

The neural underpinnings of haptically guided functional grasping of tools: An fMRI study



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ABSTRACT

The neural bases of haptically guided interactions with tools are largely unknown. Whereas in the visual domain there is clear evidence for left lateralization of the networks underlying the guidance of actions involving tools, comparable evidence in haptic modality is missing. Therefore, we examined whether the temporo-parieto-frontal networks responsive to interactions with tools also support haptically guided functional grasping. We used event-related functional magnetic resonance imaging (fMRI) to measure brain activity while, in the absence of vision, 21 right-handed participants performed the following tasks with either their dominant or non-dominant hands: haptic exploration of real 3-D tools or size-matched control objects, subsequent planning of functionally appropriate grasps of tools and most convenient grasps of non-tools, and the resulting grasp execution. As predicted, haptic exploration of tools (vs. non-tools) was associated with significant asymmetrical/left-lateralized increases of activity in temporo-parieto-frontal networks. While grasp planning did not reveal differences between tools and control objects, the execution of functional grasping of tools (as compared to control grasps) re-recruited mainly dorsal cortical regions engaged earlier during the exploration phase. These results demonstrate that haptically guided grasping of tools invokes only subsets of cortical regions typically associated with tool-directed actions. They also call for a re-interpretation of what we assumed would be happening during the exploration phase, as this early stage of processing most likely included preliminary grasp planning. After all, the requisite integration of structural and conceptual tool features, as well as relevant action knowledge mediated at the neuronal level by the temporo-parietal projections in the early stage of processing, is not then critical for the execution of the preprogrammed functional grasp.

1. Introduction

Our current understanding of the neural underpinnings of human interactions with tools is almost entirely based on studies that capitalize on visual and visuo-motor processing, with little consideration of somatosensory cognition (Avanzini et al., 2016). Moreover, whereas manual somatosensation encompasses both passive tactile and active haptic processing (Smith et al., 2009), mainly the latter is expected to play a vital role in preparation and guidance of object-directed actions. This comes as no surprise, as haptics inherently link active touch to stored object representations which are supramodal, or shared across different modalities (Snow et al., 2015; Monaco et al., 2017), and this process requires an intricate collaboration of complex brain networks (Dijkerman and de Haan, 2007). Thus, studying purely haptic interactions with tools may shed a new light on the outcomes from research

on visually guided actions directed at tools.

Although, as compared to haptics, vision may seem somewhat more passive, the processing of visual information related to tools invokes a specialized left-hemisphere network of temporo-parieto-frontal brain regions (Goldenberg and Spatt, 2009; Orban and Caruana, 2014), often referred to as the praxis representation network (PRN; see Frey, 2008). When actions come into play, the main function of this network is to integrate and transform conceptual and sensorimotor information for skilled and purposeful responses directed at functional objects (Frey, 2007; Krolczak and Frey, 2009). Yet, because very little is known about the neural underpinnings of haptic interactions with tools, here we investigated whether or not, similarly to vision, the same temporo-parieto-frontal brain regions would be involved. Given the paucity of research in this domain, we focused on the most basic manual interaction with a tool, namely a functional grasp, as it is a prerequisite to

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any successful actions involving tools. Importantly, it also requires complex neural activity encompassing different nodes of PRN (Przybylski and Kroliczak, 2017).

Performance of functional grasp depends critically on integration of local processing of structural characteristics of a target object. After all, an effective grasp of a tool requires the recognition of a graspable, as well as a functional part of an object (Creem and Proffitt, 2001; Creem-Regehr and Lee, 2005; Goodale et al., 2005). In the haptic modality, these two perceptual acts are clearly detached, as opposed to vision wherein their processing occurs almost simultaneously (Macdonald and Culham, 2015). Specifically, while looking at a hammer, one almost immediately knows where its head vs. handle is located and, by the same token, infers that it is a tool with a specific function. Meanwhile, during haptic exploration of a tool these perceptual acts are temporally separated. For example, touching a hammer head first – while often enabling its immediate recognition – may not provide full and direct information about the size, orientation, and location of its handle, which is necessary for the proper grasp and must be acquired next. Conversely, touching a handle first – while invoking a possible grasp – does not necessarily convey information necessary for object recognition and further exploration is still required. This detachment in recognition of graspable and functional parts at the behavioral level allows, in our view, to capture the integrative processes accompanying haptic interactions with objects at the neuronal level prior to any actions involving tools, even if limited to functional grasping.

A distinction between functional grasp of a tool and involving the same movement kinematics grasping of a non-tool object is non-trivial, as only the former requires the inclusion of conceptual/functional knowledge on a target at hand. Thereby, a functional grasp depends on the interplay between neurocognitive systems devoted to function knowledge, and motor control (Osiurak et al., 2017). The functional knowledge system, usually associated with the ventral processing stream, in particular the caudal middle temporal gyrus (cMTG), contains semantic information about tools and long-term representations of typical tool use (Buxbaum and Saffran, 2002; Buxbaum, 2001). The motor control system, on the other hand, is associated with the dorso-dorsal processing stream (Rizzolatti and Matelli, 2003), as well as the more inferior projections along the intraparietal sulcus (IPS). The former, more superior pathway, is responsible for processing of object form or shape and their moment-to-moment changes in spatial orientation (Goodale and Milner, 1992; Binkofski and Buxbaum, 2013; Sakreida et al., 2016) for computing egocentric hand-tool relationships. These computations include matching a hand posture to an object for its appropriate grasp, regardless of the on-going action (Osiurak and Badets, 2016; cf. Vingerhoets et al., 2013; Johnson and Grafton, 2003). The latter pathway, primarily along IPS, has been typically associated with grasp production, namely the control of grasp kinematics (Kroliczak et al., 2008; see also Reynaud et al., 2016). Yet, the integration of inputs from the functional knowledge and grasp production systems is assumed to take place in the anterior supramarginal gyrus (aSMG/PFt) of the inferior parietal lobule (Orban and Caruana, 2014; Reynaud et al., 2016).

This study investigated the brain regions involved in haptically guided functional grasps. To this end, functional magnetic resonance imaging (fMRI) was used to examine blood-oxygen-level-dependent (BOLD) signal modulations while participants manually explored different tools, implements, and utensils with an intention to performing grasps suitable for an immediate use, as compared to simple manual exploration and later grasping of non-tool objects. Based on earlier studies (e.g., Marangon et al., 2016), we hypothesized that haptic exploration of tools with a view to performing function-appropriate grasps would invoke the left-hemisphere PRN. Its engagement in haptically guided actions was postulated to be similar to visually guided tasks involving functional objects (see Przybylski and Kroliczak, 2017). Moreover, we hypothesized that haptically guided functional grasps of tools would particularly invoke the left anterior IPS (aIPS), aSMG and cMTG (Goldenberg and Spatt, 2009; Orban and Caruana, 2014). The

involvement of these areas would corroborate that performance of a function-appropriate grasp requires the integration of motor control processing with conceptual knowledge. We also assumed that following object exploration – i.e., during a delay interval devoted to grasp planning – the major nodes of PRN, or their subdivisions, would reveal greater sustained activity for subsequent grasp execution (see Singhal et al., 2013; cf. Marangon et al., 2016). Yet another aim of this study was to test if the areas engaged during haptic exploration would be later invoked for functional grasp execution (cf. Fiehler et al., 2011; Singhal et al., 2013). Finally, as object exploration in our task was exclusively haptic, we were interested to know if recognition of tools and identification of their graspable parts would also invoke cortical areas located outside of PRN but still critical for haptic analyses of object shape and orientation (Reed et al., 2005; Sathian, 2016).

In sum, we used a three-stage haptic paradigm to examine neural activity associated with (1) manual exploration of tools and non-tools, (2) haptically guided grasp planning (whether functional or not), and (3) subsequent execution of functional or control grasps. We expected that the left-hemisphere temporo-occipital and parieto-frontal networks typically invoked for visual interactions with tools will be also engaged when such interactions are purely haptic.

2. Methods

2.1. Participants

Twenty-one young volunteers (11 females) with age ranging from 20 to 29 years (mean age = 22.5, SD = 2.3), and with no history of neurological or psychiatric disorders participated in two fMRI testing sessions. All of them were right-handed as measured with the Edinburgh Handedness Inventory (Oldfield, 1971), with mean lateralization quotient = 92.6 (SD = 8.7). All volunteers gave their written informed consent and were compensated financially for their time and efforts related to participation in this study, whose protocols were approved by the Bioethics Committee at Poznań University of Medical Sciences (Ethical Approval No. 63/12), and therefore conformed to the WMA Declaration of Helsinki.

