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Characterizing Tool-Selective Areas With Human Neuroimaging

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Abstract

Humans, unlike any other species, use tools to achieve complex goals. New Caledonian Crows, among the best of avian tool-makers, use twigs to retrieve food in crevices, and veined octopuses use coconut shells as shelters. Humans, however, go above and beyond these simple behaviours. Even when compared to orders that are evolutionarily closest to humans such as non-human primates, tool use is indisputably more advanced in humans. Conventionally, neuroimaging researchers who have studied complex tool use in humans do so by presenting pictures of tools and measuring the brain activity evoked by actions potentiated by the tools. This method has revealed tool-selective regions that activate in response to *pictures* of tools but, critically, also activate in response to *real actions* with *real tools*. Though there is overlap between regions that respond to both pictures of tools and to real tool use, it is unclear whether tool pictures are indeed an effective proxy for real tool use. In light of this, the overarching goals of this thesis were, 1) from a methodological perspective, to determine whether different proxies for studying tool use are more effective than using *pictures* but less technically challenging than using *real actions* on *real tools*; and 2) from a theoretical perspective, to determine what these proxies can reveal about tool-related processing, particularly in brain regions involved in visuomotor control. In sum, the results from this thesis revealed, 1) that presenting videos of familiar tool actions is an optimal proxy to study tool use, and 2) that tool-selective regions are areas selective for actions afforded by tools, for the characteristic motion associated with tools, and for familiar tools of which functional associations are well-established. Taken together, this thesis offers support to the notion that tool-selective regions process information with the purpose of predicting upcoming actions and reasoning possible ways to use a tool to interact with a target. In agreement with the affordance perspective, tool-selective regions do so even when there is no intent to act on a tool.

Keywords

Visuomotor, Action, Tool, Non-Tool, Hand, Action Observation, Real Object, Familiar, Unfamiliar, fMRI, Localizer, Affordance, Motion, Video, Picture, Elongation

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List of Abbreviations

ACPC	Anterior Commissure Posterior Commissure plane
aIPS	Anterior Intraparietal Sulcus
aLOTC	Anterior Lateral Occipitotemporal Cortex
aSMG	Anterior Supramarginal Gyrus
aSPL	Anterior Superior Parietal Lobule
BA	Brodmann Area
BET	Brain Extraction Tool
BOLD	Blood-Oxygen-Level Dependent
CDT	Cluster Determining Threshold
CFS	Continuous Flash Suppression
EPI	Echo-Planar Imaging
FA	Flip Angle
FEAT	FMRIB's Expert Analysis Tool
FILM	FMRIB's Improved Linear Model
FLAME	FMRIB's Local Analysis of Main Effects
FLIRT	FMRIB's Linear Image Registration Tool
fMRI	Functional Magnetic Resonance Imaging
FNIRT	FMRIB's Non-Linear Registration Tool
FSL	FMRIB Software Library
FWHM	Full-Width Half-Maximum
FMRIB	Oxford Centre for Functional Magnetic Resonance Imaging of the Brain
GLM	General Linear Model
ITI	Inter-Trial Interval
iPAT	Integrated Parallel Imaging Techniques acceleration factor
IPS	Intraparietal Sulcus
MB4	Multi-band Slice Acceleration 4
MB6	Multi-band Slice Acceleration 6
MNI	Montreal Neurological Institute (stereotaxic space)
MRI	Magnetic Resonance Imaging
MT+	Middle Temporal Motion Complex
MTG	Middle Temporal Gyrus
LED	Light-Emitting Diode
LOC	Lateral Occipital Cortex
LOTC	Lateral Occipitotemporal Cortex
pLOTC	Posterior Lateral Occipitotemporal Cortex
PMd	Dorsal Premotor Area
PMv	Ventral Premotor Area
PPC	Posterior Parietal Cortex
ROI	Region of Interest

RFX	Random Effects Group Analysis
SMA	Supplementary Motor Area
SPL	Superior Parietal Lobule
T	Tesla
TE	Time to Echo
TR	Repetition Time

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Chapter 1

1 General Introduction

1.1 Complex tool use: A defining characteristic of humans

Humans, unlike any other species, use tools to achieve complex goals (Frey, 2007). New Caledonian Crows, known to be the best among of avian tool-makers, use twigs to retrieve food in crevices (Kenward et al., 2006), while veined octopuses have been known to use coconut shells as shelters (Finn, Tregenza, & Norman, 2009). Humans, however, go above and beyond these simple behaviours. Our hominid ancestors joined stone and wood together to form tools with the aim of accomplishing specific goals such as crafting spears. Tellingly, humans formed and used tools that did more than simply extend the function and range of their arms and hand; they formed tools such as knives and chisels to cut and carve, thus enabling functions that could not be accomplished with their bodies alone. In doing so, humans have set themselves apart from species like the crow and octopus who can only use tools to improve actions that they can already perform.

The breadth in the tools that humans can use is part of what sets our species apart from others. Thus, being able to define distinct classes of tools is critical to convey the human advantage in using tools that are more complex than twigs and shells. The Oxford Dictionary defines a tool as “device or implement, especially one held in the hand, used to carry out a particular function: [as in] *gardening tools*.” (Oxford Dictionaries, 2017). A more effective approach for cognitive neuroscientists in classifying an object as a tool may be to consider what factors can differentiate tools from other objects such as semantic, mechanical (e.g., leverage, torque, etc.), and functional properties. The semantic knowledge of a hammer, for instance, would be knowledge that it is often used to pound nails in a workshop, home, or construction site. The mechanical properties, based on the elongation of the handle and composition of the functional end, would enable someone who had never seen a hammer before to deduce that it would provide leverage, heft, and a firm surface for pounding. Comparatively, the functional knowledge of a hammer would be knowledge of the kinematics required to operate it (e.g., grasped at the base of its handle with a power grip and swung with a particular action). Although these three properties often co-occur, they can be dissociated by context. For example, a hammer has all three properties; however, when camping in the absence of a hammer, one might deduce from mechanical properties that a shoe, not normally considered a tool, would suffice to pound in a tent peg. By describing objects using these three properties, they can be placed on a spectrum of “toolness” whereby objects can range from simple to complex tools. On one end of the spectrum, there are simple tools that are akin to twigs and rocks that extend the mechanical capabilities of upper limbs to amplify basic functions such as reach, leverage, or torque (Frey, 2007). On the other end of the spectrum, there are complex tools (e.g., a hammer) which, in comparison to simple tools, typically require semantic and functional knowledge to operate. Simple tools often have minimal semantic and functional properties whereas complex tools are frequently used to perform actions that are qualitatively different than actions possible with the hand (Frey, 2007).

Humans can use both complex and simple tools, but orders that are closest to humans from an evolutionary perspective, such as non-human primates, almost exclusively use simple tools (Vaesen, 2012). In part, this is because human tool use is more sophisticated in terms of its eye-hand coordination, causal reasoning, and social learning (Vaesen, 2012). The human brain has evolved to solve complex problems using tools facilitated by an advanced ability to reason (Osiurak, Jarry, & Le Gall, 2010). Though non-human primates demonstrate an aptitude for tool use and simple reasoning relative to other species, like the crow or the octopus, non-human primates cannot reason and learn at the level of humans (Vaesen, 2012). The human advantage in tool use is likely driven by differences in brain structure as well as in brain function between humans and other species. Complex tool use in humans is associated with an increase in overall brain size relative to the rest of the body. Moreover, compared to other non-human primates, humans show considerable expansion in association areas of the brain that are distinct from basic sensory and motor regions (Buckner & Krienen, 2013). For example, regions of posterior parietal cortex (PPC), which are implicated in tool use, show a 30-fold expansion compared to the macaque monkey. In stark contrast, sensory and motor areas are comparable between both macaques and humans (Van Essen & Dierker, 2007). It has even been proposed that there is no homologue in the non-human primate brain for certain human brain areas that are critical for complex tool use (Peeters et al., 2009). Further, where there exist putative homologues for tool-processing in brain areas between both orders, the brain areas appear to serve more cognitively advanced functions in humans than in non-human primates (Kastner, Chen, Jeong, & Mruczek, 2017). As such, researchers interested in the neural correlates of tool use have focused on the expanded association areas (including putative homologues) in the human brain to better understand why humans are unparalleled in tool use relative to other species.

In particular, researchers have given special consideration to association areas and putative homologues in the *left* hemisphere of the brain. Reports on neuropsychological patients who cannot properly use tools, such as patients with apraxia, have revealed that the left hemisphere is specialized for tool use (e.g., Buxbaum, Shapiro, & Coslett, 2014). Lesions in the left parietal cortex have revealed a principle of spatial organization that guide the topography of association areas. This principle is the basis for the theory of action mentalization-to-execution whereby *posterior* regions of parietal cortex plan an action before *anterior* regions carry it out (Goldenberg, 2009). Evidence from patients with apraxia corroborate this theory as these patients can show profound dissociations between *knowing how* to use a tool and *being able to perform* an action with a tool (Frey, 2004). For instance, patients with ideational apraxia, due to lesions in the left PPC, can accurately perform actions with a tool but do so in improper contexts suggesting a conceptual deficit related to tool use. For example, one patient with ideational apraxia reportedly attempted to eat food with a toothbrush and brush their teeth with a comb or spoon when foils were presented with the appropriate tool (Ochipa, Rothi, & Heilman, 1989). In comparison, patients with ideomotor apraxia, due to lesions more *anterior* than those observed in patients with ideational apraxia, have intact conceptual knowledge of tools but they cannot perform actions from memory. Patients with ideomotor apraxia demonstrate greater deficits in pantomiming tool actions (i.e., imitating tool actions without holding the tool) relative to performing that same action with the tool in hand (Frey, 2004). Crucially, patients with ideomotor apraxia are only impaired when pantomiming in response to *familiar* tools but can still infer function from the structure of novel tools. This suggests that their impairment lies in inferring function from memory and not from inferring function from the structure (Buxbaum, Sirigu, Schwartz, & Klatzky, 2003).

1.2 What happens when you *see* a tool?

With the advent of functional magnetic resonance imaging (fMRI), it has become possible to probe the function of these left-lateralized areas involved in tool processing to understand how the cortical expansion in these areas has set us apart from other species.

Conventionally, to study tool use in humans using fMRI, researchers have presented healthy participants with *pictures* of tools and measured the brain activity evoked by the "affordances" of the tools. Affordances are implicit cues about both the function of the tool as well as cues about the appropriate grasp required to use the tool. A Gibsonian perspective argues that affordances are evoked automatically and that they exist for all objects in the visual field (Gibson, 1977). According to this perspective, even the ground affords information about its potential for action through cues such as stability and texture. In the case of affordances evoked by tools, function can be inferred for instance by the protrusion of a handle as well as the weight of its functional end. For example, the configuration of a hammer's handle and functional end (e.g., the peen) affords the opportunity to pound a nail into wood more so than the configuration of a screwdriver. Importantly, affordances are distinct from "associations" which are related to the semantic memory of a tool and which can only exist for *familiar* tools (Goldenberg & Hagmann, 1998). Affordances, in contrast to associations, provide the potential to use an *unfamiliar* tool or to use a familiar tool in a novel way (e.g., using the heel of a shoe to pound a nail).

Affordances can be better understood by distinguishing between a structural affordance and a functional affordance (Jax & Buxbaum, 2010). The functional affordance of a hammer cues that its peen, a sturdy and blunt bit, is well-suited to pound a nail. The structural affordance of a hammer, on the other hand, cues the appropriate grasp to manipulate the hammer's handle. For the hammer, its most salient structural cues are its protruding handle and heavier weight at its functional end. Without any prior knowledge of the hammer’s function, one could in theory deduce the proper way to grasp the handle to pound a nail from structural cues alone.

