Using EEG (SS-EPs) to characterize the brain activity in response to textured stimuli in passive touch *

Athanasia Moungou, Jean-Louis Thonnard, and André Mouraux

***Abstract*— When sliding our fingertip on a surface, complex vibrations are produced in the skin. In the present study, we used electroencephalography (EEG) to record steady-state evoked brain potentials (SS-EPs) and characterize the cortical activity related to the passive tactile exploration of textured surfaces. In a first experiment, the right index fingertip was passively scanned against square-wave gratings having a spatial period (SP) ranging between 0.4 and 1.6 mm, using a constant normal force (1.5N) and two constant exploration velocities (17.6 mm/s, 48 mm/s). The movement of the grating was achieved using a robot with a feedback force sensor. Depending on the SP, we expected that these dynamic stimuli would elicit SS-EPs at frequencies ranging between 11 and 120 Hz and, possibly, their harmonics. We found that consistent SS-EPs can be recorded at the lowest frequency (11 Hz). In a second experiment, the fingertip was scanned against a 3.52 mm sinusoidal grating onto which a textured fabric was glued. We found that periodically modulating the magnitude of texture-induced high-frequency vibrations can elicit a measurable SS-EP in the recorded EEG. Our results suggest that SS-EPs could be used to isolate and study the brain responses related to the tactile exploration of textures.**

I. Introduction

During the last decades, there has been an increased interest in studying touch perception [1-3] using neuroimaging techniques [4-7]. Texture information is a fundamental material characteristic of any object's surface providing important information for its perception.

Until recently, most studies in the field of texture perception have focused on the coding and the perception of roughness of coarse gratings/Braille dot patterns using neuroimaging techniques [e.g. [8, 9]] and/or single-unit recordings [10]. It has been established that slowly adapting Type I (SAI) and rapidly adapting (RA) receptors (which innervate the fingertip skin) convey important information for the spatial characteristics of a texture when in contact with the fingertip. While coarse surfaces are predominantly mediated by SAI receptors, the perception of fine surfaces is achieved by RA receptors [11-13].

Characterizing the neural activity related to the perception of real materials and natural textures is technically demanding. Most importantly, whereas a large amount of experiments have been conducted to assess the response properties of SAI afferents, natural textures consist of textural characteristics that are too fine to be determined by spatial discrimination mechanisms taking into account the information conveyed by SAI afferents. Indeed, because SAI afferents do not elicit robust responses to natural textures, the neural mechanisms underlying the perception of natural textures are probably different from those underlying the perception of gratings and Braille dot patterns.

When we slide our fingertip on a surface, vibrations are produced in the skin. It has been suggested that the frequency composition of these vibrations can provide knowledge on texture characteristics. Several studies have hypothesized that the frequency spectrum of texture induced vibrations could be used to extract texture characteristics, including vibrations generated in the forearm of humans during active fingertip exploration of textures [14]. Supporting this hypothesis, Manfredi et al. [15] recorded the vibrations induced by exploring a wide range of textures from gratings to silk using a laser Doppler vibrometer, and showed that these textures could be accurately classified based on the spectral content of the induced vibrations.

The main aim of the present study was to develop a novel means to characterize the cortical activity related to texture perception using scalp electroencephalography (EEG). Specifically, we attempted to record *steady-state evoked potentials* (SS-EPs) induced by passively scanning the index finger pad on various textures ranging from gratings with a constant spatial frequency to periodically-modulated natural textures.

SS-EPs are elicited by the periodic modulation of a stimulus feature. For example, periodically modulating the amplitude of an auditory stimulus at a given frequency elicits a consistent peak in the EEG frequency spectrum at the frequency of amplitude modulation and its harmonics. This peak is thought to result from synchronized periodic activity generated in neuronal populations responding to the periodically-modulated feature [16]. In the somatosensory modality, several studies have used SS-EPs to characterize the cortical activity related to the perception of pure mechanical vibrations [e.g. [17, 18]] or electrical stimulation [e.g. [19-21]]. The majority of these studies have focused on relatively low frequencies, typically, around 20 Hz.