2.2. Stimuli

The experimental stimuli consisted of three-dimensional 96 scanner-friendly objects made of plastic or wood. There were 48 tools and 48 control objects such as sticks, boards, tubes, blocks, slats and pebble-shaped things. Examples are presented in Fig. 1. Control objects were similar in size to tools, which in turn were of the same size as real tools. Appropriate for the adult hand grip, the average length of the tools and control objects was approximately 15 cm, with their width varying between 3 and 10 cm, and average depth of approximately 2 cm. The following tool types were utilized: a screwdriver, spanner (or wrench), pipe wrench, hammer, paper cutter knife, hand rake, trowel, syringe, kitchen tongs, pliers, pincers, and scissors. All 96 experimental stimuli were organized into six sets, each consisting of 8 tools and 8 non-tools. The 16 items of each set were attached in a pseudorandom order to a Velcro belt (4.4 m long and 20 cm wide), and were approximately 16 cm apart. Although general object orientation was kept identical for tools and non-tools, given that tools have handles, their presentation in fact involved one orientation more. The four possible orientations for tools were: 90° - with a tool in a horizontal position and its functional part directed to the right; 270° - with a tool in a horizontal position but with its functional part directed to the left; 135° - a tool in a skew position with its functional part directed rightward; 225° - a tool in a skew position with its functional part directed leftward. As control objects did not have functional parts nor handles they had the following orientations: horizontal, 135° and 225°. The orientations of tools and control objects were counterbalanced. Although there were 12 types of tools, the longer tools such as a hammer, hand rake, pipe wrench, kitchen tongs and trowel

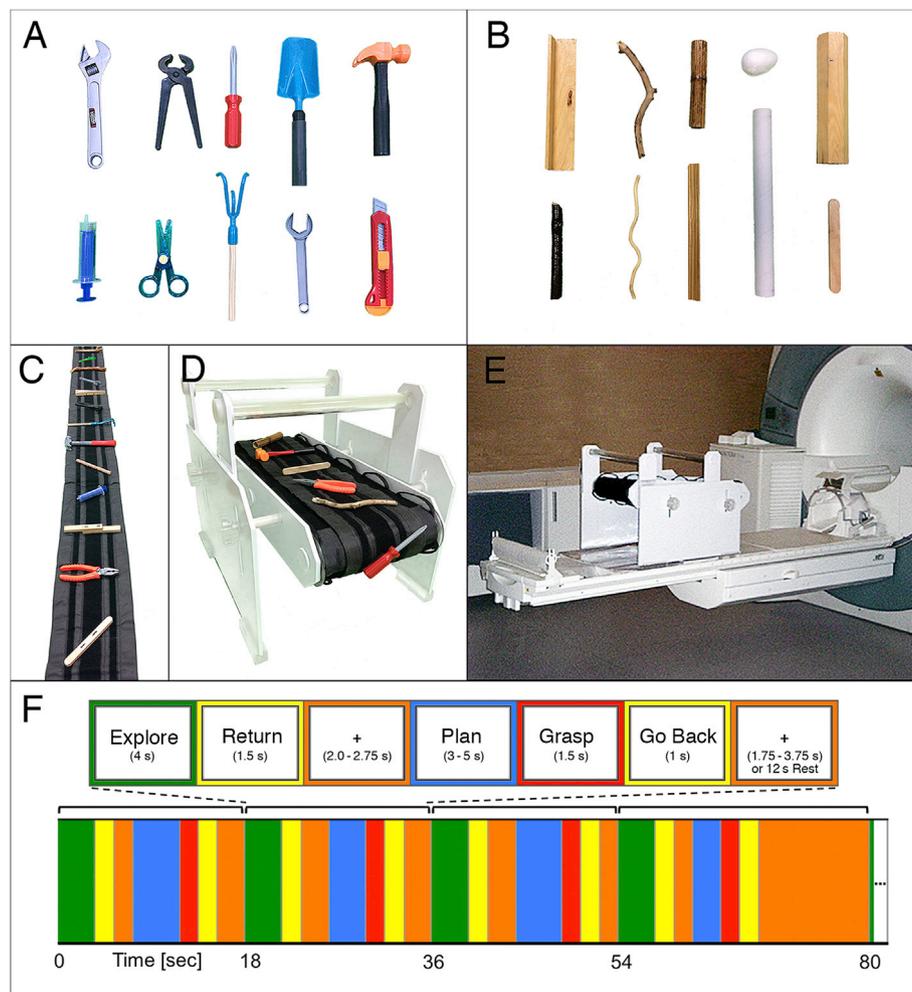


Fig. 1. Stimuli, apparatus and design. (A) Tools. (B) Control objects. (C) One of the ordered stimulus sets attached to the belt. (D) Conveyor device – *Grasparatus* – with one of the stimulus belts. The screwdriver at the front demonstrates the location where participants explored and grasped an object. (E) *Grasparatus* on the MR-scanner bed prepared for participant testing. (F) Trial structure and timing of the main experiment. See text for details.

were presented only in the two horizontal orientations of 90° and 270° , and appeared only on two belts. A few exemplars, such as a screwdriver, spanner and syringe appeared on all six belts, whereas a paper cutter knife, pliers, pincers and scissors appeared only on five belts. Yet, each tool appeared only one time on a given belt.

2.3. Procedure

A single belt was placed on a custom-made MR-compatible device consisting of two rotating drums connected with a conveyor belt, and mounted on the supporting sides (Fig. 1) attached to the scanner bed. This device, which resembled the “*Grasparatus*” used elsewhere (e.g., Kroliczak et al., 2008), was put above the participants’ legs so that the front of the drum was positioned around participants’ hips, within a reach of the hand while in the scanner. (Technical and further details related to this apparatus, and the associated equipment, can be obtained from the corresponding author and from our future publication.) Participants could not see the stimuli on the belt, neither directly nor via the mirror (which actually reflected instructions from the screen located behind the scanner). Similarly, the participants did not have any visual feedback of their hands. Tools and control objects were mounted to the belt with the use of strands attached along middle parts of each stimulus, and therefore they could not be picked up and used but could be comfortably grasped. Only one stimulus was presented in a single trial and, while the presentation order was set, its pace was controlled by the

signals delivered via headphones to the experimenter, who manually moved the belt.

The experiment had an event-related design wherein participants performed their tasks guided by instructions, seen via the mirror attached to the headcoil, displayed on a NordicNeuroLab (<http://www.nordicneurorolab.com>) 101.6 cm 4K UHD monitor positioned behind the scanner bore. At the beginning of each run, a ‘GET READY’ command was presented. Participants had to lay their both hands along their bodies and press the buttons of the LU400-Pair response pads (<http://cedrus.com/lumina/>) with their working hands. Throughout the whole run, a participant acted only with one hand while the other one remained static. The first trial began 10 s after the ‘GET READY’ command. Each trial consisted of the following sequence of events. Initially, the word ‘EXPLORE’ was displayed for 4 s, which indicated the exploration phase. Participants’ task was to raise their hands, reach to the location of the stimulus and haptically explore it in order to recognize whether it was a tool or a control object and determine its orientation. In the case of a tool, exploration also required identifying the object and where its functional part and its handle was located. A participant did not know neither the identity nor orientation of the upcoming stimulus, which was supposed to be explored for the whole task interval. Subsequently, the word ‘RETURN’ ending the exploration phase was displayed for 1.5 s, and the participants’ task was to move their hands back and press the start button. A variable duration (2, 2.25, 2.5 and 2.75 s) inter stimulus interval (ISI), associated with a small black cross in the middle of the screen, preceded

the following grasp planning phase. ISIs were counterbalanced across the trials and stimulus sets (belts). Next, during a variable interval of 3, 4 or 5 s, a participant's task was to plan a grasping movement of the just explored stimulus, while still keeping the working hand on the button. For each planning interval, throughout the first 1.5 s the visual 'PLAN' command was presented, and for the remaining time (that is for 1.5, 2.5 or 3.5 s) a black cross was displayed in the middle of the screen. These variable planning intervals were counterbalanced across trials and belts. Participants were required to plan the following actions: in the case of non-tools the task was to plan the simplest possible reach and grasp movement. In the case of tools, participants' task was to plan a grasping movement that would allow for tool use action consistent with its function. After the planning phase, the word 'GRASP' was displayed for 1.5 s and the participant's task was to raise a hand from the button and execute the pre-planned grasping action (execution phase). Participants were instructed to not correct for any grip imprecision, and not to lift the objects from the belt surface. Subsequently, a 'GO BACK' command was shown for 1 s which indicated to participants to finish their grasps, withdraw their hands and move them back to the starting position where the start button should be pressed and held. When a 'GO BACK' command disappeared, a black cross was displayed for a variable inter trial interval (ITI) of 1.75, 2.75 or 3.75 s. ITIs were also counterbalanced across trials and stimulus sets. When an ITI ended, a new trial began. Trial structure and timing is shown in Fig. 1. During ITIs the experimenter manually moved the belt on the conveyor device thus delivering a new stimulus for the next trial. A single run consisted of 16 trials including pseudo-randomly ordered 8 tools and 8 non-tools. Twelve trials of each run had a duration of 18 s each, and four trials (two for tools and two for non-tools) had an additional rest ITI lasting 8 s (with a black cross displayed on the screen). This additional rest interval occurred always in trials with the longest, 3.75-s ITI. Because MRI scanner triggers were produced every 2 s, each rest interval lasted 12 s in total. Trials with the rest ITI had a duration of 26 s and were pseudo-randomly inserted within a single run. There were always at least two trials preceding a trial with rest. Given the adopted duration and variability of events within trials, a single run lasted typically 5 min 45 s. Visual displays and event durations were controlled with the use of the SuperLab 4.5.4 software. Each trial was digitally synchronized with the MRI scanner.

2.4. Pre-training and experiment proper

Participants received training on safety issues related to participation in an fMRI study, as well as on the to-be-performed tasks, including their exact instructions and a general layout of experiments within a single study session. All participants were presented with all objects from the main experiment, they could freely touch and grasp these objects using one hand, with and without eyes closed, in order to get familiarized both with tool and non-tool control stimuli, and the associated exploration and grasping tasks. Subsequently, they were also familiarized with stimuli and tasks from "Haptic Tool Use", as well as "Visual Motion – Hand Motion" localizers. Both before the study proper and localizer runs, while already in the scanner but prior to actual scanning, there was also a short practice involving two random trials, in order to get familiarized with a given study protocol.

Each participant took part in two scanning sessions on two consecutive days. Because there were only five experimental runs devoted for the main study, during a single scanning session five pseudo-randomly chosen sets of stimuli (out of six that were prepared ahead of time) were run in a random order. Typically, there was a 1-min break between runs for the replacement of a just used stimulus set with a new set (a belt to be attached to the "Grasparatus"). The same five belts, but run in a different order, were used for each participant on both scanning sessions. Within a single session, the participant performed all tasks with the use of one, pre-defined hand, with the hand order counterbalanced across all subjects. Namely, ten participants used their right (dominant) hands on the first day and their left (non-dominant) hands on the second day, and

for the remaining 11 participants the order of the tested hand was reversed. A single scanning sessions also included several, subsequently run functional localizers whose order was also pseudo-randomized.