The distinction between a structural and functional affordance is made clear when considering how the two are dissociated in “conflict” tools. Conflict tools are a class of tools that afford different actions depending on whether the tool is used or simply held. Calculators, for instance, are processed differently by the visuomotor system depending on whether the actor’s intention is to simply hold them or to press their buttons (Jax & Buxbaum, 2010). Broadly speaking, this distinction exists for all tools as different grasps are typically adopted for *using* a tool and *moving* a tool. While moving a tool requires only evaluation of rudimentary factors such as determining its center of mass, using a tool requires additional processing such as assessing the interaction between the tool and its target (Valyear et al., 2011; Brandi et al., 2014; Squires et al., 2016). In sum, different types of affordances can be evoked by the visual cues of a tool (i.e., a functional or structural affordance) as well as the goal of manipulating a tool (e.g., hold, move, or use).

One seminal behavioural study in particular has ushered in many follow-up experiments and propelled research on tool affordances. Tucker and Ellis (1998) asked participants to make left- or right-hand button presses in response to pictures of tools in which the tool handles were directed towards or away the from the responding hand. Critically, the direction of the handle was unrelated to the task which was to indicate whether the tool was upright or inverted. Their results revealed that when the tool’s handle was directed *towards* the responding hand (as opposed to *away* from it) the participants were faster at initiating a response with that hand. Adopting a Gibsonian perspective, the authors argued that the tool’s handle, even though an irrelevant feature for the task, primed a response with the hand that it was directed towards. This stimulus-response compatibility effect has also been observed using pictures of tools that require different grasp types (e.g., precision vs. power grip; Tucker & Ellis, 2010) and even when responses are made with the feet instead of the hands (Symes, Ellis, & Tucker, 2005). Unfortunately, a lack of replicability and specificity of this effect has challenged the validity of this seminal paper (see Cho & Proctor, 2010 and Wilf, Holmes, & Makin, 2013). Opponents of the affordance perspective propose that effects of stimulus-response compatibility driven by attention (e.g., the Simon effect) are difficult to disentangle from effects driven by affordances. Alternatively, the opponents of the affordance perspective argue that actions are planned immediately before their execution (Cant et al., 2005). In other words, they suggest that the visuomotor system cannot be primed by the mere presentation of a picture of a tool.

Despite the short-comings of the seminal Tucker and Ellis (1998) study, follow-up experiments nevertheless provide convincing evidence that presenting pictures of tools can indeed evoke affordances. Witt et al. (2010), for instance, showed that affordances evoked from a picture of a tool can interfere with the latency of naming a tool if that tool's handle is directed towards a hand occupied with another object. This affordance effect was not apparent when pictures of animals were presented with their heads or tails directed towards or away from the occupied hand, challenging the notion that affordances can be explained solely by attention.

In addition to this, pictures of tools have also revealed an area in the visual field where affordances are most salient. Right-handed participants are faster to recognize pictures of tools as compared to pictures of non-tools when the tools are presented in the participants' right visual fields; Comparatively, this advantage is not present when the tools are presented in the left visual field (Handy, Grafton, Shroff, Ketay, & Gazzaniga, 2003; Verma & Brysbaert, 2011). This result is in agreement with neuroimaging studies demonstrating that certain visuomotor areas activate most strongly to real objects in the lower-right visual field relative to left or upper visual fields (Gallivan, Cavina-Pratesi, & Culham, 2009; Rossit, McAdam, Mclean, Goodale, & Culham, 2013). These studies demonstrate that affordances evoked by pictures of tools as well as real objects are most salient in the preferred acting space of right-handed individuals.

Tellingly, neuroimaging studies using pictures of tools have also supported the notion that pictures of tools evoke similar affordances as real tools. For example, passively-viewing pictures of tools has been shown to recruit a network of regions that is also activated when a real tool is used (Lewis, 2006; Brandi et al., 2014; Gallivan et al., 2013). As with lesions that cause apraxia (Frey, 2004), many of these tool-selective areas are lateralized to the left hemisphere. As the affordance perspective would predict, tool-selective regions are responsive to changes in the orientation of tools (Valyear et al., 2006) but not to changes in the orientation of non-graspable objects (Rice et al., 2007). The orientation of a tool is a relevant cue for areas that guide actions with tools whereas the orientation of a non-graspable object is not.

There are, however, alternative explanations that may account for why tools evoke orientation-selective activation whereas non-graspable objects do not. For instance, neurons selective for elongated stimuli, like tools, exist in grasp-selective areas in the non-human primate brain (Sakata et al., 1997). Furthermore, when continuous flash suppression (CFS) is used to putatively isolate processing to certain visuomotor regions, elongated tools and elongated non-tools have been found to be processed similarly (Almeida, Fintzi, & Mahon, 2013). This suggests that the critical factor for tool-selectivity may be elongation as opposed to being a tool. Indeed, there are visuomotor areas that activate more in response to tools than non-tools that also activate more in response to elongated than stubby objects (Chen et al., 2017). That said, elongation is often a diagnostic feature of tools because elongated objects offer mechanical advantages (such as bodily extension, leverage and torque). Tools are often also asymmetric, with a handle and a functional end. In elongated, asymmetrical objects, especially tools, it is important that the orientation of the hand matches the orientation of the tool before a grasp is carried out. Thus, objects with an elongated axis as opposed to symmetrical objects, for instance, are more likely to afford distinct grasps. The debate as to whether the visuomotor system is indeed selective for changes in the orientation of tools relative to the orientation of elongated objects is discussed further in Chapter 2.

1.3 Tool-selective regions

Commonly, neuroimaging researchers have presented pictures of tools to participants to evoke affordances and to activate tool-selective areas (Chao & Martin, 2000; Lewis, 2006). However, recently researchers have also adopted more ecologically valid techniques to achieve the same end. For instance, instead of presenting pictures, researchers have presented real tools (Gallivan et al., 2013; Brandi et al., 2014), had participants perform real actions on real tools (Gallivan et al., 2013; Brandi et al., 2014), or presented videos of actors using tools (Peeters et al., 2009). Presenting pictures is a popular proxy to studying tool use as pictures are available in databases, they are easy to edit, and they are quick to present. Conversely, real tools are difficult to use in fMRI because space is confined in the scanner's bore, stimuli are limited to tools without ferrous metal, and motion artifacts may arise from excessive head movement when real actions are performed. There are, however, benefits to using real tools over pictures. Real objects differentially activate object-selective brain areas as compared to pictures of the real objects (Snow et al., 2011). These differences may arise because the potential for action is more salient with real objects relative to pictures of objects which, of course, cannot be grasped. Even from a young age, humans prefer to examine real objects over pictures of objects likely due to differences in graspability (Gerhard, Culham, & Schwarzer, 2016).

Fortunately, even though real tools and real actions are difficult to use in fMRI experiments, using videos of tool actions may serve as an optimal approach between the artificial method of using pictures of tools and the technically challenging (yet ecologically valid) method of using real tools. Videos of tools have the benefit of displaying an action from start to finish and they demonstrate the interaction between the tool and its target. Furthermore, there is no ambiguity in the goal of a tool presented in a video relative to the goal of tool presented in a picture. The benefits of using videos of tools to study tool-selective regions are discussed further in Chapter 3.

To study tool-selective regions in fMRI, neuroimaging researchers have typically compared the brain activity evoked when a picture of a complex tool is presented to when a picture of a non-tool such as a large object or animal is presented (Chao & Martin, 2000; Lewis, 2006). Such contrasts reveal brain activity selective for a manipulable class of objects that extends (or transforms) the current function of the hands or arms. Tellingly, many tool-selective regions overlap with association areas that showed expansion in the human brain which coincided with advances in human tool use (Buckner & Krienen, 2013).

Tool-selective regions (see Figure 1) span two cortical streams that use vision for two broadly dissociable functions: the dorsal stream (occipito-parietal to motor cortex), which processes “vision for action”, and the ventral stream (occipito-temporal cortex), which processes “vision for perception” (Goodale & Milner, 1992). Tool-selectivity has been observed in dorsal-stream regions such as the dorsal and ventral premotor areas (PMd and PMv, respectively), the superior parietal lobule (SPL), the anterior intraparietal sulcus (aIPS), the anterior supramarginal gyrus (aSMG), and ventral-stream areas such as the posterior part of the lateral occipitotemporal cortex (pLOTC) along the middle temporal gyrus (MTG). Though these regions often co-activate in response to tools, they tend to process different aspects associated with tools (i.e., their mechanical, semantic, and functional properties). The premotor areas (PMd/PMv) are often co-activated when actions with a tool or a hand are performed and these areas are thought to represent semantic information related to goal irrespective of whether a hand or a tool is used. This is the case in both humans (Gallivan et al., 2013) and macaque monkeys (Umiltà et al., 2008). The SPL uses functional information to guide actions on tools currently in the visual field (Rizzolatti & Matelli, 2003). Similarly, aSMG is thought to store functional associations of complex tools (not necessarily in the visual field) and, interestingly, this area has no known primate homologue (Peeters et al., 2009). Lastly, areas such as pLOTC (Bracci, Cavina-Pratesi, Ietswaart, Caramazza, & Peelen, 2012), are likely selective for the semantic information of tools and communicate with functional areas like aIPS which are selective for grasping (Culham et al., 2003).

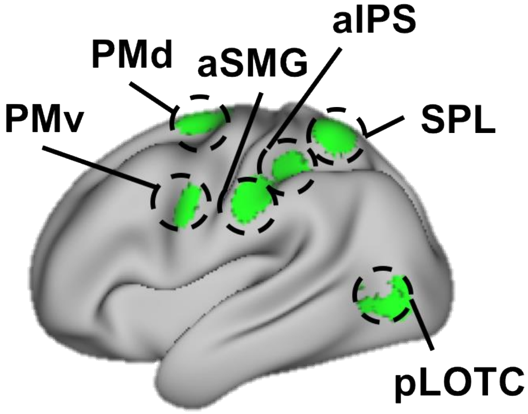


Figure 1. Commonly reported tool-selective regions.

A further functional separation of the dorsal stream into two substreams has also revealed an additional division of labour in tool processing. In this further separation, a dorso-dorsal stream guides the online control of action, while a ventro-dorsal stream subserves space perception and action understanding (Rizzolatti & Matelli, 2003). The dorso-dorsal stream extends from the intraparietal sulcus (IPS), into the SPL, finishing in the PMd. This stream, characterized as the "use system", processes the shape, size, and orientation of objects *currently* in the visual field (Binkofski & Buxbaum, 2013). Interestingly, past research has revealed that humans and non-human primates differ significantly in cognitive functioning supported by areas in the dorso-dorsal stream which is perhaps a contributing factor to the human advantage in tool use (Kastner et al., 2017). The ventro-dorsal stream, in contrast, extends from the angular gyrus, into the supramarginal gyrus (SMG), ending in PMv. This stream, defined as the "grasp system", is thought to store information about skilled actions associated with familiar objects (Binkofski & Buxbaum, 2013). The division of the dorsal steam into "use" and "grasp" substreams is a useful framework to evaluate the extent to which pictures of tools or real tools can evoke affordances. Affordances evoked by *unfamiliar* tools, for instance, would be more likely to recruit the "use" system than the "grasp system" as the grasp system is especially responsive to familiar tools. The effect of familiarity is discussed further in Chapter 4.

