9$; $ps < .01$), showing a large negative deflection (N2-like component) over posterior sites in the randomly mixed condition. It is noteworthy that all P300 time windows except one (700–800 ms) yielded a significant three-way Roughness by Presentation by Anterior–Posterior axis interaction ($2.5 < Fs_{(6, 114)} < 4.6$; $.0001 < ps < .05$).

In the mixed condition, parietal P300 amplitude corresponding to rough3 was significantly greater than that of rough2. Although rough1 and rough0 also differed as a function of presentation conditions, the difference was only statistically significant under the mixed condition. Specifically, a *post hoc* pairwise comparison analysis in the 400–500 ms time window conducted on the pure condition revealed non-significant effects in multiple comparisons among textures. In contrast, in the mixed block condition, rough1 *vs.* rough2, rough0 *vs.* rough2, and rough0 *vs.* rough3 were all significantly different ($ps<.01$, for all comparisons).

Moreover, in the mixed block condition, comparisons of rough0 *vs.* rough2, and rough0 *vs.* rough3 were statistically significant ($MD=5.4$, $p<.001$ and $MD=5.2$, $p=.001$, respectively), as was rough1 *vs.* rough2 ($MD=3.7$, $p<.05$). In the pure condition, P300 amplitude was significant at the 500–600 ms time window only for pairwise comparisons of rough 0 *vs.* rough3 and rough1 *vs.* rough2 ($ps<.05$). It is noteworthy that rough0 and rough1 differed significantly in amplitude ($MD=2.4$, $p=.05$) at both the 700–800 ms and the 800–1000 ms time windows. Table 1 shows the results of all the statistical analyses corresponding to the four factors at each time window.

3. Discussion

The present study had two aims: (1) to investigate how brain activity is modulated while perceivers process tactile stimuli varying in roughness; and (2) to find out how brain activity is affected by the presentation condition. The results show that levels of roughness are clearly related to changes in the P300 amplitude at centro-parietal sites. As a whole, this suggests that the P300 component reveals a mapping between roughness and neural activation, very probably concentrated in the somatosensory areas.

The main result of the present study was the significant three-way interaction on P300 amplitude between roughness, anterior–posterior axis and presentation condition. This may be due to a different pattern of discrimination between targets and non-targets and a differential recruitment of attentional resources as a function of the presentation condition. Moreover, since discrimination ability is clearly based on the physical properties of the tactile stimuli, our results suggest that the P300 component might be a neural correlate of both bottom-up (stimulus-driven) processing involved in roughness detection and top-down (attention-driven) processing of the textured stimuli. The top-down influence reflected on the P300 component could be an effect of uncertainty about the level of roughness in the upcoming trial in mixed blocks (see Los, 1996). This combined influence of stimulus properties and cognitive factors is in line with the findings of Nakajima and Imamura (2000) that the P300 amplitude was modulated by the intensity of the stimuli, but only under attended and infrequent conditions. To highlight the main findings obtained in the P300 component in the light of the two types of processing (top-down and bottom-up), we discuss the results for each presentation condition separately.

The P300 component was sensitive to stimulus-driven texture levels earlier in the mixed condition (400 ms post-stimulus) than in the pure blocked condition. These results are similar to those obtained by Fitzgerald and Picton, 1983, suggesting that changes in target discriminability are related to different modulation in the N200-P300 complex. In the pure condition, the physical properties of rough2 and rough3 stimuli were both highly discriminable from the rough0 or non-target stimuli. This difference was related to a noticeable P300 amplitude in both target stimuli that was absent in the non-targets. This finding is in agreement with previous findings observed in the auditory modality (Duncan-Johnson and Donchin, 1982; Fitzgerald and Picton, 1983), showing that P300 amplitude was less positive for the more difficult target discrimination condition than for the non-target condition. Moreover, rough2 and rough3 target stimuli showed similar P300 waveforms (see Fig. 3), suggesting that these targets required similar attentional effort when roughness stimuli were presented in the pure blocked condition. In contrast, discriminating between rough1 and rough0 entails great difficulty as suggested by the fact that the positive deflection corresponding to rough1 parallels that of rough0. Later in latency (beyond 500 ms), the P300 waveform elicited by rough1 began to diverge from rough0, increasing its amplitude compared with rough0. However, despite this increment in amplitude in rough1, it remained below that of rough2 and rough3 (see Fig. 3). From this ERP pattern, we can conclude that textures that are similar in roughness might also be evaluated as similar and non-informative during the first stages of information processing. Ruchkin and Sutton (1978) referred to this effect as a loss of information due to the subject's uncertainty about having perceived a different event. Nonetheless, Nonetheless, continuous exposure to the tactile stimulus (560 ms from onset to offset) could allow the perceiver to extract more and more information, leading eventually to categorization of the stimulus as a target or non-target. This information leads eventually to the categorization of the stimulus as a target or as a non-target. Fitzgerald and Picton (1983) referred to this process as a dynamic updating of the information held in working memory. These authors observed a decrease in P300 amplitude as target discriminability diminishes. The existence of similar effects on the P300 with auditory and tactile stimuli is remarkable.