2.5. MRI procedures

Scanning was performed on a 3T Siemens Trio MRI scanner (Siemens Medical Solutions, Germany), with a standard 32-channel head coil, in the Laboratory of Brain Imaging at the Nencki Institute of Experimental Biology in Warsaw (www.lobi.nencki.gov.pl). Before the start of functional runs, Auto Align Scout and True FISP sequences were executed to help with the prescription of slices. The BOLD echoplanar images were collected using T2*-weighted segmented gradient-echo imaging sequence with interleaved slice acquisition. Functional data were obtained with the following parameters: field of view (FOV) = 196 mm; 64×64 matrix; in-plane resolution = 3.06×3.06 mm; flip angle (FA) = 90° ; time to echo (TE) = 30 ms; time to repetition (TR) = 2000 ms. Each volume was made up of 35 contiguous axial slices of 3.1 mm thickness. The initial first four volumes in each scan series were discarded. A single run of haptic experiment was composed of 170 volumes. Standard anatomical scans were collected in both sessions using a 3D T1-weighted magnetization prepared rapid gradient echo (MP-RAGE) pulse sequence with the following specifications: TE/TR = 3.32/2530 ms; inversion time (TI) = 1200 ms; FA = 7° ; 176 contiguous axial slices; in-plane resolution = 1.0×1.0 mm; slice thickness = 1.0 mm; voxel matrix size = 256×176 ; FOV = 256 mm. Fast spin echo T2-weighted anatomical images were also obtained with the following parameters: TR = 3200 ms; TE = 402 ms; FA = 120° ; 512×512 voxel matrix size; FOV = 256 mm; 176 contiguous sagittal slices; in-plane resolution = 0.5×0.5 ; slice thickness = 1 mm. DICOM images were converted to FSL Nifti format using MRI-Convert software (<http://lcn.uoregon.edu/~jolinda/MRIConvert/>).

2.6. fMRI data analyses

Imaging data were preprocessed and analyzed using FSL software version 5.0.7 (Jenkinson et al., 2012). The preprocessing procedures included: nonbrain tissue removal using brain extraction tool (BET; Smith, 2002), the application of motion correction MCFLIRT algorithm (Jenkinson et al., 2002), spatial smoothing with a Gaussian kernel of full width half magnitude (FWHM) = 6.2 mm, and high-pass temporal filtering with a cutoff = 50 s. FSL Linear Registration Tool (FLIRT, Jenkinson and Smith, 2001) was used to implement registration of functional images to standard native anatomical and standard space images (Montreal Neurological institute [MNI-152] 2 mm brain template). Each participant's anatomical image used for coregistration was obtained by averaging T1-weighted anatomical scans from the first and the second scanning session using FMRIB Linear Image Registration Tool - FLIRT (flirt_average).

FSL's fMRI Expert Analysis Tool (FEAT) was used for whole brain (voxelwise) analyses. At the first level, each run was analyzed individually, separately for the right and left hand. Each condition was modeled with a canonical hemodynamic response function (double-gamma HRF) and General Linear Model (GLM). In the statistical model, estimates of the degrees of freedom were corrected for autocorrelation in the data by using the FSL's FILM prewhitening algorithm (Woolrich et al., 2001), a procedure which makes all the statistics valid and maximally efficient. Eleven Explanatory Variables (EVs) were used. Two separate EVs were for Exploration – tools and non-tools, respectively. There were four EVs for Grasp Planning – two for tools (rotated and non-rotated) and two for controls (rotated and non-rotated). There were also four EVs for Grasp Execution – two for tools (rotated and non-rotated) and two for controls (rotated and non-rotated). In the case of tools, whether or not their grasping required hand rotation depended on the used hand and handle orientation. Namely, while for the right hand only the handle pointing leftwards (whether positioned horizontally or diagonally) requires a

substantial hand rotation, the opposite is true for the left hand. (Thus, a working hand and tool orientation were factors that allowed determining whether an EV belonged to a rotated or non-rotated category.) In the case of control stimuli, all objects in a horizontal position were classified as non-rotated and all in diagonal positions were treated as rotated, no matter which hand was used for task performance. There was also one more EV for modeling the Rest periods (i.e., longer intervals between consecutive trials). Exploration and grasp-related activity was modeled for their entire duration, that is for 4 s and 1.5 s, respectively. Grasp planning activity was modeled for a duration of 3 s starting from the onset of the instructional cue (i.e., presented visually for 1.5 s) and lasting through the end of the shortest (1.5-s) planning interval (wherein the black cross was displayed in the middle of the screen). Rest intervals were modeled for their entire duration (12 s). Although the remaining time intervals – i.e., return, go-back, variable ISIs, the remaining delays of the grasp planning, as well as ITIs – as conditions of no interests were not explicitly modeled, they served an important function of separating trial events, thus reducing the temporal coupling between the tested phases (exploration, planning, grasping), and enabling an easier deconvolution of the signals from these tasks (see [Kroliczak and Frey, 2009](#)). Temporal derivatives for each EV were automatically created as additional regressors in order to correct for any timing discrepancies detected in the latency of the peak in HRF. Balanced weighting was applied to each of the contrasted conditions.

Contrast of parameter estimates (COPEs) resulting from the first-level analysis served as inputs to the second-level analysis (within subjects, across individual runs, across the left hand and right hand) using Fixed Effects model. The resulting second-level COPEs were subjected to the third-level analyses (across participants), performed using a mixed effects model, with the random-effects components of variance estimated with the default FSL procedure called FLAME stage 1 ([Beckmann et al., 2003](#)). Z (Gaussianized T/F) statistic images were thresholded using clusters not smaller than those determined by FSL values of at least $Z > 3.1$ and a corrected cluster significance threshold of $P = 0.05$ ([Eklund et al., 2016](#)). Contrasts versus rest, used to show a null effect, and their direct comparisons, were thresholded more conservatively, at $Z > 3.7$ and a corrected cluster significance threshold of $P = 0.05$.

To be more consistent with neuropsychological tradition, where typically the non-hemiparetic left hand is tested and the outcomes of such tests are critical for understanding of the hand-independent representations of higher-order motor skills, we tested both dominant (right) and non-dominant left hand and averaged the neural activity across hands. (These pre-processed data and group results from the main study can be obtained from the corresponding author, GK.) Such averaging, showing activity common for both hands, also substantially increases the power of the test. Indeed, the averaging was also important because neural activity associated with grasping with the more skilled, dominant hand was weaker. (The latter effect goes counter to earlier observations that planning tool use pantomimes based on linguistic cues is associated with greater neural activity for the right hand. Yet, it is still consistent with weaker activity observed for the right hand during the execution of the earlier planned tasks; [Kroliczak and Frey, 2009](#).)

For spatial normalization, functional (EPI) images were first aligned with the initial (T2-weighted) anatomical images with six degrees of freedom (DOF). Next, T2- and T1-weighted [MP-RAGE] images were registered to each other with seven DOF. Finally, MP-RAGE scans were warped to the atlas space (Montreal Neurological Institute [MNI-152] 2-mm template brain) using twelve DOF.

Manual comparison with an atlas ([Damasio, 2005](#)) was used for verification of localization of all clusters with significant brain activity. Their localization was also verified by projecting and visualizing these clusters using the Connectome Workbench v1.2.3 software, wherein, using trilinear interpolation, the group statistical imaging maps can be overlaid in a convenient manner onto selected brain surfaces, and also demarcated with borders of functional areas, based on multi-modal parcellation ([Marcus et al., 2011](#); [Glasser et al., 2016](#)).

Because participants performed reaching movements in order to grasp target objects, there was a risk that these movements could translate into head movements, which in turn would lead to increased noise or artifacts in the fMRI signal. To reduce the extent of the required movements, participants' upper arms were supported by extremity-positioning cushions, which substantially limited the necessity to raise the upper arm from the bed surface. Participants were also instructed that they should not move their arms too extensively and abruptly and, if necessary, they were reminded by the experimenter to primarily use their forearm and wrist/hand during object exploration and grasping.

The setting and instructions substantially limited the occurrence of shoulder and head movements. Indeed, the average absolute head displacement was very small: 0.29 mm (min 0.11, max 1.13) in right-hand sessions, and 0.3 mm (min 0.09, max 1.1) in left-hand sessions. Although from the independent component analyses (ICA) using Multivariate Exploratory Linear Decomposition into Independent Components (MELODIC; as implemented in FSL) we knew small artifacts were present in the right-hand data (at a more lenient threshold of $Z > 2.3$ and cluster corrected $p = 0.05$), none of the artefactual signals contributed significantly to group outcomes at more conservative thresholds. As indicated above, the lowest acceptable threshold we used was that of $Z > 3.1$, and a corrected cluster-significance threshold of (i.e., family-wise error rate [FWER] maintained at) $p = 0.05$ ([Eklund et al., 2016](#)).

2.7. Region of interest (ROI) analyses

Eleven ROIs were selected and/or defined based on voxelwise group results from the previously published reports ([Kroliczak and Frey, 2009](#); [Biduła and Kroliczak, 2015](#); [Hutchison et al., 2015](#); [Kubiak and Kroliczak, 2016](#); [Marangon et al., 2016](#)), the outcomes from the functional localizer scans from the on-going projects in the lab, and a combination of thereof with the Juelich cytoarchitectonic maps and/or anatomical regions from the Harvard-Oxford probabilistic atlas included in the FSL package. These ROIs were the following: aIPS, cMTG, lateral-occipital tactile-visual area (LOTv), extrastriate body area (EBA), the human homolog of the motion sensitive middle temporal complex (MT+), dorsal premotor cortex (PMd), ventral premotor cortex (PMv), anterior insular cortex (aIC), rostral middle frontal gyrus (rMFG), supramarginal gyrus (SMG), and the superior parietal lobule (SPL). The primary goal of the ROI analyses was to determine the relative contribution of each selected area to the three main studied tasks (exploration, planning, and grasping), including the hand used for task performance (left, right) and object type (tool and non-tool). To this end, a 2 (hand) x 3 (task) x 2 (object) repeated-measures ANOVA was run on brain activity from their respective contrasts vs. the resting baseline. The most common level of significance was adopted, i.e., $\alpha = 0.05$. If necessary, post hoc tests were corrected for multiple comparisons using Bonferroni corrected p values.