1.4 Research questions

Many tool-selective regions in the dorsal- and ventral-stream that activate in response to *pictures* of tools (as well as to tool sounds, tool words, and tool use imagery) also activate in response to *real actions* with *real tools* (Lewis, 2006; Gallivan et al., 2013). Although there is overlap between the areas that activate in response to pictures of tools and to real actions on real tools, it is unclear whether tool pictures are an effective proxy for real tool use, especially as this is contingent on the degree to which a picture of a tool can potentiate a real action. As such, studies of the neural processing of tools may have overestimated the role of cognitive areas and underestimated the role of motor areas in tool processing (Hermsdörfer, Terlinden, Mühlau, Goldenberg, & Wohlschläger, 2007; Paccioco, McLean, & Culham, 2012). Unfortunately, while using real tools is more likely to potentiate actions relative to using pictures of tools, the limitations of fMRI mean that even "real" tool use has constraints. For example, only non-ferrous real tools can be used in the scanner and the range of motion in real actions must be limited to avoid motion artifacts. Moreover, the experimental set up required to enable real tool use is technically challenging and time-consuming. Therefore, the impetus for the projects in this thesis are driven by a need to discover and validate the optimal proxy to study tool use in the fMRI environment.

In light of this, the overarching goals of my thesis are, 1) from a methodological perspective, to determine whether different proxies for studying tool use are more effective than using pictures but less technically challenging than using real actions on real tools; and 2) from a theoretical perspective, to determine what these proxies can reveal about complex tool processing, particularly in brain regions involved in visuomotor control.

In Chapter 2, I present a study in which the stimuli consist of real tools, which are expected to invoke a stronger potential for action than pictures of tools. Here, I will compare brain activity in response to *passively viewed real* tools to that of physically scrambled versions of the same tools. I hypothesize that 1) the tool-selective regions will remain selective for tools as compared to scrambled tools even after elongation, size, and manipulability have been matched; and 2) real tools will evoke a potential for action in that brain activation will be differentially affected depending on whether the direction of the tool's handle is oriented towards or away from the hand required to use that tool.

In Chapter 3, the stimuli consist of videos and pictures of tools. Tools are a unique category of objects that is characterized by motion and action reasoning. Unfortunately, the majority of researchers studying tools use static tools isolated on a neutral background that does not provide context for an action (Mahon et al., 2007; Orlov et al., 2010; Bracci et al., 2012; Stevens et al., 2015). I hypothesize that videos, which provide context and depict the goals of tool use, will be more effective than pictures at activating tool-selective regions. Even though *passively viewed real* tools (as in Chapter 2) may be an optimal approach to study tool-selective regions, static tools still lack the defining motion associated with tool use. Chapter 3 will explore the benefits of dynamic stimuli such as videos compared to static stimuli such as pictures to study tool use.

In Chapter 4, the stimuli will also consist of videos and here I will examine whether tool familiarity and action goals mediate activity in tool-selective regions. Depicting tools via video affords the opportunity to depict the characteristic motion associated with tool use however it is unclear if viewing a familiar tool performing a *functional* action (e.g., using a hammer to pound a nail into wood) mediates activity in visuomotor areas as compared to viewing a familiar tool performing a *non-functional* action (e.g., simply moving the hammer from one location to another) or viewing an unfamiliar tool performing either a functional or non-functional action. Often, researchers overlook whether their participants are familiar with tools presented in the study. I hypothesize that, if tool-selective regions are truly involved in action reasoning, familiarity will mediate activity in these regions especially when functional actions (as compared to non-functional actions) are observed.

Taken together, these projects will make both methodological and theoretical advances. Methodologically, I will examine the effectiveness of presenting real tools (with no action carried out), tool videos, and tool pictures for studying tool-related brain processing. Theoretically, I will examine the contributions of tool attributes such as elongation and size, motion, context, goals, and familiarity in modulating activation across a range of perceptual, cognitive, and motor areas of the human brain.

Chapter 2

2 Do human brain areas involved in visuomotor actions show a preference for real tools over visually similar non-tools?

2.1 Introduction

The adept use of tools is a cognitive ability that is enhanced in the human brain compared to other species. The advent of fMRI has afforded the opportunity to examine the brain mechanisms associated with tool use and it has revealed a number of left-hemisphere areas implicated in the use of vision for guiding actions (the dorsal stream from occipito-parietal cortex to motor cortex) and for recognizing objects (the ventral stream in occipito-temporal cortex; Goodale & Milner, 1992). Historically, to study tool-selective regions of the brain activity associated with viewing pictures of tools has been contrasted against activity when viewing pictures of control stimuli such animals, buildings (Chao & Martin, 2000), chairs (Bracci et al., 2012), scrambled images (Creem-Regehr & Lee, 2005), or other non-tool shapes. These contrasts have reliably identified tool-selective areas in the dorsal stream (e.g., SPL, ventral pre-motor cortex; PMv) and ventral stream (e.g., pLOTC), particularly in the left hemisphere. The co-activation of areas in both dorsal and ventral visual streams is thought to reflect access to motor knowledge (such as how to grasp a tool) and functional information (such as the function of the tool), respectively (Lewis, 2006; Canessa et al., 2008).

The contrast between tool and non-tool pictures has revealed many brain areas involved in tool processing however this selectivity could also be driven by stimulus confounds. Firstly, even when tools and non-tools are matched for retinal size, the differences in real-world size between tool (e.g., a hammer) and non-tool stimuli (e.g., an elephant or a building) may bias activation. Specifically, the real-world size of objects modulates the activity of areas in the ventral stream, with gradients in localization between items with large vs. small real-world sizes (e.g., houses and places vs. faces; Levy et al., 2001; Konkle & Oliva, 2012), even when retinal sizes are matched. Moreover, the graspability of stimuli could also confound the data as some brain regions show similar responses for tools and graspable objects (Mruczek, von Loga, & Kastner, 2013) while others show a preference for tools relative to graspable objects (Mahon et al., 2007; Valyear et al., 2012). The use of pictures of tools as a proxy for real tools may also impact the representation that is evoked. After all, one would never use a *picture* of hammer to pound a nail. Indeed, growing evidence suggests that both action kinematics (Holmes & Heath, 2013) and brain activation (Snow et al., 2011) differ for real objects and pictures. Real tools (matched for real-world size and graspability) may recruit areas that recognize the potential for a real action – a possibility not afforded by pictures of tools.

Secondly, some suggest that the dorsal stream may not be selective to tools *per se* but to visual elongation (Almeida, Fintzi, & Mahon, 2013; Sakuraba, et al., 2012), a property shared by stereotypical tools (but see Hebart & Hesselmann, 2012). Specifically, research using this technique purported to tap into dorsal-stream processing (CFS; Fang & He, 2005) finds that pictures of elongated non-tools (e.g., a cucumber) and tools prime activity in the dorsal stream to similar extents (Sakuraba et al., 2012). That said, priming effects have been found for elongated tools but not for elongated non-tools (Verma & Brysbaert, 2011). Thus, it is likely that *both* elongation and tool category influence tool processing; however, given that most tools are elongated, it is difficult to infer the relative contribution of each factor.

Brain imaging has revealed visuomotor regions that are selective for the change in orientation of elongated tools but not of non-graspable objects (Valyear et al., 2006; Rice et al., 2007). This suggests that the direction of the tool's handle or functional end is a relevant property for areas involved in visuomotor control (e.g., areas involved in preshaping the hand before a grasp). The selectivity of visuomotor areas for tool orientation is in agreement with a long line of behavioral research sparked by a seminal study (Tucker & Ellis, 1998) that reported that participants were faster to respond to a tool when its handle was directed toward the hand as opposed to away from it (although this result and its interpretation have been contested; e.g., see Cho & Proctor, 2010). In other words, the orientation of a tool handle may potentiate different actions for the hand depending on which hand the tool's handle is directed towards. Currently, though, it is unknown whether visuomotor areas activate preferentially to *specific* tool handle orientations. If actions with a particular hand are facilitated when a tool's handle is directed towards that hand (Tucker & Ellis, 1998), one might expect greater activation in visuomotor areas contralateral (vs. ipsilateral) to that hand. However, it is equally possible that in right-handed participants visuomotor regions will only show greater activation when the tool handle is directed towards the dominant right hand (Verma & Brysbaert, 2011).

In light of this, the goals of the current fMRI study were two-fold: 1) to determine whether visuomotor regions show a preference for real tools over visually similar non-tools even when the stimuli have been matched for real-world size and elongation, and 2) to determine whether visuomotor regions show preferential activation for left or right tool handle orientation. Importantly, real tools as opposed to pictures of tools were used to answer these questions. Pictures of tools may differentially activate tool-selective regions as it is not possible to grasp a picture.

To this end, fMRI was used to measure brain activation while participants directly viewed real tools and scrambled non-tools in different orientations (see Figure 2). Crucially, to be confident that activity was not driven by low-level features or differences in graspability, tool and non-tool stimuli were matched for elongation and real-world size. I employed traditional tools that have strong motor associations with the dominant hand (i.e., a pipe wrench and a hammer) and created "non-tools" (playfully named "hammench" and "wrammer") to control for low-level confounds. To make the non-tools, the functional ends of the hammer and pipe wrench (i.e., the hammer head and pipe wrench jaw) were cut in to pieces and recombined along both extremities of the original handles. All four objects were presented within reach and viewed directly without mirrors to optimize the perceived potential for action. Objects were placed with the axis of elongation in one of two horizontal orientations: tools were presented with the handles directed towards the left or right hand and non-tools were presented in one of two mirror-flipped horizontal orientations (see Figure 2).