Using single-unit recordings performed in animals, it has been shown that neurons in the primary somatosensory cortex (SI) are able to follow periodic input up to frequencies of 200 Hz [22], and to exhibit some degree of phase-locking for stimulation frequencies up to 800 Hz [10]. Identifying such high frequency activities using scalp EEG is challenging because the recorded signals predominantly reflect slow postsynaptic neural activity rather than action potentials. Furthermore, the scalp acts as a low-pass filter attenuating high frequency signals. Nevertheless, it has been shown that

*This work was funded by the FP7 Marie Curie Initial Training Network PROTOTOUCH, grant agreement No. 317100.

A. Moungou, J.–L. Thonnard, and A. Mouraux are with the Institute of Neuroscience (IoNS), Université catholique de Louvain, Brussels, Belgium 1200 (phone: +3227645447; e-mail: athanasia.moungou@uclouvain.be, jean-louis.thonnard@uclouvain.be, andre.mouraux@uclouvain.be).

transient electrical stimulation of a peripheral nerve can elicit activity in SI, which, in the EEG, translates as a short burst of high frequency oscillations (HFOs: 600 Hz), [23].

The present study consisted of two separate experiments. In both experiments, the index fingertip was passively scanned against a textured surface, using a constant velocity and normal force. In the first experiment, we characterized the SS-EPs elicited by sliding the fingertip against square gratings with spatial frequencies ranging between 0.4 mm and 1.6 mm. In the second experiment, we characterized the SS-EPs elicited by sliding the index fingertip against a polyester fabric glued onto a sinusoidal grating to modulate periodically the magnitude of textured-induced vibrations.

II. Materials and Methods

A. Apparatus (Platform)

A schematic view of the experimental setup is shown on Fig. 1. A forces and torque transducer (Mini40 F/T transducer, ATI Industrial Automation, USA) was mounted on a four-axis robot (four-axis SCARA HS series 4535G. DENSO, USA), driven by the LabVIEW (National Instruments, USA) software. The forces and torque transducer provided an online measure of contact forces (normal and tangential forces to the surface; NF and TF). The index of the participant was maintained using a custom hand support. The gratings and texture plates (length: 20 cm; width: 3 cm) were mounted on the force sensor, and displaced at a constant velocity. This allowed passive scanning of the index fingertip using a constant 1.5 N normal force and a constant scanning velocity. The robotic device also sent a trigger to the EEG system at the onset of each motion.

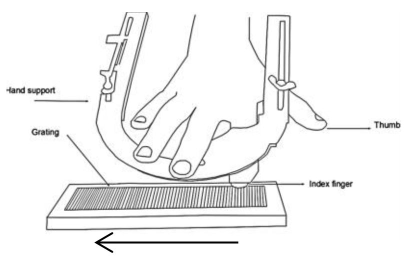


Figure 1. Schematic view of the experimental setup in which the right index fingertip is scanned against a grating. The horizontal arrow indicates the direction of the movement.

B. Participants

The EEG data were collected from 10 healthy volunteers (aged 23-34, 4 females) in Experiment 1 and from 10 other healthy volunteers (aged 19-31, 4 females) in Experiment 2. The subject was seated comfortably in front of the apparatus. Written informed consent was obtained from each participant. The study was approved by the local Ethics Committee and conformed to the latest revision of the Declaration of Helsinki.

C. Stimuli

Experiment 1

Three 20 cm aluminum square-wave gratings of varying spatial periods were used, varying from coarse (1.6 mm) to smooth (0.4 mm). Two different exploration velocities were used (v1 = 17.6 mm/s, v2 = 48 mm/s) for the passive displacement of the finger.

Depending on the spatial period of each grating and the applied velocity, the interactions between the index fingertip and the grating were expected to elicit vibrations peaking between 11 Hz and 120 Hz (Table I).

Experiment 2

A 20 cm nylon sinusoidal plate with a 3.52 mm spatial period was used. Scanning of the finger was performed using a single constant velocity (v = 17.6 mm/s; Table I). In a first condition, the finger was scanned directly against the smooth plate. In a second condition, a polyester fabric was glued onto the plate, such as to elicit a qualitatively different periodically-modulated perception of texture.