We focused only on the left-hemisphere temporo-parieto-frontal areas that are typically linked to higher order manual skills. Some areas were of special interest, as they are important for tool related actions. For example, cMTG is associated with retrieval of essential concepts and visual features of tools, as well as knowledge on the range of actions afforded by them ([Goldenberg, 2003](#); [Kroliczak and Frey, 2009](#); [Watson and Buxbaum, 2015](#)); aIPS plays a role in the processing and planning of skilled manual actions with tools ([Goldenberg and Spatt, 2009](#); [Peeters et al., 2013](#); [Kroliczak et al., 2016](#)); PMv is related to preprogramming of imminent actions; PMd plays a role in visuomotor task-response associations ([Cross et al., 2017](#)), particularly in action execution ([Ishibashi et al., 2016](#)), and rMFG is linked to the selection of action goals, and the relevant object-response associations ([Haaland et al., 2000](#); [Buxbaum et al., 2014](#); [Goldenberg and Spatt, 2009](#)). Additionally, we were also interested in such areas as EBA, LOTv, MT+, aIC, and SPL which play some roles in object recognition (whether haptic or visual) and in delayed actions on objects (e.g. [Amedi et al., 2001](#); [Reed et al., 2005](#); [Singhal et al., 2013](#); [Snow et al., 2015](#)).

2.8. Additional localizer scans

All participants were tested in two different localizer scans. Haptic Tool Use Localizer (HTUL) served to independently reveal areas belonging to PRN. HTUL involved manual tool recognition, its subsequent grasp and simulated tool use pantomimes (with the object in hand), all performed without visual feedback, only on the basis of haptic information. The control task also involved haptically guided hand movements although they were performed on the control objects such as small plastic disks or varied in shape plastic forms adopted from a study by Marangon and collaborators (2016). In the case of control objects, the task was to recognize if the presented object is a disk or a multi-shaped form, grasp it, and while holding the object in hand to draw in the air the shape of a circle (for discs) or an infinity symbol (∞ , for multi-shaped forms). This localizer was run two times, typically on two days. There were two different pseudorandom orders of task and rest blocks assigned in a counterbalanced way across hands used on a given day and testing session. Each run consisted of nine 30-s pseudorandomly ordered blocks: three blocks with tool objects (with four tools in each block), three blocks with control objects (with four non-tools each) and three blocks of rest periods. As a result, there were twelve different tools (each tool appeared only once in a run) and twelve control objects (four discs and eight multi-shaped forms) in each run. All objects were presented one at a time with the use of the Grasparatus from the main study. The tools were always presented in the most comfortable orientation for functional grasp. In the object blocks, two commands were displayed on the screen for each object with the first one being “perform action”, which instructed a participant to start the sequence of movements and the second command being “stop”, instructing to finish the action and put down the object in hand. Action periods lasted 6 s with 2-s intervals between objects. During rest periods, the fixation cross was displayed and participants refrained from any actions.

The second localizer aimed to identify human visual motion selective area MT+ and brain regions involved in monitoring hand movements. The localizer was run two times, separately for the right and left hand, and typically on two consecutive days; the visual stimuli were the same in both sessions. The stimuli and tasks of the localizer allowed identifying areas sensitive to visual rotation and expansion/contraction, and to hand rotation and extension/contraction. Visual stimuli were similar to those used by Culham et al. (1999) and consisted of superimposed radial and/or concentric gratings. In three different 14-s blocks, these stimuli were rotating either clockwise, and/or counter-clockwise (24 steps of 15° rotation per block), and in the other three different 14-s blocks the gratings were contracting and/or expanding (four subsequent steps of 1.7° forward or backward movement, changing position 24 times per block). Additionally, there were six 14-s blocks with passive viewing of stationary radial (three blocks), and/or concentric control gratings (three blocks). In hand-movement blocks, the participants' task was to rotate their wrist in four steps, clockwise and counter-clockwise in a pace similar to the previously seen visual changes (three blocks, 14 s each), or to reach out and move back the arm, again in four steps, back and forth in a pace similar to the contraction/expansion of visual stimuli (three blocks, 14-s each). With one of the two visual conditions always presented first, all the blocks were pseudorandomized in each run, including the six 14-s rest periods where a fixation dot was displayed in the middle of the screen. The critical comparison of visual responses to moving vs. stationary patterns (regardless of their type) allowed for area MT + localization. There was also another crucial comparison (used in the results' interpretation) that contrasted hand movements vs. visual movement.

3. Results

3.1. Haptic tool exploration

A direct comparison of exploration-related activity for tools vs. non-

tools, averaged across the left and right hand, showed significant BOLD increases in bilateral parieto-frontal networks, with a greater contribution of the left hemisphere. Namely, in addition to bilateral primary somatosensory and motor activity, the observed signal increases were also found in left-hemisphere areas typically associated with PRN (Kroliczak and Frey, 2009; Przybylski and Kroliczak, 2017). The obtained results are shown in Fig. 2A. The identified peak MNI coordinates and peak values of the areas/regions exhibiting significant activity in this contrast are shown in Table 1A. Specifically, on the lateral surfaces, only the SPL and superior divisions of the angular gyrus (AG) were engaged more symmetrically, whereas the modulations of activity in aIPS, aSMG (corresponding to the cytoarchitectonically defined division named PFT, Caspers et al., 2006), as well as PMd and PMv were more pronounced on the left. The rMFG, cMTG, as well as the nearby fusiform gyrus (FusG) activity was exclusively left lateralized. On the medial surfaces of both hemispheres, significant signal modulations were observed bilaterally in the precuneus (preCun), extending posteriorly to the occipito-parietal sulcus (OPS), and medial occipital cortices (involving primarily the calcarine sulcus, CalcS, corresponding to early visual areas). There was also bilateral pre-supplementary motor area (preSMA) activity, which in the left hemisphere extended into the cingulate motor area (CMA). The posterior cingulate cortex (pCC) was more involved on the left. Finally, the caudate and nearby thalamic activity was also greater in the left hemisphere.

None of the areas showed significantly greater engagement for the exploration of non-tool vs. tool stimuli. Therefore, the results described above indicate that the left-lateralized network consisting of SPL, aIPS, PMd, PMv, rMFG and cMTG is critical for haptic tool exploration and recognition, regardless of the hand involved. These areas are thought to belong to the PRN (Przybylski and Kroliczak, 2017), a network of praxis-related areas, which are devoted to processing information about manual actions directed at tools. It is of note that, surprisingly, the contrast of activity associated with exploration of tool vs. non-tool objects did not reveal any activity in the secondary somatosensory cortices (SII; Avanzini et al., 2016). This effect however, should not be construed as evidence for the lack of their engagement in the task. Conversely, it clearly implies that SII alone is not capable of distinguishing between functional and non-functional objects. Of course, SII engagement is seen in the contrasts of the two conditions vs. the resting baseline. In a similar vein, an inferior section of mid SMG (that is the area defined cytoarchitectonically as PF, Caspers et al., 2006) does not seem to differentiate between tools and non-tools during their haptic exploration, either.

3.2. Grasp planning

Counter to the exploration phase, a direct comparison of activity related to grasp planning revealed no difference between tools and non-tools, again, regardless of the tested hand. The lack of significant differences between the two conditions does not imply that during the delay interval preceding grasp execution there was no significant signal modulation above the resting baseline. Conversely, except for premotor areas, sustained activity associated with grasp planning as such (i.e., regardless of object status), was observed both in the inferior parietal lobule (IPL) and SPL, the posterior middle and inferior temporal gyri, as well as in a small cluster of activity in the rMFG vicinity of the left hemisphere. Moreover, it would be misleading to think that there was no difference whatsoever in the neural engagement for tools and non-tools for grasp planning because there was clearly bilateral and widespread significantly weaker suppression of activity for non-tools outside of the regions typically linked to the control of praxis skills (but often related to the default mode network, DMN; Raichle et al., 2001). All these effects, including the overlap of activity for tools and non-tools, and for different contrasts, are shown in Fig. 2B.