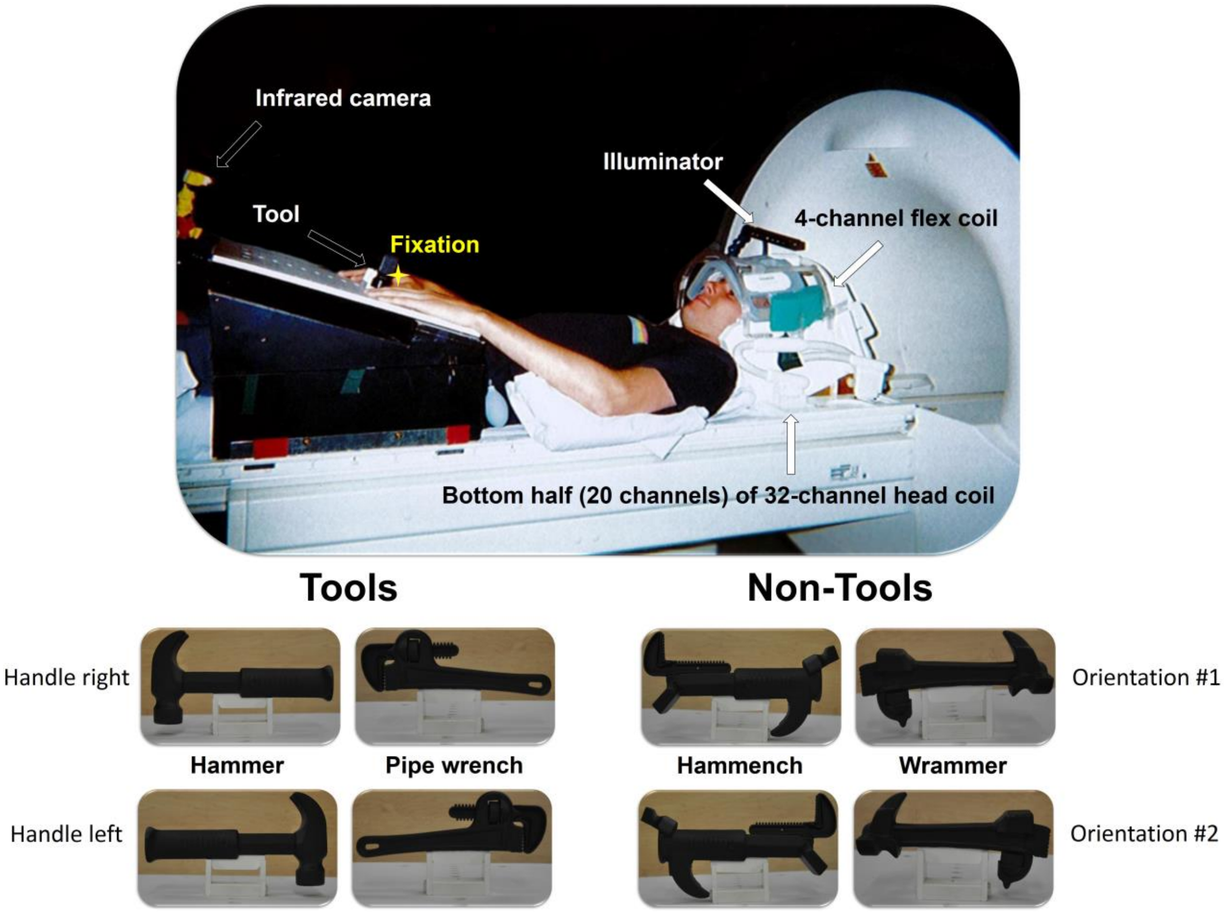


Figure 2. Setup for fMRI experiment (top panel) with tool and non-tool stimuli (bottom panel). Non-tools were created by chopping up the functional ends of the original hammer and pipe wrench (i.e., the hammer head or pipe wrench jaw) and recombining pieces from both tools along both ends of the original handle of the hammer and of the pipe wrench.

2.2 Methods

2.2.1 Participants

Twelve right-handed healthy individuals (6 women) with normal or corrected-to-normal vision participated. Data were also collected from an additional five participants but three were excluded due to technical difficulties and two were excluded due to contamination from head motion. Before scans were acquired, informed consent was obtained in accordance with the guidelines approved by Western University's Health

Sciences Research Ethics Board. All participants were naïve to the experimental hypotheses and were compensated $25 per hour.

2.2.2 Task

A 2 (Tool) x 2 (Orientation) design was employed whereby participants passively viewed either a tool or non-tool in two different orientations (see Figure 2). The objects were never grasped and participants simply passively viewed the stimuli without an instructed task (e.g., participants were not asked to imagine tool use or pantomime). Prior to the scan, however, participants grasped different plastic tools (e.g., whisk, spatula, comb, toothbrush, and pizza cutter) inside the scanner to give them a sense that real actions could be carried out in the testing environment (even though no actions were performed in the test runs).

The main tools (hammer and wrench) were plastic toy tools. The non-tools (hammench and wrammer) were created by chopping up the functional ends of additional copies of both tools into pieces (e.g., the claw of the hammer or one jaw of the pipe wrench; see Figure 2) and gluing the pieces to one of the two handles. Both tools and non-tools were painted black to provide high contrast against the white background of a platform placed above their hips. Because the non-tools were unfamiliar and roughly symmetric, they should not have evoked any particular action association or affordance.

2.2.3 fMRI setup

Participants' heads were tilted approximately 30º to allow them to view a platform fixed above the hips. The left and right hands were placed on the far left and right sides (respectively) of the platform in a "home position" throughout the entire experiment. Participants were able to comfortably view and interact with objects placed on a platform in their lower visual field (i.e., below the natural line of gaze). A fixation light was placed slightly above the platform and participants were asked to maintain fixation throughout the entire run. Importantly, participants did not hold any devices (e.g., MRI "squeeze ball" or response pad) in their hands because this can interact with tool orientation to affect tool processing (see Witt et al., 2010).

2.2.4 fMRI design

Each slow event-related run began with a 12-s baseline in which all lights were off except for the fixation LED (light-emitting diode). After the baseline period, a scene light was turned on and participants passively viewed the centrally presented object for 2 s while they maintained fixation on the horizontal mid-point of the object. A 10-s baseline followed each 2-s viewing window in which the experimenter swapped the objects. There were eight experimental runs where stimuli were presented 40 times in pseudo-random order. The object series was ordered such that each condition preceded every over condition (including itself) an equal number of times. Each of the four objects in each orientation (left or right) was presented 40 times (e.g., 40 trials of a hammer with the handle directed towards the right hand).

2.2.5 Data acquisition

Imaging was carried out on a 3-Tesla Siemens Tim Trio scanner at the Robarts Research Institute at the University of Western Ontario. To provide a high signal-to-noise ratio without occluding the view of the hand workspace, brain activation was measured using the bottom half (20 channels) of a Siemens 32-channel head coil placed beneath the head as well as a 4-channel flex coil suspended over the forehead. Both coils were tilted approximately 30 ° to allow the participant to view the stimuli directly without mirrors.

For functional scans, T2*-weighted fMRI volumes with a 3-mm isotropic resolution were collected using a gradient-echo echo-planar imaging (EPI) pulse sequence with interleaved slice acquisition (repetition time (TR) = 2000 ms; time to echo (TE) = 30 ms; flip angle (FA) = 70º; field of view = 216 mm x 216 mm; 37 slices). For anatomical scans, T1-weighted volumes with 1-mm isotropic resolution were collected (TR = 2300 ms; inversion time = 900 ms; TE = 30 ms; FA = 9º; field of view = 240 mm x 256 mm x 192 mm).

2.2.6 Data preprocessing

Prior to analysis, data underwent slice scan time correction, motion correction, and high-pass filtering (in this order) using Brain Voyager QX version 2.4 (Brain Innovation, Maastricht, Netherlands, Version 2.4.2.2070). The motion correction employed six rigid motion parameters (three translations and three rotations) to align each volume to the volume closest in time to the anatomical scan. The head motion plots were screened with an in-house script to determine which trials, runs, or participants should be excluded based on artifacts caused by motion contamination (e.g., abrupt spikes larger than 1 mm from the location of the previous volume). The temporal high-pass filter removed any low frequency signals (e.g., scanner drifts or physiological responses) under four cycles per run.

Group data were spatially smoothed with a 6-mm (full-width half-max; FWHM) kernel and predictors were convolved with Brain Voyager's default double-gamma hemodynamic response function. All anatomical volumes were aligned by manually locating the axis of each participant's anterior and posterior commissures (ACPC) and then deforming the brains into Talairach space (Talairach & Tournoux, 1988).

To correct for multiple comparisons, activity was thresholded at $p < .01$ and cluster corrected ($p < .05$) using Brain Voyager QX's cluster-level statistical threshold estimator, which yielded a minimum cluster size of 30 mm^3.

2.3 Results

2.3.1 Tools vs. non-tools

First, I examined which areas preferentially activated during passive viewing of real tools vs. non-tools. To do so, the blood-oxygen-level dependent (BOLD) activation was contrasted between responses to the two tools (hammer and wrench) and the two non-tools (hammench and wrammer) using a random-effects (RFX) general linear model (GLM) analysis on group data.

Firstly, I was interested in whether areas previously implicated in tool processing would show tool-selectivity even when real-world size and elongation were controlled. As shown in Figure 3, tool-selective activation was found in many of these areas, including left pLOTC, right PMv and left PMv, though the latter did not survive cluster correction, as well as numerous foci in PPC, particularly in the left hemisphere. The strongest activation in PPC (bilaterally) was at the junction of the postcentral and intraparietal sulci, in the aIPS. In the left hemisphere, the PPC activation spread inferior and superior to aIPS, including the inferior postcentral sulcus and aSMG, areas thought to be integral for tool use (Mruczek, von Loga, & Kastner, 2013; Orban & Caruana, 2014).

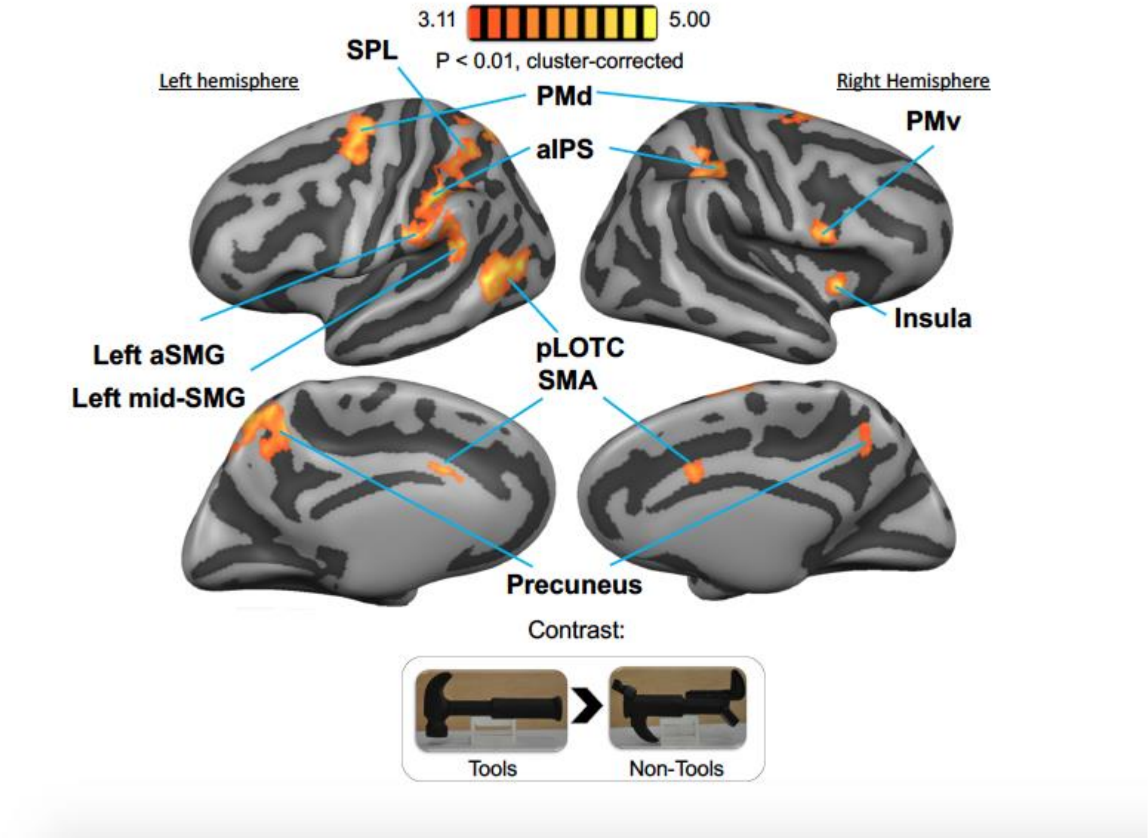


Figure 3. Areas selective for tools over non-tools in the left and right hemisphere as determined by a group RFX GLM (*p* <.01; cluster-corrected). To facilitate visualization of the activated regions, group activation in volumetric Talairach space has been rendered on the average cortical surface (derived using cortex-based alignment) of 12 participants from another study in my lab. Cortical surface activation maps were visually inspected to ensure the activation location accurately represented that seen in the original volumetric Talairach data. See Table 1 for Talairach coordinates.

