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Crossmodal interactions of haptic and visual texture information in early sensory cortex

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ABSTRACT

Both visual and haptic information add to the perception of surface texture. While prior studies have reported crossmodal interactions of both sensory modalities at the behavioral level, neuroimaging studies primarily investigated texture perception in separate visual and haptic paradigms. These experimental designs, however, only allowed to identify overlap in both sensory processing streams but no interaction of visual and haptic texture processing. By varying texture characteristics in a bimodal task, the current study investigated how these crossmodal interactions are reflected at the cortical level. We used fMRI to compare cortical activation in response to matching versus non-matching visual–haptic texture information. We expected that passive simultaneous presentation of matching visual–haptic input would be sufficient to induce BOLD responses graded with varying texture characteristics. Since no cognitive evaluation of the stimuli was required, we expected to find changes primarily at a rather early processing stage. Our results confirmed our assumptions by showing crossmodal interactions of visual–haptic texture information in early somatosensory and visual cortex. However, the nature of the crossmodal effects was slightly different in both sensory cortices. In early visual cortex, matching visual–haptic information increased the average activation level and induced parametric BOLD signal variations with varying texture characteristics. In early somatosensory cortex only the latter was true. These results challenge the notion that visual and haptic texture information is processed independently and indicate a crossmodal interaction of sensory information already at an early cortical processing stage.

Introduction

Humans need to be able to differentiate surface qualities of objects not only by touch but also visually. This is important for object recognition (e.g. nectarine vs. peach) and for the interaction with objects in our environment (Fikes et al., 1994) (e.g. for goal-directed movement: grasping a slippery piece of soap vs. a splintering piece of wood). Behavioral studies showed that both haptic and visual informations add to texture perception (Lederman and Abbott, 1981) and that a crossmodal transfer of texture information between both sensory modalities occurs (Picard, 2006).

However, it is only in the last decade that the neural basis of texture perception and its multidimensional experience have received increased attention. Several neuroimaging studies focused on texture matching and discrimination (Cant and Goodale, 2007; Cavina-Pratesi et al., 2009; Kaas et al., 2012; Peuskens et al., 2004; Sathian et al., 2011; Stilla and Sathian, 2008) as well as on different dimensions of texture perception within the tactile and visual modality; examples include spatial density (Merabet et al., 2004; Zhang et al., 2005), spatial orientation (Kitada et al., 2006; Zhang et al., 2005) and roughness (Burton et al., 2008; Merabet et al., 2004; Kitada et al., 2005; Roland and Brendan, 1998; Simões-Franklin et al., 2011). Most of the tactile studies stress the importance of the parietal operculum and the posterior insula (Kaas et al., 2012; Kitada et al., 2005; Roland and Brendan, 1998; Simões-Franklin et al., 2011; Stilla and Sathian, 2008) for processing surface textures, while studies focusing on visual texture perception often report regions near the collateral sulcus, the lingual gyrus and areas in early visual cortex (Cant and Goodale, 2007, 2011; Cant and Xu, 2012; Cavina-Pratesi et al., 2010; Peuskens et al., 2004; Stilla and Sathian, 2008; Sathian et al., 2011).

Next to the identification of cortical key players in visual and haptic texture perception a recent approach by Hiramatsu et al. (2011) aimed at investigating how visual material properties are coded in the cortex along the ventral visual pathway. The authors reported that while both early and higher-order visual areas seem to contain information distinguishing material categories (including texture information), the neural representation shifts gradually from an image-based representation in early areas (V1/V2 and V3/V4) to a perceptual representation in

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areas around the fusiform gyrus and the collateral sulcus. Hence, physical and perceptual measures of visual material qualities seem to be processed in a spatially distributed network in the visual cortex, rather than in a single localized region. A similar distributed network was described by Sathian et al. (2011) for the processing of haptic texture information. In connectivity analyses Sathian and colleagues showed a flow of texture information from task-non-selective regions of the postcentral gyrus to texture-selective areas in the parietal operculum and further to regions of the middle occipital cortex. Despite the pure tactile stimulation in many paradigms, consistent visual cortex activation was reported in several of these studies (Merabet et al., 2007; Simões-Franklin et al., 2011; Stilla and Sathian, 2008). Some findings even indicate the existence of bisensory texture-selective regions in the posterior visual cortex and the lingual gyrus by comparing activations elicited by unimodal shape, location and texture matching in both the visual and haptic modality (Sathian et al., 2011; Stilla and Sathian, 2008).