3.3. Haptically guided grasp execution

A direct comparison of activity related to grasping tools vs. non-tools,

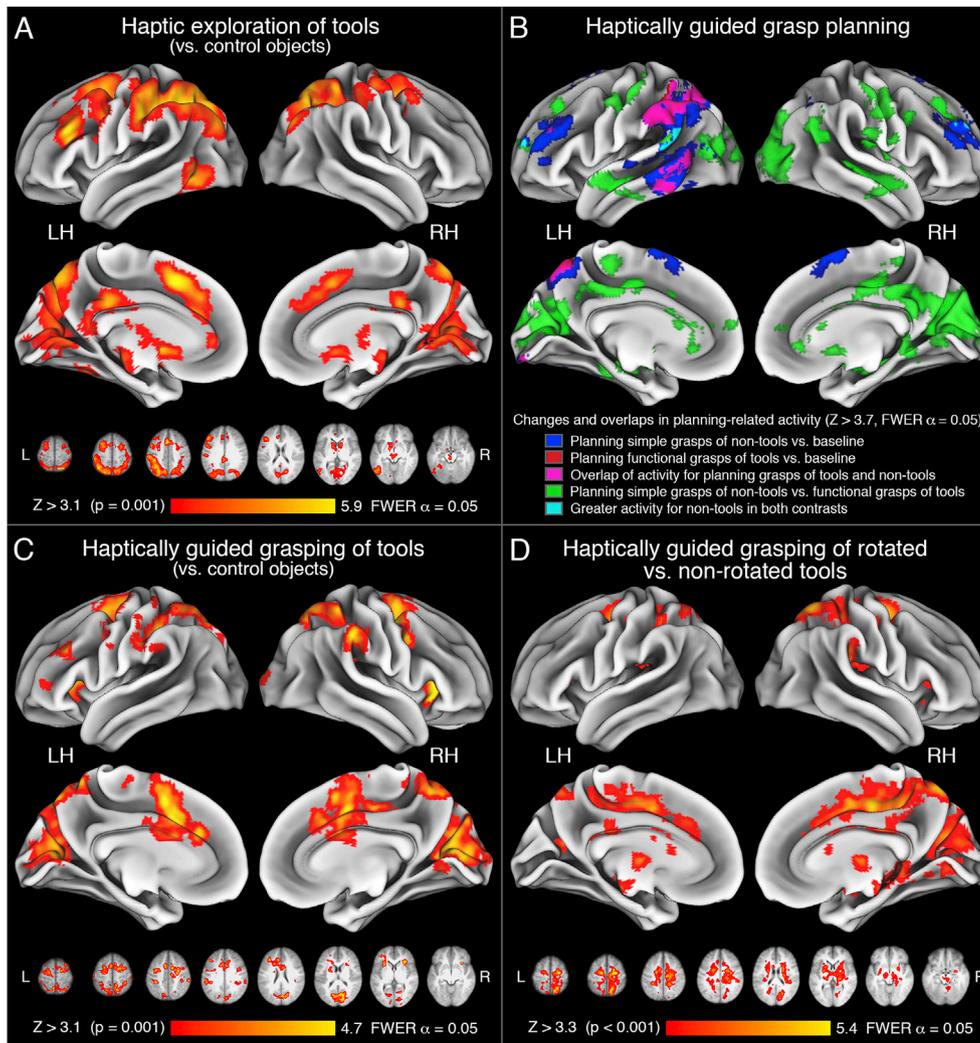


Fig. 2. Main results. Brain areas showing significantly greater neural activity during haptic tool exploration (A), grasp planning (B), and haptically guided functional grasps of tools (C and D). Functional brain activity in representative slices and volumetric surface renderings are shown. (A) Haptic exploration of tools vs. exploration of non-tool objects, averaged across hands. All the left-hemisphere areas belonging to PRN (i.e., SPL, aIPS, aSMG, PMd, PMv, MFG, cMTG), were invoked. Only SPL was engaged bilaterally. On medial surfaces, preCun, OPS, medial occipital cortices and preSMA were involved bilaterally, whereas CMA and pCC showed left-lateralized advantage. (B) Brain activity for planning functional grasps of tools vs. baseline (red), planning grasps of non-tools vs. baseline (blue), planning grasps of non-tools vs. tools (green), and their overlaps (magenta – overlap of activity for planning grasps of tools and non-tools, and cyan – overlap of greater activity for non-tools in both contrasts). Grasp planning (regardless of the object) engaged left-lateralized SPL, IPL, MTG, and a small area in MFG. Neural activity associated with non-tools (as contrasted with tools during planning phase) showed characteristic weaker inhibition of motor-related areas, as well as bilateral regions often linked to the default mode network. (C) Haptically guided functional grasping of tools vs. grasping of non-tools, averaged across hands. There was bilateral engagement of SPL, aSMG, OPS, aIC, and aIPS. MFG was invoked only in the left hemisphere. On medial surfaces preSMA, CMA and pRCG were invoked bilaterally. (D) Haptically guided functional grasping of rotated vs. non-rotated tools. Adjusting hand orientation during functional grasp engaged bilaterally aIC, pIC, aSPL, PMd, SMA, pre-SMA, CMA, whereas parietal operculum showed right-lateralized advantage. FWER = family-wise error rate.

again averaged across the left and right hand, showed significant bilateral BOLD signal increases in the majority of the superior parieto-frontal areas involved earlier in the exploration of tools. All the clusters were nevertheless much smaller. As shown in Fig. 2C, in the parietal lobe, the greater tool-related activity was found from caudal to anterior SPL (cSPL and aSPL, respectively), with signal modulations extending medially to preCun. More posteriorly, there was also substantial bilateral activity in OPS, CalcS, and the nearby cuneus (Cun). The bilateral aSPL activity also extended ventrally along the postcentral gyrus. While in the left hemisphere grasping tools partly invoked aIPS (phAIP as defined by Orban, 2016), as well as aSMG (Pft), and an inferior section of area PF, in the right hemisphere the activity was more extensive in area PF. In the frontal lobes, bilateral PMd and PMv, as well as aIC involvement was observed, whereas rMFG was only activated on the left. Finally, on the medial surfaces large bilateral preSMA clusters extended to CMA and further down to posterior divisions of rostral cingulate gyrus (pRCG). Subcortically, a small cluster of activity in the left putamen was also found. Table 1B is related to grasp execution. Peak MNI coordinates and peak values of the significantly engaged areas/regions from this contrast are shown in Table 1B.

The inverse contrast of activity associated with grasping non-tools vs. tools was empty. These results indicate that regardless of the hand, the execution of grasping actions directed at tools engaged mainly dorsal-

stream pathways, including both the ventro-dorsal and dorso-dorsal, as well as the medio-dorsal streams of processing (Rizzolatti and Matelli, 2003). Additionally, these results demonstrate that some of the most critical dorsal regions that were engaged in haptic exploration of tools were later invoked during the execution of functional grasp (cf. Singhal et al., 2013).

To enable further comparisons of our results with future studies that will also use the functional borders from the Connectome Workbench (a potential standard in data visualization; <https://www.humanconnectome.org/software/connectomeworkbench>), in Fig. 3 we also mapped our haptic exploration (Fig. 3A) and grasping (Fig. 3B) results onto flat and very inflated surfaces. We also emphasized the borders of the associated areas (of the 180 identified and delineated parcellations; Glasser et al., 2016).

3.4. Hand independent functional grasps of tools requiring hand rotation vs. no-rotation

To further explore an engagement of the dorso-dorsal stream in online control of action, we contrasted the activity related to grasps directed at differently oriented tools. Of the four orientations that were used in this study, two of them required substantial rotations for the right, and two for the left hand when they were directed appropriately at tool handles.

Table 1

Peak MNI coordinates and peak values of the regions exhibiting significant activity in two major contrasts from the main experiment.

A. Haptic exploration of tools vs. control objects ($Z > 3.1$, $p = 0.05$ cluster corrected)				
Region	MNI Coordinates			Peak value
	x	y	z	z-max
Left Lateral Occipital Cortex (inferior division)	-56	-66	-4	4.8
Left Middle Temporal Gyrus (temporooccipital part)	-46	-56	0	4.4
Left Superior Parietal Lobule	-36	-56	52	5.9
Left Lateral Occipital Cortex (superior division)	-28	-64	46	5.4
Left Superior Parieto-Occipital Cortex	-6	-72	58	4.7
Left Primary Somatosensory cortex	-52	-32	52	5.2
Left anterior Intra-Parietal Sulcus	-40	-36	42	5.1
Left Middle Frontal Gyrus (posterior part)	-28	10	54	4.9
Left Angular Gyrus	-48	-54	38	3.9
Left anterior Supramarginal Gyrus	-56	-32	40	3.9
Left dorsal Premotor Cortex	-22	2	56	4.4
Left ventral Premotor Cortex	-48	4	38	4.6
Left Middle Frontal Gyrus	-46	28	26	5.2
Left Paracingulate Gyrus	-2	16	46	5.5
Left Cingulate Gyrus	-2	-36	34	4.3
Left Precuneus Cortex	-12	-66	40	5.3
Left Fusiform Gyrus	-32	-50	-18	4.1
Right Lateral Occipital Cortex (superior division)	18	-66	62	5.7
Right Angular Gyrus	46	-54	48	3.5
Right Superior Parietal Lobule	40	-48	58	4.5
Right dorsal Premotor Cortex	28	2	54	4.4
Right ventral Premotor Cortex	39	0	40	3.5
Right anterior Intra-Parietal Sulcus	34	-42	44	3.5
Right Supramarginal Gyrus	48	-32	48	3.1
Right Paracingulate Gyrus	4	14	46	4.5
Right Cingulate Gyrus	4	-34	32	4.2
B. Haptically guided grasping of tools vs. control objects ($Z > 3.1$, $p = 0.05$ cluster corrected)				
Region	MNI Coordinates			Peak value
	x	y	z	z-max
Left anterior Intra-Parietal Sulcus	-40	-32	36	4.2
Left Superior Parietal Lobule (anterior part)	-30	-54	60	3.8
Left Primary Somatosensory Cortex	-54	-30	30	4.2
Left dorsal Premotor Cortex	-24	4	56	4.0
Left Juxtastipositional Cortex	-6	6	50	4.4
Left Supplementary Motor Area	-38	-4	42	4.1
Left Middle Frontal Gyrus	-36	30	28	4.2
Left Insular Cortex (anterior part)	-28	18	4	4.2
Left Lateral Occipital Cortex (superior division)	-8	-66	62	4.2
Left Precuneus Cortex	-6	-54	64	4.2
Left Intracalcarine Cortex	-16	-72	12	4.7
Left Paracingulate Gyrus	-12	14	38	4.6
Right Superior Parietal Occipital Cortex	16	-64	52	4.7
Right Supramarginal Gyrus	60	-34	40	4.4
Right ventral Premotor Cortex	30	-2	48	4.6
Right dorsal Premotor Cortex	18	-2	58	4.3
Right Insular Cortex	30	24	-2	4.7
Right Juxtastipositional Cortex	12	6	44	4.3
Right Intracalcarine Cortex	12	-70	14	4.6

Thus, when task difficulty was matched for both hands and the activity associated with hand rotation vs. a lack of thereof was contrasted, in addition to substantial subcortical engagement of the bilateral thalamus and putamen, as well as bilateral involvement of the aIC and posterior insular cortex (pIC), the remaining activity was observed primarily along the medio-dorsal pathways (extending from the primary motor cortex, SMA, preSMA, and through the CMA), and the dorso-dorsal subdivisions of the parieto-frontal pathways (in particular aSPL and PMd). These results are shown in Fig. 2D. It is of note, that the right hemispheric dorso-dorsal stream seemed to be involved substantially more, and in the parietal operculum there was also a significant cluster of activity that extended to SII. These results are consistent with a notion that the dorso-

dorsal and medio-dorsal streams might be involved in processing of variable (moment-to-moment) object affordances, particularly their orientations, a task that is so critical for manual actions directed at tools (Sakreida et al., 2016).