In the pure blocked condition, when the target stimuli were presented in separate blocks, rough2 and rough3 textures were easily discriminable from rough0, as revealed by their differences in P300 amplitude. Interestingly, in the mixed condition, the P300 component elicited by rough3 was significantly larger than that elicited by rough2 (see Fig. 4). This was not observed in the pure block condition. Although both rough2 and rough3 targets were discriminable from the non-target, it required further attentional demands to evaluate and categorize rough3 in the mixed condition. The same occurred when participants had to discriminate between rough1 and rough0, since P300 amplitude was slightly higher for the former than the latter. Although this ERP effect was also obtained in the pure block condition, it was elicited earlier in the mixed condition. This might reflect that updating rough1 with the preceding rough0 occurred earlier in the mixed than in the pure condition. This pattern of results is in accordance with our predictions, namely that greater attentional effort is required to extract information from different levels of roughness in a mixed than in a pure condition. This could be explained by the greater effort required to extract stimulus information, as signaled by the increment in P300 amplitude (Gratton et al., 1990). When more information about the physical properties of the target is available, it is easier for the perceiver to allocate his/her attentional resources to discriminate the stimulus and to select the appropriate response. The above explanation of the effect of type of presentation on the ERP is based on an attentional account. However, the increment in P300 amplitude obtained in the mixed presentation might also signal a higher level of expectancy, as well as the greater task uncertainty that occurs in this condition (Los, 1996; Gehring et al., 1992; Hillyard and Picton, 1987). As expected, the mixed condition confers a greater uncertainty about the roughness level that will be presented in the forthcoming trial, which yields an improvement in discriminating targets from non-targets (Fitzgerald and Picton, 1983). By contrast, in the pure condition, the target stimulus is highly predictable within each block, making inter-trial variability lower.

The present results partially support Polich's theory of P300 (Polich, 2007). This theory suggests that rather than reflecting a unitary phenomenon, P300 accounts for several stages throughout the information processing cascade, including sensorial, attentional and memory mechanisms. According to this theory, after the initial sensory processing, an attention-driven comparison process evaluates the representation of the previous event in working memory. Thus, if a new stimulus is detected, attentional processes govern a change or "updating" of the stimulus representation that is actually reflected by the P300 component. This cascade includes attentional and memory mechanisms (but see Verleger, 2008). Burton and colleagues (Burton et al., 1999, 2008) also proposed that attention could be directed to a particular tactile feature depending on task conditions. This proposal enables top-down mechanisms to process specific tactile information more efficiently. Burton et al. (1999) reported that these processes could take place in the primary and secondary somatosensory regions of the parietal cortex. In these regions, top-down mechanisms may enhance the signal-to-noise ratio during tactile roughness processing, leading to an improvement of working memory management (both representation and updating). The notion of mental load is relevant at this point, as there is a greater load on short-term memory in the mixed than in the pure blocked condition.