All of the above-mentioned studies investigated texture perception in separate visual and haptic paradigms. The effect of simultaneous visual and haptic exploration of textures has been mostly neglected so far. Hence, we can only assume an overlap of visual and haptic texture representations in some brain areas, but we cannot infer from these studies whether visual and haptic information interacts in these cortical regions. The imaging study by Sathian et al. (2011) gives a first indication that this might indeed be the case. Behavioral studies also indicate the existence of such crossmodal interaction and matching effects in visuo-haptic tasks. It was shown that people consistently and absolutely match specific tactile vibration rates (simulating manual exploration of a textured surface) to visual spatial frequencies (Guzman-Martinez et al., 2012), indicating some kind of crossmodal association effect in visual and haptic texture perception. Furthermore, Lunghi et al. (2010) even showed that simultaneous tactile stimulation can disambiguate binocular rivalry, a process in which two equally salient but dissimilar monocular stimuli are presented to corresponding retinal locations. Both stimuli compete for perceptual dominance and at any instant only one is perceived consciously while the other image is suppressed. In this study subjects haptically explored a linear grating with a matching orientation to either one of two rival visual stimuli. Exploration of the haptic stimulus prolonged dominance or reduced suppression of the matching visual stimulus, indicating a crossmodal interaction. The authors infer from these results that haptic information can modulate visual processing already at a very early stage, probably in V1. This raises the question whether a change in cortical processing can be expected when matching as compared to non-matching visual–haptic texture information is provided, i.e. representing crossmodal interactions at the cortical level.

In a unimodal tactile fMRI study, Kitada et al. (2005) used a parametric stimulus set, i.e. linear gratings varying in spatial period, and demonstrated that differences in tactile roughness yield graded BOLD responses in the parietal operculum, insula and the lateral prefrontal cortex, but only when subjects actively judge rather than merely attend to roughness. Assuming that crossmodal interactions of texture information are not only presented at the behavioral but also at the cortical level, the question arises whether matching visual–haptic information is sufficient for the observation of graded BOLD responses with varying texture characteristics even without an active judgment task.

The main objective of the present study was to investigate texture perception in a paradigm that combines visual and haptic input in a single condition in order to explore crossmodal interactions at the cortical level. We propose differences in cortical processing of matching and non-matching visual–haptic texture information, representing the influence of one sensory modality on information processing in the other modality as indicated by earlier behavioral studies. Based on the studies mentioned above we would expect these crossmodal effects already in early sensory cortices, e.g. postcentral gyrus and posterior occipital cortex (Dionne et al., 2010; Hiramatsu et al., 2011; Merabet et al., 2007; Sathian et al., 2011; Stilla and Sathian, 2008), but perception-related differences rather in higher-order cortical regions, e.g. the collateral sulcus as well as the parietal operculum and the insula (Cavina-Pratesi et al., 2010; Hiramatsu et al., 2011; Kitada et al., 2005). The unfamiliar dot pattern textures used in this experiment varied only along a single texture dimension, i.e. the average center-to-center dot spacing, ensuring that changes in other surface properties like color and friction do not influence the results. Stimulus presentation was always bimodal, but the sensory information content differed as texture information was varied either in the haptic, visual or in both channels.

We analyzed the data in two different ways. First we were interested in the average difference of the BOLD signal between both unimodal and the bimodal texture variation conditions, disregarding dot pattern differences. As we did not ask subjects to perform a cognitive task with the presented textures, we would expect to find differences, if any, at a rather early sensory processing stage. Second we were interested in relative differences of the BOLD response within each of these three conditions, taking into account the parametric dot pattern variation. Is the BOLD response modulated by texture differences when texture characteristics are varied either unimodally or bimodally? Based on previous behavioral studies we expected perceived roughness by touch to be almost perfectly correlated with the inter-dot spacing (Connor et al., 1990; Dépeault et al., 2009; Eck et al., 2011), while visual spatial density estimates should be negatively correlated with average inter-dot distance. Hence, no difference in the parametric BOLD modulation was expected between the two subjective measures tactile roughness and visual spatial density and the objective texture characteristic inter-dot spacing. However, to account for possible subjective perceptual differences we used individual post-fMRI ratings of haptic roughness and visual spatial density as well as the physical inter-dot spacing of the textures in separate parametric models.

Material and methods

Participants

Seventeen right-handed, healthy volunteers (13 women, 4 men; 27 ± 5.9 years) with normal or corrected-to-normal vision participated in the study. Subjects with calluses or injuries to the hands were excluded from participation. All participants were graduate and undergraduate students at Maastricht University. They were naïve to the hypotheses and received course credit or monetary compensation for their participation in the experiment. In accordance with the Declaration of Helsinki, written informed consent was obtained from each participant and the study was approved by the local ethics committee.

Stimuli

Haptic stimuli consisted of seven 5×5 cm^2 plastic plates, six embossed with different dot patterns and one control stimulus without any dots. The dots were arranged non-periodically and were 0.8 mm in diameter and 0.6 mm in elevation. The only characteristic that varied between the textures was the mean center-to-center dot spacing of each stimulus and hence the number of texture elements (dots). The average inter-dot spacing ranged from 1.50 mm to 2.75 mm and increased in steps of 0.25 mm (see Table 1 for detailed information on the stimulus characteristics). Details about the algorithm used to produce these textures can be found in Eck et al. (2011). For each dot matrix a 3D wireframe model was created and computer-rendered in AutoCAD® 2010 (Autodesk Inc., San Rafael, CA, USA) in order to create a set of matching visual stimuli. Two distant light sources following the direction of the viewpoint provided the lighting of each stimulus in such a way that all faces of the model were illuminated (see Fig. 1).

Experimental setup

All textures were arranged on a circular wooden board which was covered by a second wooden plate with a rectangular cut out. The