3.5. Haptic Tool Use Localizer

A direct comparison of haptically based tool use actions vs. arbitrary hand movements with non-tool objects in hand (i.e., with movement kinematics accounted for), again averaged across hands, revealed significant BOLD signal increases in the left occipito-temporal cortex (see Fig. 4). When the obtained cluster was delineated by borders of functional areas defined in our additional localizers, peak activity associated with tool use actions was localized in, what was earlier identified as, the LOTv area, yet the whole cluster also included the more anteriorly located cMTG. Fig. 4 also clearly demonstrates that neither area MT + nor EBA was substantially involved. Little MT + engagement corroborates that movement kinematics were comparable for tools and non-tools, whereas the absence of EBA contribution indicates that the visualization of the acting hand did not play any greater role for handling tools. Thus, our HTUL revealed that the critical source of tool concepts, typical functions of tools and possibly the associated manipulation knowledge is stored ventro-laterally in the occipito-temporal cortex.

3.6. ROI analyses

Our hypothesis was that some of the areas invoked more by haptic exploration of tools would also reveal greater activity during functional grasp planning, and this activity could be later utilized for the guidance of the tool grasping hand. Surprisingly, no area showed such a pattern of results. Although there were temporal, parietal and even frontal regions that were engaged above the resting baseline for grasp planning, none of these areas showed greater activity for tools. Therefore, we performed ROI analyses in eleven externally-defined areas to investigate whether or not any of these regions would reveal such a pattern. Because the whole-brain analyses were collapsed across hands, the signal related to exploration, planning and functional grasp of tools and control objects were extracted separately for each hand. Notably, the obtained ROI signals were always referenced to baseline from rest intervals.

Statistical analyses from these externally defined ROIs are presented in Table 2. This table also shows MNI coordinates of peak voxels observed in signal changes in studies from which they are derived (Kroliczak and Frey, 2009; Biduła and Kroliczak, 2015; Hutchison et al., 2015; Kubiak and Kroliczak, 2016; Marangon et al., 2016).

The goal of these ROI analyses was to show the direction and amplitude of (%) signal changes in all main study condition relative to resting baseline with the emphasis on task, object, and hand effects. Out of the eleven regions tested here, six of them (i.e., cMTG, SMG, SPL, PMv, PMd, rMFG) are typically linked to PRN (Frey, 2008). Consistent with their putative roles in planning tool related actions, cMTG, SMG and rMFG showed significantly greater activity in grasp planning (at least when compared to exploration). However, similarly to the whole-brain analysis, none of them showed greater activity for tools. Nearly the opposite pattern of results was observed in PMv and PMd, wherein planning-related activity was significantly lower as compared to exploration and grasping. Only in the latter two tasks the activity for tools was significantly higher than for control objects. SPL showed the least expected pattern of activity and it was such that there was a gradual decrease of activity from exploration through grasping, with the latter being significantly lower than exploration- and planning-related activity. A significant decrease of activity from exploration to grasp planning and execution was also observed in PMd. Yet, consistently with earlier ROIs (except for grasping in cMTG), both during exploration and grasping tool-related activity was significantly higher than the one for control objects. More details on ROI analyses can be found in the Supplemental materials.

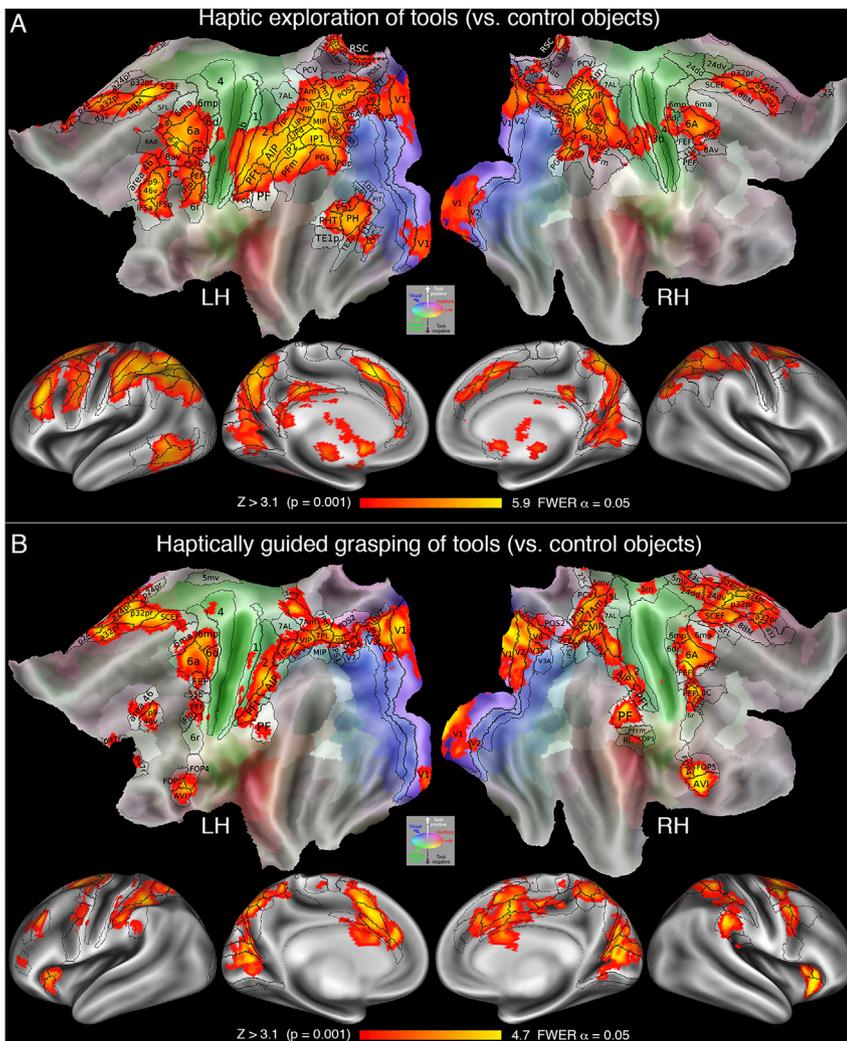


Fig. 3. The key results mapped onto flattened and very inflated cortical surfaces from the Connectome Workbench software. (A) Neural activity associated with haptic exploration of tools vs. control objects. (B) Neural activity associated with haptically guided functional grasping of tools vs. control objects. The most relevant functional areas and their borders/parcellations identified and delineated by Glasser et al. (2016) are shown. Color codes on the flat maps indicate the extent to which a given area (at rest) is associated with certain kind of processing, as illustrated in the legend in the middle.

4. Discussion

In this three-stage haptic paradigm, we examined the patterns of neural activity associated with manual exploration of real functional (tool) and non-functional (control) objects, a delay interval for grasp planning, and subsequent execution of functional and control grasps of tools and non-tools, respectively. First and foremost, regardless of the hands utilized by our right-handed participants for manual exploration of the unseen stimuli, a widespread, predominantly left-hemispheric temporo-occipital and parieto-frontal network of regions, encompassing major areas of PRN (Kroliczak and Frey, 2009), was engaged more for familiarization with tools, their orientations, and locations of their graspable parts. During processing of this information, areas from ventral and dorsal pathways were activated, in particular the left temporo-occipital regions, left IPS and left aSMG/PfT (along with weaker contribution from the left mid SMG), that is regions and areas typically associated with human tool use (Goldenberg and Spatt, 2009; Orban and Caruana, 2014). The greater increases in neural activity observed during haptic exploration of tools vs. control objects were neither maintained nor invoked elsewhere in the brain during a delay interval, putatively devoted to grasp planning. Furthermore, but also consistent with our hypothesis, cortical areas invoked more in subsequent execution of functional grasps of tools were typically located within the confines of regions that were previously engaged more for tool exploration (Singhal et al., 2013). Yet, again, even the areas that displayed similar increases of activity common for tool exploration and grasping, that is numerous

subdivisions of SPL, rostral IPL and/or premotor cortices, did not show selectivity for tools during the grasp planning phase. Finally, our study also corroborates that the dorso-dorsal streams of neural processing play a pivotal role in online monitoring of object position, distance, and orientation (Jeannerod, 1988), or the so-called variable affordances (Borghi and Riggio, 2015), for the adjustment of the grasping hand.