TABLE I. Expected SS-EP Frequencies

V		17.6 mm/s	48 mm/s
Trial duration		**9.3 s**	**3.1 s**
Experiment 1			
SP = 1.6 mm	GD = 1.2 mm	11 Hz	30 Hz
SP = 0.8 mm	GD = 0.6 mm	22 Hz	60 Hz
SP = 0.4 mm	GD = 0.3 mm	44 Hz	120 Hz
Experiment 2			
SP = 3.52 mm	GD = 0.4 mm	5 Hz	
SP = 3.52 mm	(polyester)	5 Hz	

SP: spatial period; GD: groove depth.

D. Data acquisition

1. Electrophysiological measurements

The EEG was recorded using 64 Ag–AgCl electrodes placed on the scalp according to the International 10/10 system (Waveguard64 cap, Cephalon A/S, Denmark). Electrode impedances were kept below 10 kΩ. Signals were amplified and digitized using a sampling rate of 1000 Hz, using an average reference (64-channel high-speed amplifier, Advanced Neuro Technology, The Netherlands). During the recording, participants were instructed to attend a fixation cross and listened to white noise presented through headphones to avoid any contribution of auditory input to the recorded EEG responses.

The first experiment consisted of a total of six blocks: three blocks with 20 strokes at 17.6 mm/s (lasting approximately 10 seconds) and three blocks with 20 strokes at 48 mm/s (lasting approximately 3.5 s). There was a random pause of 4-6 s between the strokes in each block. The second experiment consisted of a total of two blocks: one block for each condition. Such as in experiment 1, each block consisted of 20 strokes.

2. EEG data analysis

The EEG data were analyzed in MATLAB (The Mathworks, MA) using the Letswave toolbox (http:/www.nocions.org/letswave; see also [24]). Statistical analyses were performed using SPSS 21 (IBM, USA) and *G*Power* for post hoc power analysis [25]. The data were imported and high-pass filtered at 0.1 Hz to remove slow drifts in the recorded signals. In experiment 1, EEG epochs were segmented from +0.20 s to +9.46 s relative to the onset of each motion for the velocity of 17.6 mm/s and from +0.20 s to +3.34 s for the velocity of 48 mm/s. In experiment 2, EEG epochs were segmented from +0.20 s to +9.46 s. These EEG segments corresponded to the time interval during which the finger moved passively against the plate at a constant velocity. The first 0.2 s were discarded from the analysis because of the large amplitude broadband vibrations occurring at movement onset [26].

Artifacts due to eye blinks or eye movements were removed using an independent component analysis (FastICA algorithm) for blind-source decomposition of the data into 64 components [27]. The data were re-referenced offline to an average reference and all EEG epochs were averaged across trials in the time domain.

The obtained average waveforms were then transformed in the frequency domain using a discrete Fourier Transform [28], yielding a frequency spectrum ranging from 0 to 500 Hz. Because of their variable length, the frequency resolution of the FFT varied according to scanning velocity (0.107 Hz at 17.6 mm/s; 0.31 Hz at 48 mm/s). Amplitude spectra were then obtained using the modulus of the complex Fourier coefficients (Fig. 2, 3).

Assuming additive noise, the obtained EEG frequency spectra may be expected to correspond to the sum of (1) EEG activity induced by the somatosensory stimulation, i.e. somatosensory SS-EPs and (2) unrelated background noise due, for instance, to spontaneous EEG activity, muscle activity or eye movements. Hence, to obtain estimates of the magnitude of the elicited SS-EPs, the contribution of this noise was removed by subtracting, at each bin of the frequency spectra, the average amplitude measured at surrounding frequency bins (three frequency bins ranging from −2 to −5 bins and three frequency bins ranging from +2 to +5 bins). This procedure is justified by the fact that, in the absence of an SS-EP, the amplitude at a given frequency should be similar to the amplitude of the mean of the surrounding frequencies [26, 29]. Thus, in the absence of an SS-EP, the noise-subtracted amplitude should tend towards zero.

3. *Statistical analyses*

To assess the significance of the elicited responses, the noise-subtracted spectra of the EEG signals measured at parietal and temporal electrodes contralateral to the stimulated fingertip were averaged (i.e. T7, C1, C3, C5, CP1, CP3, CP5, P1, P3, P5, P7, TP7). Considering their position relative to SI, these electrodes may be expected to elicit the strongest response [e.g. 30].

One-sample t-tests against zero were then used to assess whether the amplitude of the signal obtained at expected SS-EP frequencies were significantly greater than zero.