Interestingly, tool-selective activation was also observed in brain regions associated with sensorimotor function. Tools evoked greater activation than non-tools bilaterally in PMd, supplementary motor area (SMA), SPL, and precuneus, as well as in the left posterior IPS, right putamen, right anterior insula (with homotopic left hemisphere activation that did not survive cluster correction), and left cerebellum.

2.3.2 Left tool handles vs. right tool handles

Secondly, I examined whether any regions preferentially activated to left or right tool handle orientations. To do so, an RFX GLM group contrast was carried out to compare activation when tool handles were oriented toward the left vs. right ($p < .01$ cluster-corrected, 18 mm^3). As shown in Figure 4, this contrast revealed spatially symmetric clusters of activation in early visual areas that showed higher responses when the tool's functional end was in the participant's contralateral visual field. The activation was confined to occipital cortex and included foci near the calcarine sulcus (likely primary visual cortex, V1), in Brodmann's Area (BA) 17 and 18, the fusiform gyrus (left hemisphere only), and on the lateral surface of the occipital lobe, likely corresponding to the motion-selective middle temporal complex (MT+) and/or the object-selective lateral occipital complex (LOC), which overlap to an extent (Kourtzi et al., 2002). Notably, in contrast to expectations, no orientation-selective activation was observed in more anterior tool-selective, sensorimotor, or motor areas.

No such orientation effects in early visual areas were observed with the non-tools. Note that it is not straightforward to test for an interaction effect of (Tool handle left – Tool handle right) > (Non-tool orientation 1 – Non-tool orientation 2) because the two orientations of the non-tools do not have any obvious correspondence with each other (assignments to orientation 1 vs. 2 were arbitrary) or with the orientation of the tool handles. That is, while the tools have unequivocal handles and "left" and "right" are meaningful, the non-tools are more symmetric and have no clear handle and, as such, no clear mapping to the tool orientations. Because testing for an interaction was not straightforward, orientation effects in non-tools were tested using two other means. First, two voxelwise contrasts were carried out testing for orientation effects in non-tools with the two possible correspondences between orientations (using the same parameters as the earlier contrast for non-tools): (1) (Hammench1 + Wrammer1) > (Hammench2 + Wrammer2) and (2) (Hammench1 + Wrammer2) > (Hammench2 + Wrammer1). Neither of these contrasts yielded activation in occipital cortex. Second, I examined the activation for non-tools in the regions that showed significant orientation effects for tools. Although this analysis is non-independent (Vul & Kanwisher, 2005; Kriegeskorte et al., 2009), it corroborates the voxelwise findings suggesting no signs of orientation differences for non-tools.

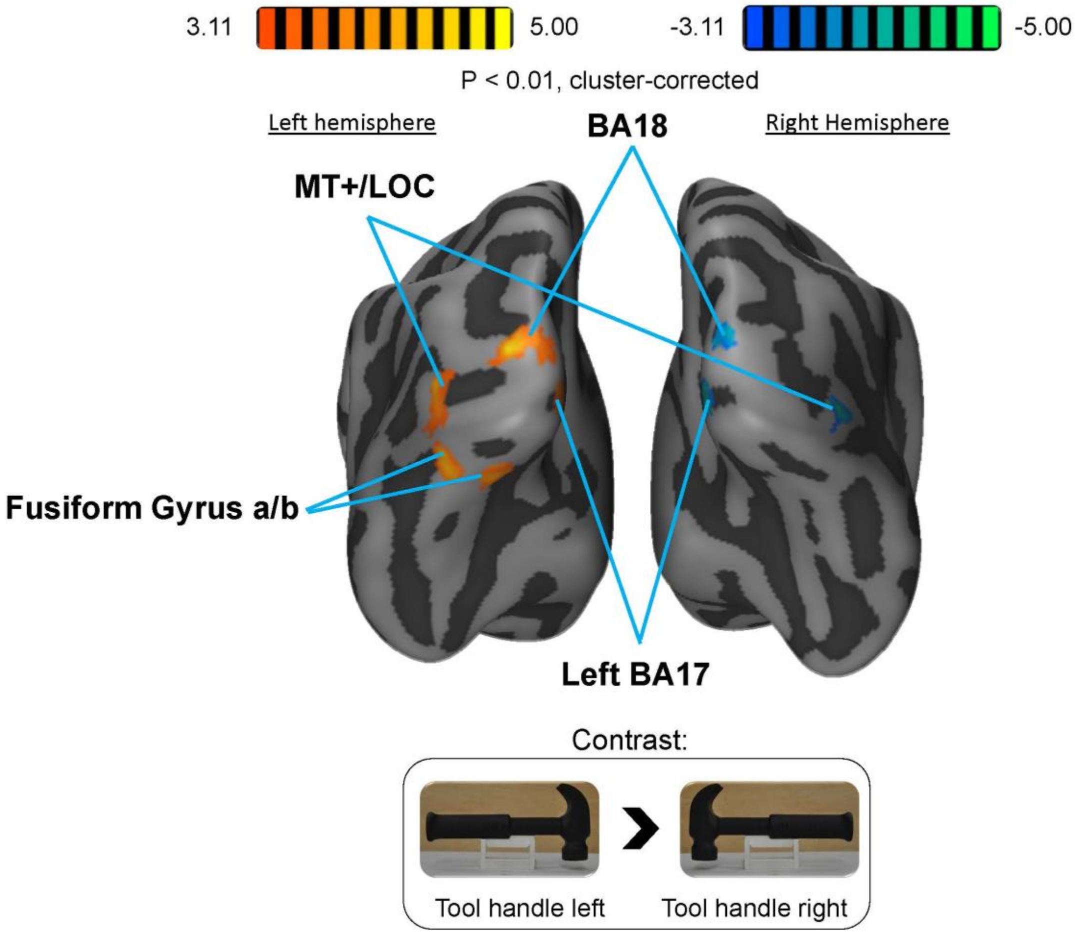
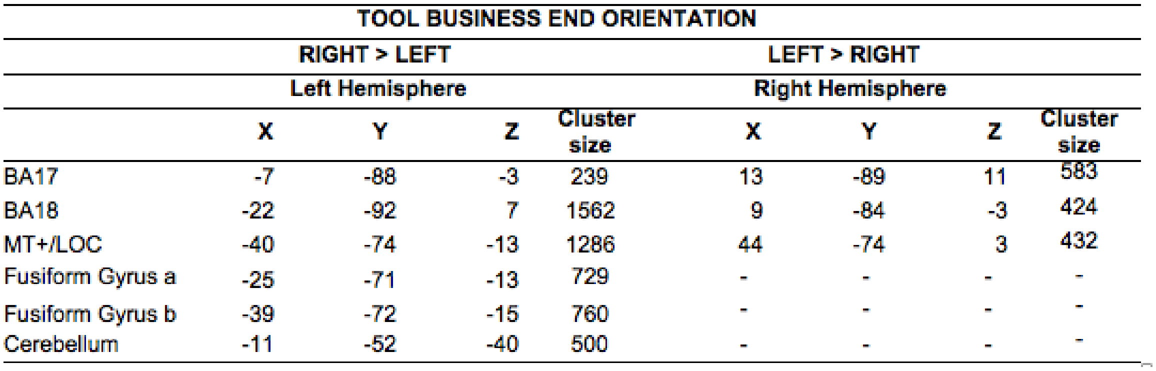
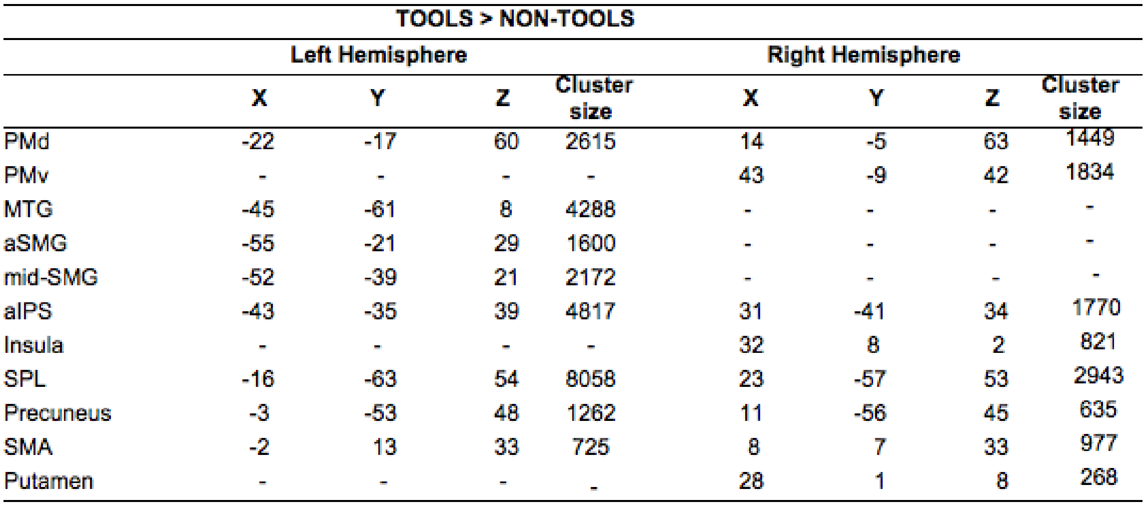


Figure 4. Areas selective for tools when their handles are directed leftwards (vs. rightwards) in the left and right hemisphere (posterior viewpoint) as determined by a group RFX GLM (*p* <.01; cluster-corrected). See Table 1 for Talairach coordinates.

Table 1. Talairach coordinates for the peak voxel in group-averaged areas selective for tools over non-tools (top panel) and areas selective for rightward and leftward tool handle orientations (bottom panel).



TOOL BUSINESS END ORIENTATION								
	RIGHT > LEFT				LEFT > RIGHT			
	Left Hemisphere				Right Hemisphere			
	X	Y	Z	Cluster size	X	Y	Z	Cluster size
BA17	-7	-88	-3	239	13	-89	11	583
BA18	-22	-92	7	1562	9	-84	-3	424
MT+/LOC	-40	-74	-13	1286	44	-74	3	432
Fusiform Gyrus a	-25	-71	-13	729	-	-	-	-
Fusiform Gyrus b	-39	-72	-15	760	-	-	-	-
Cerebellum	-11	-52	-40	500	-	-	-	-



TOOLS > NON-TOOLS								
	Left Hemisphere				Right Hemisphere			
	X	Y	Z	Cluster size	X	Y	Z	Cluster size
PMd	-22	-17	60	2615	14	-5	63	1449
PMv	-	-	-	-	43	-9	42	1834
MTG	-45	-61	8	4288	-	-	-	-
aSMG	-55	-21	29	1600	-	-	-	-
mid-SMG	-52	-39	21	2172	-	-	-	-
aIPS	-43	-35	39	4817	31	-41	34	1770
Insula	-	-	-	-	32	8	2	821
SPL	-16	-63	54	8058	23	-57	53	2943
Precuneus	-3	-53	48	1262	11	-56	45	635
SMA	-2	13	33	725	8	7	33	977
Putamen	-	-	-	-	28	1	8	268

2.4 Discussion

I show that even after confounding variables such as real-world size and elongation are controlled, real tools evoke more activity in tool processing and sensorimotor control areas than non-tools. Interestingly, this selectivity occurred without any explicit intention to *use* the tool – all tools were passively viewed. The findings suggest that tools evoke activity that is associated with the functional and motor aspects of tools (compared to non-tools) and that this activation is not entirely attributable to visual differences between tools and non-tools. Finally, the results show that the leftward or rightward orientation of tool handles does not differentially activate tool-selective or sensorimotor areas, but rather only does so in early visual areas. Early visual areas in the left and right hemisphere were activated when the functional end of the tool was in contralateral (vs. ipsilateral) visual field, perhaps due to the presence of more visual features on the tool’s functional end (vs. its handles). No effect of orientation was observed for different orientations of non-tools.