4.1. Haptic object exploration

Consistent with the existing work on haptic shape processing and object perception (Amedi et al., 2001; Amedi et al., 2002; James et al., 2002; James et al., 2007; Reed et al., 2005; Lucan et al., 2010; see also Debowska et al., 2016; Gurtubay-Antolin et al., 2018), when our participants haptically explored tools with a view to later functional grasping, in addition to bilateral involvement of somatosensory and superior parieto-frontal cortices, we observed predominantly or exclusively left-lateralized activity in inferior parieto-frontal and occipito-temporal regions. Interestingly, more in-depth ROI analyses demonstrated that, when compared to other phases, only two dorso-dorsal regions, namely the left SPL and PMd, showed the highest activity during tool exploration and its significant decrease in subsequent two phases (planning and grasping). This characteristic engagement of left SPL is in line with studies showing that more superior subdivisions of the parietal lobe are involved in haptic object localization (Reed et al., 2005) and discrimination (cf. Binkofski et al., 1999). Yet, as the goal of the exploratory finger movements was a preparation for later grasping (and not only

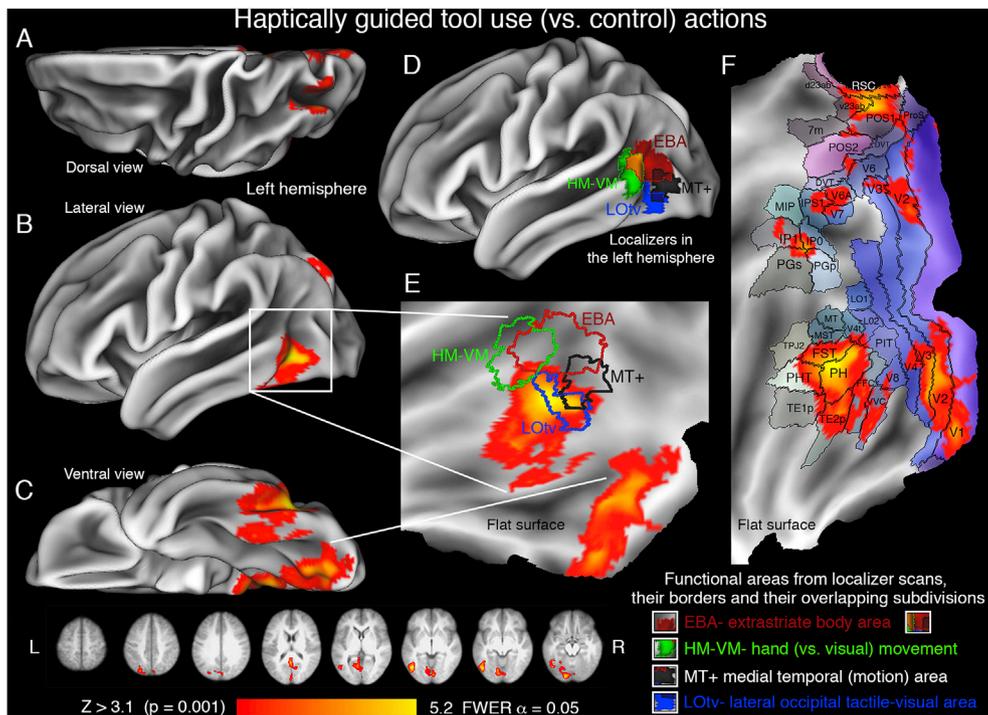


Fig. 4. Significant brain activity from “Haptic Tool Use Localizer” (HTUL), as revealed by a contrast of haptic tool use actions vs. arbitrary hand movements with non-tools, averaged across hands. (A–C) Dorsal, lateral, and ventral views of the left hemisphere. As can be seen in these panels, and the associated inset, in addition to the superior parieto-occipital cortex and ventro-medial visual regions, haptic tool use revealed a large, left-lateralized cluster of activity in the occipito-temporal cortex. (D) The borders and locations of activity from the localizer tasks. (E) The temporo-occipital cluster shown on a flat map, and enlarged. The borders of functional areas obtained in other localizers from our laboratory are also overlaid. EBA – extrastriate body area; MT+ – visual motion-sensitive complex; LOtv – lateral-occipital tactile-visual area; HM-VM – an area delineated by a hand movement vs. visual movement contrast. (F) HTUL activity mapped onto flattened cortical surface, and visualized against the background of the most relevant functional areas and their borders from the Connectome Workbench multi-modal parcellation. FWER = family-wise error rate.

encoding of object identity) the greater bilateral engagement of SPL in tool exploration can be associated with locating and extracting spatial coordinates for the upcoming function-appropriate grasp of a tool. As the latter act also requires a suitable task-response association and maintenance of prospective action sequence, the additional greater engagement of PMd in tool exploration (as compared to other phases) is not surprising, either (Cross et al., 2017). After all, PMd belongs to the dorso-dorsal stream which is thought to be responsible for on-line control of actions (Rizzolatti and Matelli, 2003; Galletti and Fattori, 2018), though in the case of tool exploration there is no need for any moment-to-moment control but a mere preparation for performance of a subsequent grasp. Its proper encoding will critically depend on processing of the so-called variable affordances, that is transient object characteristics, including here changes of orientation in space, that will require appropriate adjustments of hand posture (Sakreida et al., 2016). Indeed, whereas one of the functions of the neighboring medio-dorsal regions is to determine the orientation of the graspable part of a tool and its egocentric relation to the used hand, PMd may play a greater role in prospective encoding of the upcoming grasp.

Despite the importance of the dorso-dorsal processing in tool-directed actions, of most interest is the neural activity in three more ventrally-located regions: a set of areas belonging to the left IPS, aSMG, and the left temporo-occipital region. In fact, it is the interplay between these areas that seems to be most critical for preparation of the haptically guided functional grasps of tools. Similarly to its involvement in visually guided actions, haptic information processing within the intraparietal sulcus is also associated with encoding of object shape and orientation (Sathian, 2016). Not surprisingly, then, and consistent with the existence of motor-dominant neurons in this vicinity (Murata et al., 2000), the intraparietal sulcus is a region responsible for manual affordance encoding (Buccino et al., 2004), including the ones for tools (Vingerhoets, 2014). Once a global object shape and local orientation of its parts is established, IPS processing may give pointers as to which potential grasp type is most optimal. Affordance processing is crucial for grip performance and the involvement of IPS in grasp preparation is not unexpected (Mruczek et al., 2013; Reynaud et al., 2016), even in the haptic domain. Yet, neither the dorso-dorsal processing stream discussed above nor IPS alone is capable of extracting and/or guiding the most optimal

grasp contingent on function of a tool someone is interacting with.

There is convincing evidence that the temporo-occipital region, in particular cMTG, plays such a key role, and its involvement was quite pronounced during exploration of tools. In fact, this effect was clearly corroborated by the outcomes of the ROI analyses. As cMTG is linked to storage of conceptual knowledge related to tools, their functions and/or their use, as well as the postural (i.e., grip) aspects of the guided hand (e.g., Heilman et al., 1982; Rothi et al., 1991; Buxbaum, 2001; Buxbaum et al., 2014; see also Chao et al., 1999; Krolczak and Frey, 2009; Przybylski and Krolczak, 2017; and the result of our Haptic Tool Use Localizer), its contribution to haptic guidance of the exploring hands towards graspable and functional parts of tools must be critical. Yet, it will not do without a support from the nearby LOtv. Although this vicinity was previously associated with visual processing of object shape, there is also convincing evidence for its involvement in haptic shape processing (Amedi et al., 2001; Sathian, 2016). Here, we also observed that haptic exploration of tools invoked a rather large temporo-occipital cluster encompassing both cMTG and LOtv, with the latter known as bimodal (tactile and visual) and perhaps even playing a role in visualization of the haptically explored shapes of tools. Thus, these temporo-occipital subdivisions are in a position to encode/retrieve grasp-related parts of tools, namely their handles, and to target them for future transformations necessary for grasp performance (c.f., Mahon et al., 2007; Mruczek et al., 2013; Vingerhoets et al., 2013).

The LOtv/cMTG ventral-stream complex, while providing allocentric inputs on shape/function associations, would not suffice for the preparation of functional grasps. Indeed, its contribution needs to be orchestrated with inputs from IPS. Because of massive engagement of SPL in haptic object exploration, a small area with such a putative function, namely aSMG/PfT, might be easily overlooked. Yet, earlier research clearly points to aSMG/PfT as the core region for the integration of signals coming from the parietal and temporal cortex (Orban and Caruana, 2014), and its role in planning tool-related actions (Reynaud et al., 2016). It is tempting to speculate that the greater involvement of this area in haptic exploration of tools plays a preliminary role in planning subsequent performance of functional grasp.

Finally, the most unexpected result – in contrast to most studies on tool-related actions in the visual domain – is much weaker engagement of

Table 2

Regions of interest (see method section for their sources), MNI coordinates of their peak voxels, their Z values, and the results of statistical analyses.

Region	MNI coordinates			Peak Z value	Main Effect of Hand (right, left)	Main Effect of Task (exploration, plan, grasp)	Main Effect of Object (tool, control)	Interactions
	x	y	z					
Left cMTG	-58	-48	4	3.35	***	***	0.9	H x T *** T x O * H x T x O **
Left LOTv	-53	-72	-5	3.09	**	**	**	H x T **
Left MT+	-46	-78	2	7.12	*	0.6	*	H x O trend p = 0.09 T x O ** H x T x O **
Left EBA	-48	-70	12	5.72	**	0.16	0.6	H x T * H x O ** T x O **
Left SPL	-16	-78	50	n.a.	0.38	**	***	H x T trend p = 0.1 H x O *
Left SMG	-54	-32	50	7.2	***	***	*	T x O *** H x T ***
Left aIPS	-32	-49	29	3.90	***	0.17	***	T x O * H x T *** H x O *
Left PMv	-57	10	23	3.18	***	**	*	T x O *** H x T *** H x O **
Left PMd	-28	-10	50	4.92	***	***	***	T x O * H x T *** H x O **
Left rMFG	-38	39	13	3.60	***	**	*	T x O ** H x T *** H x O *
Left Insula	-32	20	0	5.9	***	0.11	***	T x O ** H x T x O ** H x T *** H x O *** T x O * H x T x O trend p = 0.06

Four regions – cMTG, SMG, rMFG and EBA – showed increases of planning related activity (although in EBA this effect was barely at a trend level). Although all these regions showed greater activity for the left hand, this effect was driven primarily by differences in exploration (and in cMTG and rMFG in grasping). Except for EBA, exploration-related activity was always higher for tools. Four other regions – PMv, PMd, aIPS and MT + - showed decreases of planning related activity (although in MT + at a trend level). Yet, aIPS showed this effect only for tools. As before, all these regions showed greater activity for the left hand, although in aIPS there was no difference between hands during grasping, and in PMd during grasp planning. Again, in all these regions the activity for tools was higher than control objects but only in exploration and grasping. In sharp contrast, SPL and LOTv showed gradual decreases of activity through planning to grasping, with the latter being always significantly lower than exploration. While in LOTv there was still a familiar effect of hand (with activity for the left hand higher, except for grasping), in SPL there was no difference between hands whatsoever. Both regions showed greater activity for tools during exploration, yet SPL also for grasping. The most unexpected were signal modulations discerned in the anterior Insula. There were gradual increases, with the highest activity for grasping, but with the left hand always showing a rather steady higher level, yet again with tool-related activity being higher during exploration and grasping. More detailed descriptions of these analyses can be found in supplemental materials. Asterisks indicate a significant difference with p-value of 0.05 (*), 0.01 (**), or 0.001 (***). H – hand, T – task, O – object.