Finally, to assess the hemispheric lateralization of the elicited responses, we compared the magnitude of the signals measured over contralateral parietal electrodes to the magnitude of the signals measured over ipsilateral parietal electrodes (T8, C2, C4, C6, CP2, CP4, CP6, P2, P6, P8, TP8), using a paired-sample t-test.

Significance level was set at $p < 0.05$.

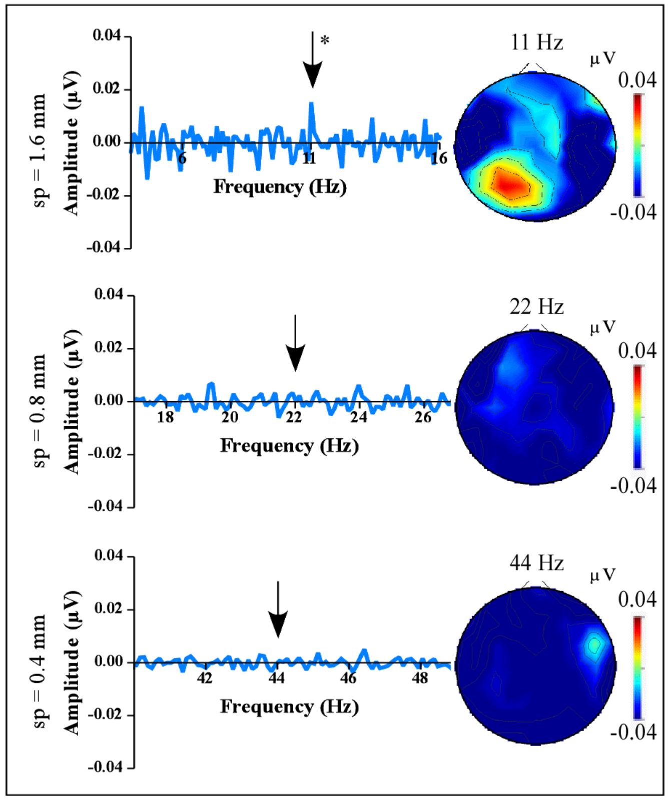


Figure 2. Grand-average EEG frequency spectra during passive scanning of the right index finger tip across square-wave aluminum gratings at a constant velocity of 17.6 mm/s. The vertical arrows mark the frequency of the expected SS-EPs (first harmonic). *x*-axis: frequency (Hz), *y*-axis: average noise-subtracted amplitude (µV) of the EEG signals recorded from left parietal electrodes. The scalp topographies show the topographical distribution of the signal at the expected SS-EP frequency.

III. RESULTS

Experiment 1

For the coarse grating (SP = 1.6 mm) and the slow velocity (17.6 mm/s), a significant increase of EEG signal amplitude was observed at 11 Hz, corresponding to the expected frequency of the vibration elicited by the interaction of the fingertip with the grating (Fig. 2). The scalp topography of the elicited response was clearly maximal over the parietal region contralateral to the stimulated fingertip. The one sample t-test showed that the amplitude at 11 Hz was significantly greater than zero ($t(9) = 2.853$, $p = 0.019$, 95% CI [0.003, 0.027]).

Comparison of the signals obtained from the ipsilateral and contralateral electrodes showed that the magnitude of the signal measured over the contralateral hemisphere was significantly greater than the magnitude of the signal measured over the ipsilateral hemisphere ($t(9) = 2.944$, $p = 0.016$).

When the same grating (SP = 1.6 mm) was scanned using the higher velocity (48 mm/s), no significant increase of amplitude was observed at the expected frequency of 30 Hz ($t(9) = -0.777$, $p = 0.457$, 95% CI [-0.007, 0.003]). There was also no significant SS-EP elicited by the finer gratings (SP = 0.8 mm; SP = 0.4 mm), regardless of velocity (Table II).

No significant SS-EP was observed at harmonic frequencies.