2.4.1 Tools vs. non-tools

Past research has identified a network of brain areas selective for tools as compared to non-tools; however, the tools and non-tools in previous experiments differed considerably in their low-level features. Here, I show that activation evoked during the viewing of tools vs. non-tools is not simply a confound of low-level stimulus features (e.g., elongation or real-world size). The tools and non-tools were matched for elongation, both absolute and familiar size, viewing distance, material properties, and graspability but nevertheless higher activation was found for tools. While this does not rule out the possibility that tool processing is influenced by elongation (Sakuraba et al., 2012; Almeida et al., 2014) and real-world size of the object (Konkle & Oliva, 2012), the data show that these confounds cannot fully account for the differences in activation between tools and non-tools. Rather, the critical factor in tool-selective activation is the learned associations between a tool’s structure and its function.

In addition to activity in tool-selective regions, activation in areas implicated in sensorimotor control was observed – namely the SMA, PMd, SPL, and the insula. These areas are recruited when actions with real tools and planned and executed (Imazu et al., 2003; Gallivan et al., 2013; Brandi et al., 2014). The results indicate that similar visuomotor areas are recruited when a tool is viewed and when an action on the tool is prepared (see also Chao & Martin, 2000). Although I did not include tool images in this experiment, the results raise the question of whether real tools – which afford genuine actions – may evoke stronger activation or different representations than pictures of tools (Snow et al., 2011). However, the tool-selective foci identified here have been observed in other studies that used only tool images (e.g., Lewis, 2006). Thus, it seems real tools and tool images activate the same foci, though future research could investigate whether they do so to the same degree. That said, it is possible that the plastic toy tools used here may not have potentiated actions to the same extent as *actual* tools. I used toy replicas of a hammer and a wrench as such it would not be possible to use them purposefully. In future, real MR-compatible tools (e.g., plastic cutlery or kitchen utensils) may be a better choice.

2.4.2 Tool handle orientation preference

A secondary goal of this study was to determine whether visuomotor areas showed a preference for different tool handle orientations (e.g., with the handle oriented toward or away from the hand; Tucker & Ellis, 1998). To this end, activity associated with when tools were viewed with handles directed towards the right was contrasted against that of tools when handles towards the left. This contrast revealed bilateral clusters of activity in early visual cortex. The nature of the activation was such that visual cortex was more activated when the functional end of the tool was in the contralateral visual field (i.e., regions in left occipital cortex showed higher activation when the functional end was in the right visual field and vice versa). That said, no effect of orientation was observed for either of the non-tool orientations, and no effect of orientation was observed using tool-selective areas as a mask.

These results came as a surprise for two reasons. First, no higher-order sensorimotor or visuomotor regions showed preferential activation to one tool orientation over the other, as would be expected for viewing of stimuli that afford an action with the dominant hand (Gallivan, Cavina-Pratesi, & Culham, 2009; Handy et al., 2003). Second, the areas that did show an orientation preference demonstrated higher activation when the functional end – not the handle – was in the contralateral visual field. Past research would have predicted one of two outcomes: 1) the tool’s handle would elicit more activity in visuomotor areas in the contralateral hemisphere (Tucker & Ellis, 1998) or 2) the tool’s handle would elicit more activity in visuomotor areas only when it was directed towards the *right* hand (for right-handed participants). Accordingly, greater activation was expected in visuomotor areas when then *handle* was oriented towards the *contralateral* *hand* or, possibly, only when it was oriented towards the *right hand*. This was not the case with the data.

In fact, the only orientation effects observed for tools were in early visual cortex, but this effect was not greater than that for non-tools. Moreover, given that the tools I used were more clustered on the functional end (relative to the handle), retinotopic stimulation alone may account for the data. While all stimuli were horizontally elongated and positioned below fixation, they differed in the density of object pieces in left vs. right visual fields. Specifically, the tools had more pieces (head of the hammer and claw of the wrench) on the functional end than the handle; whereas the non-tools had the pieces (scrambled head and claw) approximately symmetrically attached to the handle. It appears that the early visual areas were more activated when the asymmetric tools were placed with more pieces in the contralateral visual field. By logical extension, in these early visual areas there may be nothing special about tools beyond their asymmetry (e.g., if participants saw a picture of a lobster, more early visual activation would be expected contralateral to the claw side). To summarize, in no region of the brain was activation stronger when the handle appeared within the contralateral visual field, as might be expected from behavioural research (especially Tucker & Ellis, 1998). Rather the only differences observed were in early visual areas and were consistent with retinotopic features.

2.5 Conclusion

Tool-selective brain activity cannot be explained solely by the differences in elongation and real-world size between tools and non-tools. Rather, tool-selectivity is driven by the learned association between the function and structure of objects. Even without intent to act with the tool, such functional associations are automatically evoked and these associations are not specific to a particular hand.

Chapter 3

3 Videos are more effective than pictures at activating tool- and hand-selective areas in human neuroimaging

3.1 Introduction

Pictures have often been used by neuroimaging researchers to understand the neural basis of human visual processing, particularly in fMRI. Such approaches have revealed human brain areas that show selective activation for a variety of categories including faces, scenes, objects, bodies, tools and hands. Pictures are an attractive choice for experimenters as pictures are readily available in databases, easy to edit, suitable for developing well-matched control stimuli (e.g., scrambled versions), and enable rapid presentation.

With pictures, one view of an object can be presented at a single point in time, however, they cannot be used to portray dynamic changes in visual stimuli that may be critical for recognition and visual processing. This limitation is especially problematic for animate stimuli such as faces, bodies, and hands. Pictures of faces, for instance, do not drive activity in brain areas that process characteristic eye, head, and mouth movements of the face (Pitcher et al., 2011). As with faces, pictures of hands do not portray the distinctive motion features of the hand that are represented in hand-selective brain areas (Orlov et al., 2014). The limitations of pictures are also problematic for inanimate stimuli (such as tools) that can be animated and thus have distinctive motion. Hammers, for example, are typically rotated about their lower handle, a characteristic that cannot easily be conveyed in a picture. Indeed, tool-selective brain areas are more strongly activated to tools being moved as compared to static pictures of tools (Beauchamp et al., 2002). Accordingly, within the ventral visual stream, areas selective for animate and inanimate categories associated with motion are clustered near motion-selective area MT+ in LOTC (Beauchamp et al., 2002; Hasson et al., 2003).

While videos seem to be better than pictures at evoking activity for stimuli like tools (Beauchamp et al., 2002), they have been scarcely used in neuroimaging (but see Peeters et al., 2009; Valyear & Culham, 2010; Yoon et al., 2012; Hafri, Trueswell, & Epstein, 2007). Instead, the majority of studies have used pictures to reveal a core network of areas that show stronger activation to tools and/or hands compared to other categories such as objects or animals (Mahon et al., 2007; Orlov et al., 2010; Bracci et al., 2012; Stevens et al., 2015), though activated regions show considerable variability between studies (Lewis, 2006). Moreover, the pictures that are employed typically lack context, showing a tool or a hand against a neutral background, for example, rather than in a specific interaction with an object in a scene.

There are many reasons to expect that videos are more effective than pictures at characterizing brain areas involved in processing tools and hands. Videos have the advantages of depicting a tool or hand action from start to finish, providing context to the scene, and emphasizing the interaction between an effector and its target. With pictures, especially those that lack context, the ultimate *goal* of the tool or hand is unclear. Of course, in a video, there is no ambiguity in this regard. The ability to capture the goal of a tool interacting with its target is important as understanding a tool's function is more complex than just understanding its basic spatial relationship with a target (Bach, Peelen, & Tipper, 2010). Moreover, drawing attention to the interaction between a tool and its target leads to different activation relative to focusing on the tool's identity alone (Yoon et al., 2012). Attending to an action is more likely to yield activation in the dorsal stream whereas attending to identity is more likely evoke activation in the ventral stream. Imagine, for instance, that a picture of a hammer is presented. Would the brain activity evoked solely relate to the identity of the tool, to the associations from when the hammer was *used* to pound a nail into wood (or used to pry a nail from it), from when the hammer was moved out of a toolbox, or from when remembering someone else using a hammer on a home renovation show? The breadth of possibilities is larger with a picture compared to a video. The mere difference between moving or using a tool is sufficient to recruit different motor systems (Valyear et al., 2011; Squires et al., 2016).

If videos are indeed more effective stimuli for activating category-selective regions, their use would provide two benefits for neuroimaging researchers. First, they would enable more powerful comparisons between experimental conditions. Second, researchers who use localizers to identify category-selective areas for further exploration (Nieto-Castañón & Fedorenko, 2012; Saxe, Brett, & Kanwisher, 2006), a common practice to avoid the need for very conservative corrections for multiple comparisons, would find areas more reliably and efficiently than with pictures.

The goal of this study was to directly contrast the effectiveness of videos vs. pictures for the study of tool- and hand-selective areas. This interest was sparked while I was planning a neuroimaging experiment to study tool- and hand-selectivity in upper-limb amputees and wanted a localizer to reliably identify regions of interest in a short amount of time.

To this end, the first approach (Experiment 1) compared activity between a traditional *picture* localizer vs. a new *video* localizer that I developed. The traditional localizer included pictures of complex tools or hands, as well as objects (e.g., lamps, plants) and low-level visual control stimuli, with each item portrayed on a neutral background without context as in common practice (for example, see Mahon et al., 2007; Orlov et al., 2010; Bracci et al., 2012; Stevens et al., 2015). The new video localizer was comprised of the same categories, but portrayed brief (7-s) video clips that showed the hands, tools and objects moving naturally in an contextual setting (Figure 5).

Although the results from the first approach revealed that videos were generally more effective than pictures at identifying regions that showed selective activation for tools and hands (compared to objects), the comparison was vulnerable to low-level confounds (such as visual differences between videos and pictures, the number of stimuli in each format, and differences in the scene context) as well as differences in experiment design and imaging protocols. Nevertheless, even this somewhat “apples and oranges” contrast suggested that videos were considerably more effective than pictures at revealing tool- and hand-selective regions. These promising results led to the second approach to corroborate the original findings with better stimuli and protocols that were closely matched. Specifically, Experiment 2 included improvements to the videos such as using static images taken from the videos (to ensure visual similarity), matching of the design and imaging protocol, and adding a task (i.e., to detect subtle a subtle increase in frame brightness) to better equate attention across conditions.

It was hypothesized that for both experiments, videos would be more effective than pictures at 1) yielding stronger category-selective activation within tool- and hand-selective regions, perhaps even revealing category selectivity in additional areas, especially within visuomotor areas of the dorsal stream; and 2) localizing tool- and hand-selective areas in individual participants.

3.2 Methods

3.2.1 Participants

Twenty-six (10 in Experiment 1 and 16 in Experiment 2) right-handed healthy adults with normal or corrected-to-normal vision provided informed consent to be scanned and were compensated at £10/hour (Experiment 1) or $25/hour (Experiment 2). The experimental protocols were approved by Oxford University Hospital NHS (Experiment 1) and Western University's Health Sciences Research Ethics Board (Experiment 2).