IPL subdivision dubbed mid SMG/PF, as this region is considered to be fundamental for tool related action preparation and performance, including the global organization of movement kinematics (Heilman et al., 1982; Rothi et al., 1991; Buxbaum, 2001; Buxbaum et al., 2014; see also Krolczak and Frey, 2009; Potok et al., 2019). Nevertheless, a recent meta-analysis of studies on praxis skills suggests that mid SMG/PF should be involved more in tool use tasks, implemented on the basis of mechanical knowledge stored in this vicinity (Osiurak, 2014; Reynaud et al., 2016; see also Osiurak and Heinke, 2018). Because in our study tool-related actions were limited only to the performance of functional grasps, without any further tool manipulation, whether real or pantomimed, weaker contribution of mid SMG/PF mechanisms to haptic exploration of tools (in fact none of its more inferior subdivisions) is consistent with previous knowledge on its function.

4.2. Grasp planning

Although none of the PRN areas that showed greater activity for tools in the exploration phase maintained or regained its higher signal in a delay interval devoted to grasp planning, a wide network of regions outside of PRN demonstrated the inverse pattern of activity. Namely, during planning of grasps for non-tools, a widespread network of areas

that included components of the default mode network (DMN; Raichle, 2015) was revealed. Such a pattern of results may indicate that DMN and its immediate vicinities, as well as sensorimotor regions, were also less inhibited for non-tools during the exploration phase and these differences were then reflected in a delay interval. Interestingly, even the neighboring “task positive” regions such as cMTG, PMv, and MFG (Spreng et al., 2010; Glasser et al., 2016) responded consistently and, in the grasp-planning phase, showed greater increases of activity in the control task (although revealed only by our ROI analyses). Notably, the substantial overlap of (and little between-task differences for) the temporo-occipital and inferior parietal cortices, i.e., their similar engagement above baseline in planning both kinds of grasps, goes against an interpretation of tool-specific control of skilled hand postures and kinematics exerted by these regions in the absence of overt movements (cf. Buxbaum et al., 2014; Osiurak and Badets, 2017).

4.3. Haptically guided grasp execution

Consistent with a plethora of earlier studies on delayed manual actions, including grasping (e.g., Fiehler et al., 2011; Singhal et al., 2013), and partly corroborating our results obtained in the haptic exploration phase, the execution of haptically guided functional grasps of tools was

associated with greater bilateral engagement of the medial and superior lateral (dorso-dorsal) parieto-frontal regions typically considered as the seat of essential motor control (Jeannerod, 1988; Milner and Goodale, 1993; see also Kroliczak et al., 2008; Monaco et al., 2015). Even though no visual feedback was present, there was also substantial bilateral involvement of early visual cortices (suggesting a role of visual imagery, Singhal et al., 2013) and aIC, which has been previously linked to grasping tasks as well (Fink et al., 1997; Kroliczak et al., 2007; Mutschler et al., 2009; see also Kurth et al., 2010).

Counter to earlier studies showing contributions from the occipito-temporal cortices in guidance of actions involving tools (Garcea and Mahon, 2014; Buchwald et al., 2018), we did not observe any engagement of cMTG during functional grasps. Furthermore, there was little engagement of left IPL, except for very inferior section of area PF, but similar to the exploration phase involvement of area Pft. Finally, the clusters of activity in the parieto-frontal cortices were much smaller, as compared to neural activity during the preceding haptic exploration phase. One could even argue that, similarly to the planning phase, these outcomes are consistent with the reasoning-based approach, which suggests that selection, programming, and execution of motor acts linking the hand and tool depends more on the SPL/IPS processing, that is, a network invoked irrespective of the task (e.g., Osiurak and Heinke, 2018; see also our comments on orientation processing). In agreement with this notion, the engagement of cMTG is not critical because grasp execution does not require explicit thinking about the whole tool, its properties and function. Instead, for an effective grip, directing the hand towards the preselected grasp points would be sufficient for the appropriate control of grip kinematics (Goodale et al., 1994). The observed weaker engagement of PRN during grasp execution, as compared to its involvement in tool exploration, is also consistent with earlier findings by Przybylski and Kroliczak (2017), who demonstrated that PRN contributes more to planning of functional grasp than to the actual grasp execution. We can speculate that a more global processing of a given tool (e.g., the identification of its affordances; Osiurak et al., 2017) and subsequent focus on its handle has been already achieved during haptic exploration and was a foundation for the extraction of relevant target points on the graspable part of a tool.

Closer inspection of results from a contrast of cortical activity observed during grasping rotated and non-rotated tools, and their comparison with the above-mentioned findings, strengthens such an interpretation of our results because it is also consistent with the literature on functions of the dorso-dorsal parieto-frontal neural pathways (Rizzolatti and Matelli, 2003). One of the dorso-dorsal streams, starting from the parieto-occipital area V6/V6A and projecting indirectly, via MIP, or directly to PMd, is functionally linked to online control of actions (Binkofski and Buxbaum, 2013) regardless of object type. It is a key pathway for processing of inputs on grasp-relevant features of target objects one is currently acting on (Johnson and Grafton, 2003) and their transformations into appropriate motor hand response (Marangon et al., 2016). Both the activity that underlies grasping tools vs. control objects and grasping rotated vs. non-rotated tools revealed bilateral signal increases in critical nodes of the dorso-dorsal stream, in particular aSPL and PMd. Because the latter contrast comprised of tools on both sides of the compared neural activity, the revealed significant differences – in particular the ones which happen to overlap with the activity demonstrated by the execution of tool-related vs. control grasp – can only be associated with processing that is not tool specific. Namely, the observed clusters of activity can be linked to egocentric transformations necessary for the requisite hand rotation and/or increased spatial attention required for the appropriate orientation of the grasping hand (Astafiev et al., 2003; see also Goodale et al., 2005; Binkofski and Buxbaum, 2013). Indeed, the processing of object orientation in space is one of the critical computations for resolving the problem of variable affordances, that is temporary object characteristics that define current state of the object, and are computed for action control in these superior parieto-frontal nodes (Sakreida et al., 2016).

While the overlap of activity discussed above revealed transformations of neural signals that are not tool specific, the remaining ventro-dorsal signal changes must have closer affinity to the processing of invariant tool characteristics, such as shape, size, or even function, often referred to as stable affordances (Borghi et al., 2012; Binkofski and Buxbaum, 2013). Specifically, the ventro-dorsal clusters, in particular aSMG/Pft accompanied by aIPS, while encoding action goals and detailed movement kinematics, respectively, must incorporate stored knowledge on tools (from cMTG inputs) with haptically derived object structure and orientation (from V6/V6A and caudal IPS) for specification of tool-appropriate grip. The subsequent transformations of these inputs require further elaboration within PMv, which contributes to encoding of proper motor programs, with the inclusion of stored information on previous similar actions with tools and their contexts provided by rMFG (Kroliczak et al., 2008). Yet, it is quite surprising that the observed ventro-dorsal activity did not include the same mid-to-posterior subdivisions of SMG that were involved more in tool exploration, namely the superior section of area PF, and Pfm. The lack of their involvement is nevertheless consistent with the notion that they play a pivotal role in tool manipulation rather than its prerequisite, a functional grasp of a tool, or in processing inputs on tool semantics (Reynaud et al., 2016).

Finally, the results of ROI analyses also revealed that the left aIC was predominantly involved in haptic guidance of functional tool grasp. This comes as no surprise as insular engagement is consistent with earlier results which linked object grasping to this region (Fink et al., 1997; Kroliczak et al., 2007; Mutschler et al., 2009). Although in this study the insular activity was linked more to functional grasps, it cannot be a core region associated with praxis skills because its greater engagement for tools was observed neither during the exploration nor the planning phase.

4.4. Limitations of the study

Although our paradigm included a variable time interval that we hoped would be devoted for grasp planning, the analyses of neural activity preceding grasp execution suggest that it was merely treated as a simple delay period. Specifically, the higher activity for tools from the exploration phase subsided to the levels comparable to control objects, and we also observed some increases of activity in regions typically associated with resting state. Yet, it should be added that in the core regions of the “task positive” network the neural signals were clearly above the resting baseline. The second, though related, limitation is such that participants always explored the objects with a view to grasping them. The introduction of information on a required target-directed response, including grasping, reaching, pointing, or no-go task following the haptic exploration phase, could be not only more efficient in triggering planning-related activity but could also allow for an easier differentiation of task-related signals. By the same token, the interval devoted for the execution of the just planned response should be elongated to make it easier to disentangle neural responses associated with these additional tasks.

5. Conclusions

First, our study shows that haptic exploration and haptically guided grasping of tools engages the majority of areas linked to the temporoparieto-frontal praxis representation network, which is typically associated with processing of information related to tool-oriented actions. While this may sound obvious, the involvement of PRN in tool exploration and grasping has never been demonstrated in a haptic domain. This in turn suggests that PRN operates on modality-independent inputs. Second, the results of our study also demonstrate that during haptic exploration some preliminary planning of subsequent target-directed responses takes place and, indeed, it resembles visual affordance processing although achieved more gradually in a haptic domain. Last but not least, a functional grasp of a tool is based on integration of conceptual

tool knowledge with processing of structural tool features which starts as early as during haptic exploration, and is performed and then maintained by the anterior supramarginal gyrus. Our study convincingly shows that this inferior parietal area can efficiently guide the control of a functional grasp even in the absence of continuous inputs from the temporal regions involved in conceptual processing of tools.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.neuroimage.2019.03.043>.

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