TABLE II. MAGNITUDE OF SS-EPS RECORDED IN EXPERIMENT 1

V= 17.6 mm/s					
Grating	***M***	***SD***	***t(9)***	***p***	**95% CI**
SP = 1.6 mm (11 Hz)	0.015	0.017	2.853	0.019*	[0.003,0.027]
SP = 0.8 mm (22 Hz)	0.001	0.005	0.024	0.981	[-0.004,0.004]
SP = 0.4 mm (44 Hz)	-0.001	0.006	-0.313	0.761	[-0.005,0.004]
V= 48 mm/s					
Grating	***M***	***SD***	***t(9)***	***p***	**95% CI**
SP = 1.6 mm (30 Hz)	-0.001	0.008	-0.777	0.457	[-0.007,0.003]
SP = 0.8 mm (60 Hz)	-0.001	0.006	-0.755	0.469	[-0.003,0.002]
SP = 0.4 mm (120 Hz)	0.001	0.010	0.046	0.965	[-0.007,0.007]

* $p < 0.05$

In summary, only the roughest grating (SP = 1.6 mm) presented at the slowest scanning velocity (17.6 mm/s) elicited a consistent SS-EP, whose scalp topography was maximal over the parietal region contralateral to the stimulated fingertip.

Experiment 2

Passive scanning of the fingertip against the smooth sinusoidal plate did not elicit a clear SS-EP, both at 5 Hz (corresponding to the expected frequency), and at 10 Hz (corresponding to the second harmonic), (Table III). In contrast, when the polyester fabric was glued onto the plate, passive sliding of the finger elicited a significant SS-EP at the second harmonic frequency (10 Hz) ($t(9) = 3.443$, $p = 0.007$, 95% CI [0.0050, 0.0242]), (Table III). Such as in Experiment 1, the scalp topography of this SS-EP was maximal over parietal regions contralateral to the stimulated fingertip (Fig. 4).

The paired-samples t-test showed that the magnitude of the EEG signal at 10 Hz recorded while presenting the grating with the glued polyester fabric was significantly greater than the magnitude of the signal obtained at 10 Hz while presenting the grating without fabric ($t(9) = 2.707$, $p = 0.024$).

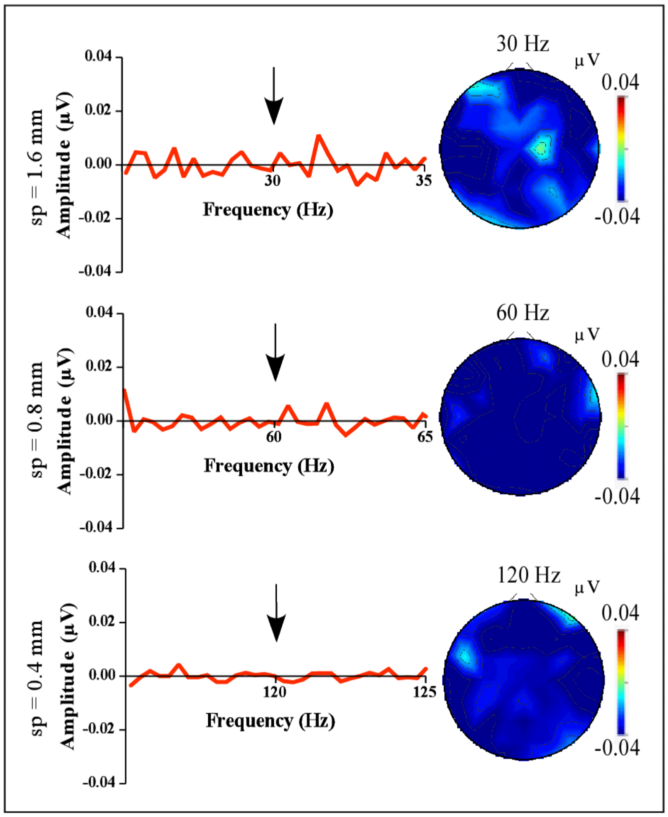
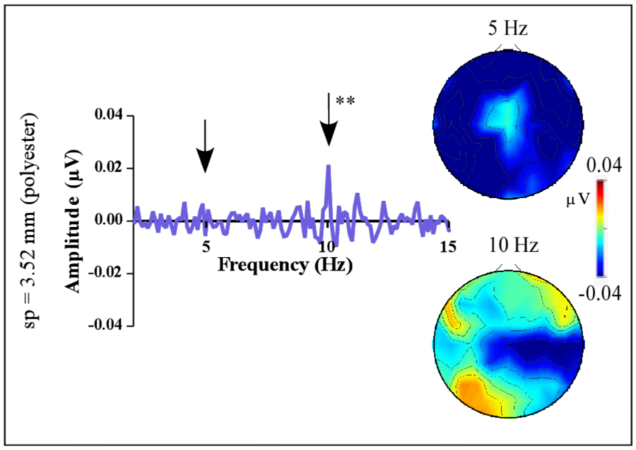