3.2.2 fMRI design and task

3.2.2.1 Experiment 1

In the first approach, participants viewed videos and pictures of tools, hands, and two types of control categories: objects and low-level visual control stimuli (see Figure 5). Initially, I did not plan to directly contrast activity evoked by videos and pictures. The picture data were intended to examine neural responses to hands, tools, and other stimulus categories in people born missing an upper limb (congenital one-handers), people who lost an upper-limb after birth, and normal two-handed control participants. One of the challenges anticipated in testing the patients was the need to identify ROIs for fMRI studies under tight time constraints. As such, I wanted to test whether I could develop a localizer more effective than a traditional picture localizer that could be used to quickly flag tool- and hand-selective regions. Thus, data was collected for a traditional localizer using *pictures* and a newly developed localizer using *videos* was also piloted. As the results will show, the videos activated a more extensive set of brain regions with greater reliability as compared to pictures even in individual participants.

Although the results were suggestive, there were numerous methodological differences between the picture and video stimuli that may have confounded the data. Thus, the impetus for running a second experiment was to directly compare brain activity in response to videos and pictures with those confounds controlled. Nevertheless, I have included data from the first, suboptimal, experiment for three reasons: (1) tool- and hand-selectivity was examined within format (e.g., $\text{Tool}_{\text{picture}} > \text{Object}_{\text{picture}}$) such that format-specific components should "subtracted out"; (2) pictures in the first experiment are typical of tool- and hand-localizers and therefore provide a comparison between the new approach with the typical approach; and (3) the similarity of the results between the two experiments demonstrates reproducibility of the key findings (an important concern in research, see reproducibility project; Nosek, 2015) despite considerable methodological differences.

For video stimuli, tools, hands, objects and a low-level visual control were presented. Three exemplar videos for each category were filmed from an egocentric perspective. For the videos of tool and hand actions, actions were chosen that could be accomplished in a similar fashion with a tool or hand in such a way that looked natural. These actions included moving chocolates from a table to a cup with a hand or a pair of tongs, flipping small rectangular pieces of wood with a hand or spatula, and mixing flour in a bowl with a hand or a wooden spoon. For the object control condition, videos of graspable objects in motion were created. These included marbles rolling across a table, plastic leaves falling on a table, and playing cards being thrown on a table among a pile of poker chips. Although many studies have contrasted pictures of tools against substantially different visual stimuli (e.g., Chao & Martin, 2000), often animals (e.g., Bracci et al., 2012; Almeida, Fintzi, & Mahon, 2013), contrasting tools to non-tool objects (e.g., Chen et al., 2017) is a fairer comparison as both stimuli are more similar to one another. Comparing tools to non-tool objects circumvents confounds that result in differences driven by factors like inanimacy (e.g., Kriegeskorte, Mur, & Bandettini, 2008; Konkle &

Caramazza, 2013), real-world size (Konkle & Oliva, 2012), and graspability (Valyear & Culham, 2010; Mruczek, von Loga, & Kastner, 2013; Macdonald & Culham, 2015). A comparison condition was also included that would control for low-level visual stimulation. In this condition, clips from a modern art video were presented depicting shapes and lines of different colours moving randomly across the screen. This movie was engaging but conveyed no meaning. To avoid hand-selective activation in the tool and object conditions, no hands were visible in the tool and object videos (though one could deduce that hands were manipulating the tools and objects). Participants were instructed to maintain fixation upon a cross in the centre of the screen that was visible throughout the experiment.

For picture stimuli, as with the videos, tools, hands, objects, and a low-level visual control condition were presented. The videos depicted tools that extended reach (e.g., a hammer), hands in a variety of positions, graspable non-tool objects (e.g., a plant), and dismorphed pictures from the tool, hand, and object conditions (see Stojanoski & Cusack, 2014 for dismorphing procedure) as a low-level visual control. Although a common visual control is to box-scramble the pictures from the main experimental conditions, I opted to use dismorphed pictures to minimize high-frequency noise and to maintain features from the original pictures such as form. As with videos, participants were instructed to maintain fixation upon a cross in the centre of the screen that was visible throughout the experiment.

Videos were viewed at 25 frames/s on a back-projection screen at a resolution of 1280 x 1040 pixels through a tilted mirror, and each frame subtended a visual angle of 23° x 13°. Each run began with a 20-s fixation baseline followed by five sets of five 21-s blocks (four experimental blocks and one baseline block), ending with another 20-s fixation baseline (for a total run duration of 9 min, 25 s). The order of blocks within each set was counterbalanced such that across the run, block history was the same for each condition. Each block of the video conditions was comprised of three videos of 7 s each, with each video depicting a different exemplar of the condition.

Pictures were also viewed on a back-projection screen at a resolution of 1280 x 800 pixels through a titled mirror subtending the same visual angle as above. With pictures, however, participants were required to make a button press when a stimulus repeated twice in a row (i.e., a one-back task). Although the analyses here will focus on tools, hands, objects, and dismorphed pictures, it should be noted that the data were collected as part of a larger project to investigate activation for a wider variety of categories (that included headless bodies, prostheses, and shoes) which will not be discussed here. Stimuli were presented in a random order using a rapid event-related design. Using an event-related design, each image was presented for 1500 ms with an inter-trial interval of 2500 ms ending with a 10-s fixation baseline (for a total duration of 5 min 34 s). Each run contained 81 pictures in which nine of 11 different exemplars were randomly selected and used for each condition.

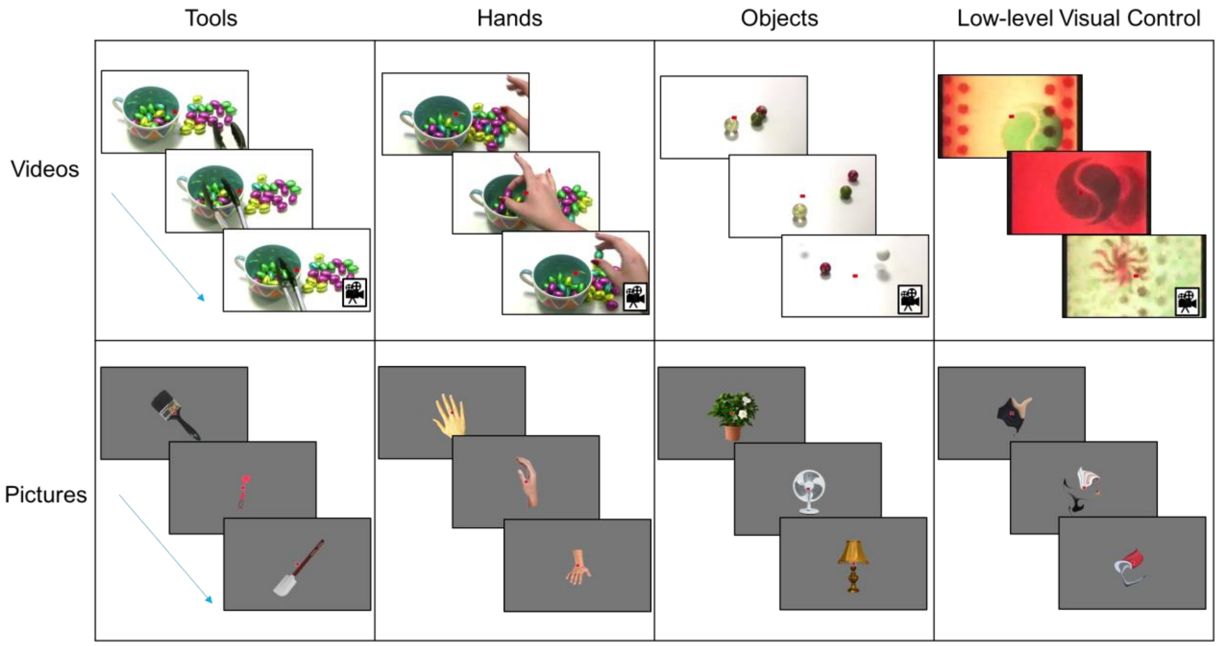


Figure 5. Blocks of videos and pictures featured tools, hands, objects, and low-level visual control images that were passively viewed over two runs.

3.2.2.2 Experiment 2

In the second approach, as with Experiment 1, participants viewed videos and pictures of tools, hands, objects, and low-level visual controls (see Figure 6). However, as the differences between pictures and videos in Experiment 1 may have been confounded by low-level differences, participants viewed videos and pictures taken from the frames of the videos. Moreover, a task was included in which participants made a button response with their left or right thumb (counter-balanced) when they noticed a subtle (~30 ms) increase in frame brightness in both the video and the picture conditions.

For video stimuli, new actions were selected in which the kinematics between the hand and the tool were better matched relative to those used in Experiment 1. The actions were grouped into four themes: barbequing, gardening, baking, and “googling” with a smartphone. Each theme contained three videos of different steps required to complete a goal either with a tool or a hand. As with Experiment 1, I selected actions that could be accomplished in a similar fashion with a tool or hand in such a way that looked natural. The selected tool actions were as follows: A) for barbequing, marinade was spread over a raw hamburger with a brush, the raw hamburger was pushed onto a grill with a fork, and the cooked hamburger was retrieved from the grill using tongs; B) for gardening, dirt was placed into a plant pot with a small shovel, leaves were pruned with scissors, and excess dirt and leaves were pushed into a pile with a broom; C) for baking, flour was spread into a bowl filled with batter using a sifter, the flour and batter were mixed with a wooden spoon, and the batter was placed onto a cookie sheet with silver spoon; D) for googling with a smartphone, using a stylus, the Google application was located amongst other applications, the word “frisbee” was typed in the search bar then the search button was pressed, and the images tab was selected then the images were scrolled through. All the tool actions were also performed with the hand alone. Participants were instructed to maintain fixation upon a cross while they watched the videos.

A new low-level visual control replaced the modern art video clip from Experiment 1. Phase-shifted versions of the tool, hand, and object videos were used instead to better match the visual statistics between the videos of the other conditions and the low-level visual control.

For picture stimuli, strategically, frames roughly 1 s apart in the video clips were used from each condition (including frames from the phase-shifted videos). Blocks of 7-s videos (played at 24 frames/s) or pictures were viewed through back-projection at a resolution of 854 x 480 pixels (43 cm from the participant's head) towards a tilted mirror, and each frame was a visual size of 11 cm x 8 cm subtending a visual angle of 36° x 26°. Each session was made up of two runs in which participants viewed either blocks of videos or blocks of pictures (blocked by category and order counter-balanced across participants). Each run began with a 21-s fixation baseline followed by four experimental blocks of 21 s that repeated four times throughout the run. Three fixation blocks were randomly interleaved between experimental blocks.

Due to a minor programming error (not discovered until after data collection), pictures were vertically by compressed by 10% compared to the video frames. This discrepancy should be inconsequential because the differences in aspect ratio were negligible and all comparisons were made within format (e.g., $\text{Tool}_{\text{picture}}$ > $\text{Object}_{\text{picture}}$).

Figure 6. Blocks of videos or pictures featured tools, hands, objects, and phase shifted images that were viewed over two runs.