To sum up, the present study suggests that both top-down (attention-driven) and bottom-up (stimulus-driven) factors interact differentially depending on the physical properties of the stimulus and uncertainty about the level of the stimulus in the forthcoming trial (pure *vs.* mixed blocks). The P300 component is a neural correlate of sensorial processing not only at earlier processing stages, but also at later stages of the information processing cascade, including attention and memory updating. Our results add further support to Näätänen's (1990) proposal that the P300 component is both an index of memory storage and serves as a link between stimulus features and attention in the tactile modality.

4. Conclusion

Tactile roughness discrimination depends not only on the physical properties of the stimuli (the different stimuli varying in the roughness dimension), but also on the way in which the stimuli are represented and manipulated in working memory. The present study suggests that manipulation of uncertainty (mixed and pure block conditions) mobilizes greater or lesser mental effort to deal with tactile stimulation efficiently. The present study reports new electrophysiological findings on the discrimination of stimuli varying in roughness explored by dynamic passive stimulation that involves a more thorough engagement of the tactile system.

5. Experimental procedure

5.1. *Participants*

Twenty-eight volunteers were recruited to participate in the experiment. Fourteen participants (mean age 33.1, SD. 5.7 years) were randomly assigned to the pure blocked condition and 14 (mean age 29.4, SD. 5.9 years) to the mixed condition. Two participants in the pure block condition were excluded due to the high number of artifacts in the EEG. The age difference between the two groups was not significant ($t_{24}=1.7$; $p>.1$). All the participants were right-handed undergraduate psychology students and received academic credits for their collaboration. The study was approved by the UNED Ethical Committee, and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. None of the participants had symptoms requiring neurological or psychological treatment.

5.2. *Materials*

5.2.1. *Stimuli*

The stimuli used in the present study were four rectangular hard plastic parallelepipeds. Three of them had the top surface embossed with triangular gratings of different spatial periods. These periods were defined as the distance between the centers of two consecutive ridges: 0.4 mm (rough1), 1.6 mm (rough2), and 2.8 mm (rough3). The overall dimensions of the stimuli were 50 mm × 40 mm × 20 mm. The amplitude of the ridge was .5 mm, 1 mm, and 2 mm, respectively. The fourth parallelepiped had a completely smooth surface, in other words, without grooves (rough0). The latter (rough0) was defined in the experimental instructions as the non-target, while the other three stimuli (rough1, rough2, and rough3), varying along the roughness dimension, were the targets.

5.2.2. *Apparatus*

The stimuli were presented in the *tactile spinning wheel* (TSW, patent no. P200801805). See Fig. 1. The apparatus is described in more detail in Reales et al. (2010). This electro-mechanical device was specifically designed to present textured stimuli to the static fingertip of the perceiver. The apparatus is composed of: (1) a circular platform that spins at several velocities controlled by the experimenter; and (2) an interface that connects the apparatus to the EEG recording system. The device is made of black methacrylate, preventing any visual contact with the stimulus during the experimental session. A servomotor powers the spinning platform. An interface controls the speed of the platform, registers the actual stimulus code, and sends the corresponding digital trigger to the EEG system. The spinning platform is a horizontal revolving disc equipped with twelve rectangular sockets placed in the upper surface of the platform to which the textured elements are fastened. Underneath the platform, a set of pins codifies the stimulus located in the corresponding socket. Each set of pins is read by a linear array of photoelectrical sensors, and this code is recorded on the computer. The device was specifically designed to allow ERP recording of a series of stimuli by synchronizing stimulus onset with the trigger delivered to the EEG recording system (Neuroscan System). The rotation speed of the platform is controlled by a potentiometer placed at the front of the interface. The stimuli presentation platform rotated counter-clockwise at a speed of 140 mm/s. At this speed, the finger was in contact with the stimuli during 560 ms, and the interstimulus interval (ISI) was 1280 ms.

5.3. *General procedure*

During the experimental session, participants were seated on a chair in front of the apparatus. Their right arm and hand were extended and comfortably supported by a horizontal platform. The platform had a special hole allowing the right index fingertip to contact the stimulus. The finger was immobilized horizontally in the finger holder. Participants were instructed to maintain a light and constant pressure on the stimuli. They did not report any pain or discomfort when the stimuli were presented during the experiment. In order to avoid any loss of sensitivity over trials, participants were also instructed to make slow and brief movements with the fingertip between trials. In this experiment, the stimulus presentation platform rotated clockwise at a speed of 140 mm/s. At this speed, the finger was in contact with each stimulus for 560 ms, and the interstimulus interval (ISI) was 1280 ms. To make sure that participants paid attention to the stimuli, they were instructed to detect and keep a running mental count of all the targets presented in each block.