Figure 3. Grand-average FFT spectra during passive scanning of the right index finger tip across the square-wave aluminum gratings at a constant velocity of 48 mm/s. The vertical arrows mark the frequency of the expected SS-EPs. *x*-axis: frequency (Hz), *y*-axis: average amplitude (µV) of the EEG signal recorded from parietal electrodes. The scalp topographies show the topographical distribution of the signal at the expected frequency.

TABLE III. MAGNITUDE OF SS-EPS RECORDED IN EXPERIMENT 2

V= 17.6 mm/s					
Grating	***M***	***SD***	***t(9)***	***p***	**95% CI**
SP = 3.52 mm (fabric):					
5 Hz	-0.004	0.011	-1.212	0.256	[-0.012,0.003]
10 Hz	0.014	0.013	3.443	0.007**	[-0.005,0.024]
SP = 3.52 mm (no fabric):					
5 Hz	0.003	0.017	0.555	0.592	[-0.009,0.015]
10 Hz	-0.001	0.014	-0.187	0.856	[-0.011,0.009]

** $p < 0.01$



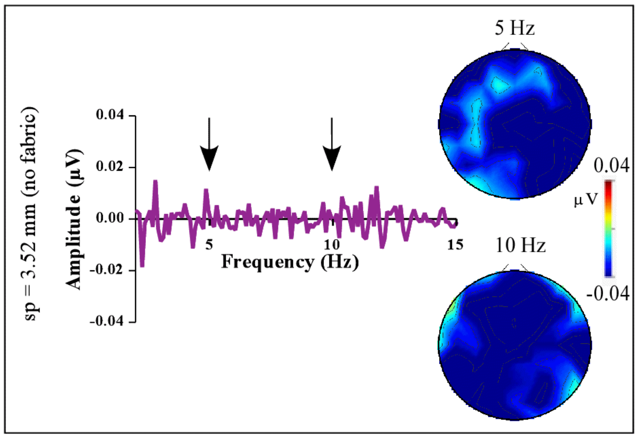


Figure 4. Grand-average FFT spectra during passive scanning of the right index fingertip across the sinusoidal plate with the glued polyester fabric at a velocity of 17.6 mm/s (above) and without the fabric (below), (see Materials and Methods). The vertical arrows mark the frequency of the expected SS-EPs. *x*-axis: frequency (Hz), *y*-axis: average amplitude (µV). The topographical maps show the average scalp topographies of the signal at 5 Hz and 10 Hz.

IV. DISCUSSION

The aim of this experiment was to isolate and characterize the cortical activity elicited by the vibrations produced in the skin as an outcome of fingertip/texture interactions.

In a first experiment, we used well-characterized artificial stimuli consisting of square gratings with spatial periods ranging between 0.4 and 1.6 mm.

Using two constant exploration velocities (17.6 mm/s and 48 mm/s) and a constant normal force (1.5 N), we expected that scanning of the fingertip would induce SS-EPs at the frequencies corresponding to the induced vibrations. However, this was only the case for the coarse grating (SP = 1.6 mm) presented at a slow velocity (v = 17.6 mm/s). Indeed, in that condition, a significant SS-EP was observed at the expected frequency of 11 Hz, over the parietal region contralateral to the stimulated fingertip. This scalp topography is compatible with activity originating, at least in part, from the contralateral SI. No significant SS-EP was observed when the finger was scanned against finer gratings (SP = 0.8 mm and 0.4 mm), or when the finger was scanned at a higher velocity (v = 48 mm/s). This could be due to a low signal-to-noise ratio of the elicited responses, to inter-trial phase-jitter of the elicited vibrations, as well as to the fact that EEG predominantly reflects post-synaptic activity. In other words, neuronal populations in SI may well be able to follow higher frequencies, but this activity does not translate into a measurable response in the recorded EEG signals.

One possible mean to increase the signal-to-noise ratio of the elicited responses would be to increase the duration of stimulation, such as to increase frequency resolution. In other sensory modalities, use of longer duration stimuli has been shown to markedly enhance the signal-to-noise ratio of the elicited SS-EPs.

In the second experiment, we used a sinusoidal grating with a large spatial frequency (SP = 3.52 mm) to periodically modulate the vibrations induced by fingertip/texture interactions. The main goal was to assess whether the presence of a fabric (i.e. polyester) would elicit SS-EPs differing from those obtained in the absence of a fabric. We found that, only in the presence of the fabric, sliding the fingertip against the grating elicited a significant SS-EP at the second harmonic (10 Hz). The significance of this response will require additional studies, performed using an array of textures, or comparing conditions of active and passive touch.

To our knowledge, this is the first study using SS-EPs to isolate, in humans, cortical activity in response to textured stimuli in passive touch.

ACKNOWLEDGMENT

The authors would like to thank Julien Lambert for excellent technical assistance.

REFERENCES

[1] G A. I. Weber, H. P. Saal, J. D. Lieber. J.-W. Cheng, L. R. Manfredi, J. F. Dammann III, and S. J. Bensmaia, "Spatial and temporal codes mediate the tactile perception of natural textures", *PNAS*, vol. 110, pp. 17107-17112, Mar. 2013.

[2] S. Kim and T. W. James, "Enhanced effectiveness in visuo-haptic object-selective brain regions with increasing stimulus salience", *Hum. Brain Mapp*., vol. 31, pp. 678-693, May 2010.

[3] R. Klatzky and S. J., Lederman, "Representing spatial location and layout from sparse kinesthetic contacts", *J. Exp. Psychol.: Hum. Percept. Perform*., vol. 29, pp. 310-325, April 2003.

[4] T. A. Whitaker, C. S. Franklin, and F. N. Newell, "Vision and touch: Independent or integrated systems for the perception of texture?", *Brain Res*., vol. 1242, pp. 59-72, May 2008.

[5] F. McGlone, E. F. Kelly, M. Trulsson, S. T. Francis, G. Wesling, and R. Bowtell, "Functional neuroimaging studies of human somatosensory cortex", *Behav. Brain Res*., vol. 135, pp. 147-158, April 2002.

[6] P. Servos, S. Lederman, D. Wilson, and J. Gati, "fMRI-derived cortical maps for haptic shape, texture, and hardness", *Cogn. Brain Res*., vol. 12, pp. 307-313, Mar. 2001.

[7] C. Simoes-Franklin, T. A. Whitaker, and F. N. Newell, "Active and passive touch differentially activate somatosensory cortex in texture perception", *Hum. Brain Mapp.*, vol. 32, pp. 1067-1080, July 2011.

[8] R. Kitada, T. Hashimoto, T. Kochiyama, T. Okada, M. Matsumura, S. J. Lederman, and N. Sadato, "Tactile estimation of the roughness of