Before the beginning of the experimental session, participants received a short training session lasting approximately 5 min to make sure that they could discriminate between the different textures accurately. Participants were also instructed to keep their eyes open and fixed on a painted cross in front of them.

5.3.1. *Pure block condition*

In this condition, we presented three pure blocks of 104 trials each (312 trials altogether). Each block comprised a target stimulus (rough1, rough2, or rough3) intermixed with instances of the completely flat, non-target stimulus (rough0) within each block. The three blocks differed only in the type of target presented. Block order was counterbalanced across participants. The target/non-target probability within a block was $P=.2$ and $P=.8$, respectively. At the end of each block, the experimenter recorded the reported counted number of targets.

5.3.2. *Mixed blocked condition*

In the mixed blocked condition, participants were presented with a single randomized sequence of the three target stimuli intermixed with instances of the non-target stimulus. The 312 trials were presented with the same probabilities used in the pure block condition ($P=.2$ and $P=.8$ for targets and non-targets, respectively). In this case, the experimenter recorded the reported number of perceived targets after 104 stimuli, during the rest period. Fig. 2 illustrates the experimental design used in both experimental conditions.

To make the experimental conditions as comparable as possible, the same number of stimuli and resting periods were used in the pure block condition (two 5-min periods, one after each block) and the mixed condition (two 5-min periods, the first after 104 trials and the second after 208 trials).

5.4. *EEG recording parameters*

Continuous EEG activity was recorded with tin electrodes from 32 scalp sites of the extended 10–20 system through 32 channels using a NuAmps amplifier (Neuroscan, INC.), located inside a soundproof, electrically shielded room. The EEG was digitized with a sampling rate of 250 Hz and online bandpass filtered from .1 to 70 Hz. Linked earlobes were used as reference and AFz electrode as ground. The overall electrode impedance was maintained below 10 kΩ. Four additional electrodes were placed above and below the left orbit and on the outer canthus of each eye to monitor electrooculographic (EOG) activity.

Continuous EEG data were lowpass FIR-filtered offline at 30 Hz (12 dB/octave) before segmentation. The epochs were made for each trial from 200 ms pre-stimulus to 1024 ms post-stimulus. Trials containing extracranial artifacts were removed from the analysis. Eye movement artifacts were subtracted from the EEG segments (Semlitsch et al., 1986). Only artifact-free segments were selected for averaging. After baseline correction (200 ms pre-stimulus), epochs were sorted by type of stimulus (target *vs.* non-target) and averaged by condition. To measure ERP amplitudes, the mean amplitudes of the ERP components (N200 and P300) were extracted from continuous time windows ranging from 100 to 1000 ms. Analyzing these short windows enabled us to explore any variation in the course of the tactile sensing processing within each procedure.

5.5. *Data analysis*

Our main aim was to investigate whether the physical attributes, the presentation conditions or the interaction between these two variables modulate the P300 component. To test these hypotheses, for each separate time window, we analyzed mean voltages using a mixed ANOVA with Presentation condition (2 levels – pure block, mixed) as the between-subjects factor, and Roughness (4 levels – rough 0, rough 1, rough 2, rough 3) × Anterior–Posterior Axis (3 levels – frontal, middle and posterior) × Laterality (3 levels – left, central and right) as within-subjects factors. For repeated measures analyses, multivariate statistics were reported. To compensate for a lack of sphericity data, statistical significances in the within-subject factor were corrected by calculating the Greenhouse–Geisser epsilon and reported in each ANOVA test. In all *post hoc* contrasts, the level of significance was Bonferroni adjusted (α=.05), and the Mean Difference (MD) and the significance level were reported to emphasize the experimental effect. When referring to significant statistics involving several time windows, the *F*-statistic was also reported in the corresponding time interval.

Conflict of interest

The authors declare no conflict of interest.

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