gratings yields a graded response in the human brain: an fMRI study", *NeuroImage*, vol. 25, pp. 90-100, Dec. 2004.
[9] T. Harada, D. N. Saito, K. Kashikura, T. Sayo, Y. Yonekura, M. Honda, and N. Sodato, "Asymmetrical neural substrates of tactile discrimination in humans: a functional magnetic resonance imaging study", *J. Neurosci*., vol. 24, pp. 7524-7530, Aug. 2004.
[10] M. A. Harvey, H. P. Saal, J. F. Dammann III, and S. J. Bensmaia, "Multiplexing stimulus information through temporal codes in primate somatosensory cortex", *PLoS Biol*., vol. 11, e1001558, May 2013.
[11] M. Hollins, S. J. Bensmaia, and S. Washburn, "Vibrotactile adaptation impairs discrimination of fine, but not coarse, textures", *Somatosens. Mot. Res*., vol. 18, pp. 253-262, Dec. 2001.
[12] C. E. Connor and K. O. Johnson, "Neural coding of tactile texture: comparison of spatial and temporal mechanisms for roughness perception", *J. Neurosci.*, vol. 12, pp. 3414-3426, Sep. 1992.
[13] S. J. Lederman, "Tactual roughness perception: spatial and temporal determinants", *Can. J. Psychol.*, vol. 37, pp. 498-511, Dec. 1983.
[14] B. Delhaye, V. Hayward, P. Lefevre, and J.-L. Thonnard, "Texture-induced vibrations in the forearm during tactile exploration", *Front. Behav. Neurosci*., vol. 6, doi: 10.3389/fnbeh.2012.00037, July 2012.
[15] L. R. Manfredi, H. P. Saal, K. J. Brown, M. C. Zielinski, J. F. Dammann III, V. S. Polashock, and S. J. Bensmaia, "Natural scenes in tactile texture", *J. Neurophysiol*., vol. 111, pp. 1792-1802, May 2014.
[16] D. Regan, "*Human brain electrophysiology. Evoked potentials and evoked magnetic fields in science and medicine*" Elsevier, New York, 1989.
[17] S. Tobimatsu, Y. M. Zhang, and M. Kato, "Steady-state vibration somatosensory evoked potentials: physiological characteristics and tuning function", *Clin. Neurophysiol.*, vol. 110, pp. 1953-1958, Nov. 1999.
[18] A. Z. Snyder, "Steady-state vibration evoked potentials: descriptions of technique and characterization of responses", *Electroencephalogr. Clin. Neurophysiol.*, vol. 84, pp. 257-268, May 1992.
[19] E. Colon, S. Nozaradan, V. Legrain, and A. Mouraux, "Steady-state evoked potentials to tag specific components of nociceptive cortical processing", *NeuroImage*, vol. 60, pp. 571-581, Mar. 2012.
[20] D. Kourtis, E. Seiss, and P. Praamstra, "Movement-related changes in cortical excitability: A steady-state SEP approach", *Brain Res.*, vol. 1244, pp. 113-120, Sep. 2008.
[21] C. M. Giabbiconi, N. J. Trujillo-Barreto, T. Gruber, and M. M. Muller, "Sustained spatial attention to vibration is mediated in primary somatosensory cortex", *NeuroImage*, vol. 35, pp. 255-262, April 2007.
[22] V. B. Mountcastle, W. H. Talbot, H. Sakata, and J. Hyvarinen, "Cortical neuronal mechanisms in flutter-vibration studies in unanesthetized monkeys. Neuronal periodicity and frequency discrimination", *J. Neurophysiol*., vol. 32, pp. 452-484, May 1969.
[23] G. Curio, B. M. Mackert, M. Burghoff, J. Neumann, G. Nolte, M. Scherg, and P. Marx, "Somatotopic source arrangement of 600 Hz oscillatory magnetic fields at the human primary somatosensory hand cortex", *Neurosci. Lett.*, vol. 234, pp. 131-134, Oct. 1997.
[24] A. Mouraux and G. D. Iannetti, 2008, "Across-trial averaging of event-related EEG responses and beyond", *Magn. Reson. Imaging*, vol. 26, pp. 1041-1054, May 2008.
[25] F. Faul, E. Erdfelder, A.-G. Lang, and A. Buchner "G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences". *Behav. Res. Meth*., vol. 39, pp. 175-191, May 2007.
[26] S. Nozaradan, I. Peretz, M. Missal, and A. Mouraux, "Tagging the neuronal entrainment to beat and meter", *J. Neurosci.*, vol. 31, pp. 10234-10240, July 2011.
[27] A. Hyvarinen, and E. Oja, "Independent component analysis: algorithms and applications", *Neural networks*, vol. 13, pp. 411-430, May 2000.
[28] M. Frigo and S. G. Johnson, "FFTW: an adaptive software architecture for the FFT", presented at the 1998 Int. Conf. of Acoustics, Speech, and Signal Processing, Seattle, WA.
[29] A. Mouraux, G. D. Iannetti, E. Colon, S. Nozaradan, V. Legrain, and L. Plaghki, "Nociceptive steady-state evoked potentials elicited by rapid periodic thermal stimulation of cutaneous mechanoreceptors", *J. Neurosci.*, vol. 31, pp. 6079-6087, April 2011.
[30] E. Porcu, C. Keitel, and M. Muller, "Concurrent visual and tactile steady-state evoked potentials index allocation of inter-modal attention: a frequency tagging study", *Neurosci. Lett.*, vol. 556, pp. 113-117, Nov. 2013.