3.2.3 Data acquisition

3.2.3.1 Experiment 1

Functional and anatomical volumes were acquired using a 3-Tesla Siemens Verio scanner (Siemens, Erlangen, Germany) with a 32-channel head coil at Oxford University's Centre for Functional Magnetic Resonance Imaging of the Brain (FMRIB). For videos in Experiment 1, functional T2*-weighted fMRI volumes with a 3-mm isotropic resolution were collected using a gradient-echo EPI pulse sequence with interleaved slice acquisition (TR = 2000 ms; TE = 30 ms; FA = 90º; 35 slices). For pictures in Experiment 1, functional T2*-weighted fMRI volumes with a 3-mm isotropic resolution were collected using a multiband (MB6) pulse sequence with interleaved slice acquisition (TR = 1300 ms; TE = 40 ms; FA = 66º; 72 slices). Anatomical T1-weighted fMRI volumes with a 1-mm isotropic resolution were collected using a gradient-echo EPI pulse sequence (TR = 2040 ms; TE = 4.7 ms; FA = 8º; 192 slices).

3.2.3.2 Experiment 2

Functional and anatomical volumes were acquired using a 3-Tesla Siemens Prisma MRI scanner with a 32-channel head coil at the University of Western Ontario's Robarts Research Institute. Functional T2*-weighted fMRI volumes with a 3-mm isotropic resolution were collected using a multiband (MB4; no iPAT acceleration) pulse sequence with interleaved slice acquisition (TR = 1000 ms; TE = 30 ms; FA= 70º; 44 slices). Anatomical T1-weighted fMRI volumes with a 1-mm isotropic resolution were collected using a gradient-echo EPI pulse sequence (TR = 2300 ms; TE = 2.98 ms; FA = 9º; 176 slices).

3.2.4 Data preprocessing

All imaging data were processed using FSL 6.0 (FMRIB Software Library, www.fmrib.ox.ac.uk/fsl). Prior to analyses, all functional runs were screened for large motion spikes (motion otherwise difficult to correct with linear motion parameter regression) using FSL's Motion Outliers tool. A confound matrix was generated for time points where a motion spike exceeded 1 mm and these time points were modeled in the GLM to remove their influence on other parameter estimates. Following this, functional data underwent linear motion correction with FMRIB's Linear Image Registration Tool (MCFLIRT; Jenkinson et al., 2002), brain-extraction using the Brain Extraction Tool (BET; Smith, 2002), spatial smoothing using a Gaussian kernel (full-width at half-maximum, FWHM = 5 mm), mean-based intensity normalization, and high-pass filtering with a 100-s cut-off. Time-series statistical analyses were carried out using FMRIB's Improved Linear Model (FILM) with local autocorrelation correction. Functional data were aligned to structural images (within-subject) initially using linear registration (FMRIB's Linear Image Registration Tool, FLIRT), then optimized using Boundary-Based Registration (Greve & Fischl, 2009). Structural images were transformed to standard Montreal Neurological Institute (MNI) space using a non-linear registration tool (FNIRT), and the resulting warp fields applied to the functional statistical summary images.

3.2.5 Data analysis

I analyzed the data using two main strategies. First, the effectiveness of pictures vs. videos was determined in activating tool- and hand-selective regions at the group level. To do so, voxel-wise contrasts were carried out between conditions across the whole brain at the group level using a mixed-effects model. Second, the effectiveness of pictures vs. videos for activating tool- and hand-selective regions at the individual level was assessed. To this end, several ROIs (see Figure 7) were defined to determine how many participants showed activation in these regions and, of those who showed activation, how many voxels reached significance at a fixed threshold.

3.2.6 Generation of statistical maps

Functional data were analyzed with FMRIB's expert analysis tool (FEAT, version 6.00). Explanatory variables were convolved with a gamma function. First-level GLMs were computed for each participant with FEAT, and higher-level analyses GLMs for grouped data were computed using FEAT's mixed effects: FLAME 1+2 for Experiment 1 (recommended for 10 or fewer participants) and Flame 1 for Experiment 2. A cluster threshold was applied to correct for multiple comparisons, and activity was thresholded at $Z = 2.3$ and corrected against a cluster determining threshold (CDT) of $p < .001$.

Although the assumptions underlying cluster thresholding have recently been challenged (see Eklund, Nichols, & Knutsson, 2016), the problems are modest for a CDT of $p < .001$. Volumetric statistical maps in MNI space (MNI 152; 2-mm isotropic voxels) were rendered on to surface space using FreeSurfer v5.3 (surfer.nmr.mgh.harvard.edu) on surfaces downloaded from the human connectome project (unrelated 20 subjects beta 0.83; www.humanconnectomeproject.org). Surface activation maps were verified to ensure they accurately reflected volumetric activation maps.

3.2.7 Region of interest selection

To select ROIs (see Figure 7), I used the Neurosynth database (Yarkoni et al., 2011) to download reverse inference maps related to the term "action". Unlike typical heat maps of brain activation, high activation in maps from Neurosynth denote high overlap in studies reporting activity related to a keyword in any given voxel. To create the "action" ROIs, a sphere (9-mm radius) was centered on the voxel with peak activation (see Table 2) from the Neurosynth maps in areas known to be involved in action planning and production. ROIs were defined as the peak voxel nearest the expected anatomical landmarks, as follows:

- LOTC: lateral temporal cortex along the MTG;
- aSPL (including parts of aIPS): intersection of the intraparietal sulcus (IPS) and the postcentral sulcus in the SPL;
- aSMG: posterior to the postcentral sulcus, at the anterior end of the inferior parietal lobule;
- PMd: intersection of the superior frontal sulcus and the precentral sulcus;

- PMv: anterior to the precentral sulcus near the inferior frontal gyrus;

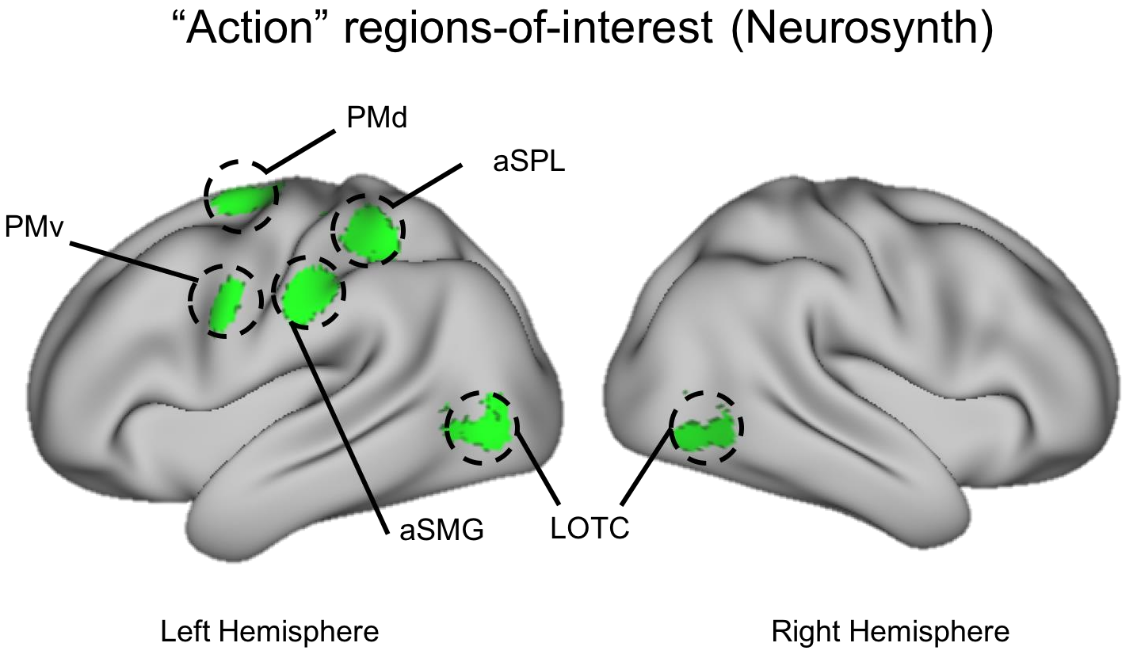


Figure 7. Regions of interest created using Neurosynth’s reverse inference maps for the keyword “action”. Spheres with a 9 mm radius were centered around peak voxels (see Table 2) in MNI space (2-mm isotropic voxels).

Table 2. MNI coordinates for the peak the voxel in Neurosynth’s reverse inference maps for “action” ROIs.

NEUROSYNTH ROI PEAK VOXEL COORDINATES			
	X	***Y***	***Z***
Left PMd	-24	-6	64
Left PMv	-56	4	36
Left aSPL	-36	-38	50
Left aSMG	-54	-22	36
Left LOTC	-50	-72	2
Right LOTC	52	-66	-2

3.2.8 Parameter estimate extraction

Z-values were extracted from statistical maps thresholded at Z = 2.3 using FSL's fslmeants function with "action" ROIs as a mask. Statistical maps were generated from either a [Tool > Object] or [Hand > Object] contrast separately for pictures and videos.

3.3 Results

3.3.1 Experiment 1

Before *directly* comparing videos to pictures, *tool-selective* areas were examined in a mixed-effects GLM analysis on group data. To this end, activity in response to tools was contrasted against non-tool objects, using subtraction logic to isolate activation specific to tools beyond contributions from other low-level visual factors that would also be present in object stimuli. I first examined tool-selectivity separately for pictures [$\text{Tool}_{\text{picture}} > \text{Object}_{\text{picture}}$] and videos [$\text{Tool}_{\text{video}} > \text{Object}_{\text{video}}$] to determine the areas that would be activated and to determine the degree of activation for conventional picture localizers compared to the new video localizer. Next, a *direct* comparison was carried out between tool selectivity for videos compared to pictures ([$\text{Tool}_{\text{video}} – \text{Object}_{\text{video}}$] > [$\text{Tool}_{\text{picture}} – \text{Object}_{\text{picture}}$] and vice versa) to determine whether the differences in tool-selectivity across formats reached statistical significance. Although I could have performed a direct contrast between videos of tools and pictures of tools [i.e., $\text{Tool}_{\text{video}} – \text{Tool}_{\text{picture}}$], this would have reflected not just differences in tool selectivity but also other confounds specific to format differences (e.g., motion). Thus, it was strategic to examine differences in tool-selectivity (after subtracting out format-specific confounds, also present in object conditions) rather than examine tool activation *per se*.

3.3.1.1 Tool-selectivity for pictures and videos at the group level

As shown in Figure 8A, for pictures, tools only elicited greater activity than objects in the ventral visual stream of the left hemisphere. Specifically, the activation focus was in a region that has previously been called the LOTC (e.g., Bracci et al., 2012) or posterior MTG (e.g., Lewis, 2006), and which is one of the most frequently reported areas in a meta-analysis of paradigms involving tools (Lewis, 2006). No tool-selectivity was observed in the dorsal visual stream for pictures.

For videos, on the other hand, tool-selectivity was observed in many dorsal visual stream areas including a swath of activation in left anterior parietal cortex (including the postcentral sulcus, aIPS, aSMG, and anterior superior parietal lobule, aSPL) as well as left PMd, and bilateral SMA. Although a past meta-analysis of paradigms involving tools found activation in these dorsal regions, it was relatively inconsistent across studies (Lewis, 2006). In contrast to pictures, no tool-selectivity was found in the ventral visual stream for videos.

In sum, pictures revealed tool-selectivity in ventral but not dorsal-stream regions; whereas, videos revealed tool-selectivity in dorsal but not ventral-stream regions. The fact that each format revealed tool-selective regions that the other format did not find may be due to limited power (related to the use of one run in a relatively small sample, N=10). Nevertheless, it suggests that power to detect activation in each of the two streams differs between videos and pictures, a conjecture that will be tested further with a larger sample size in Experiment 2.

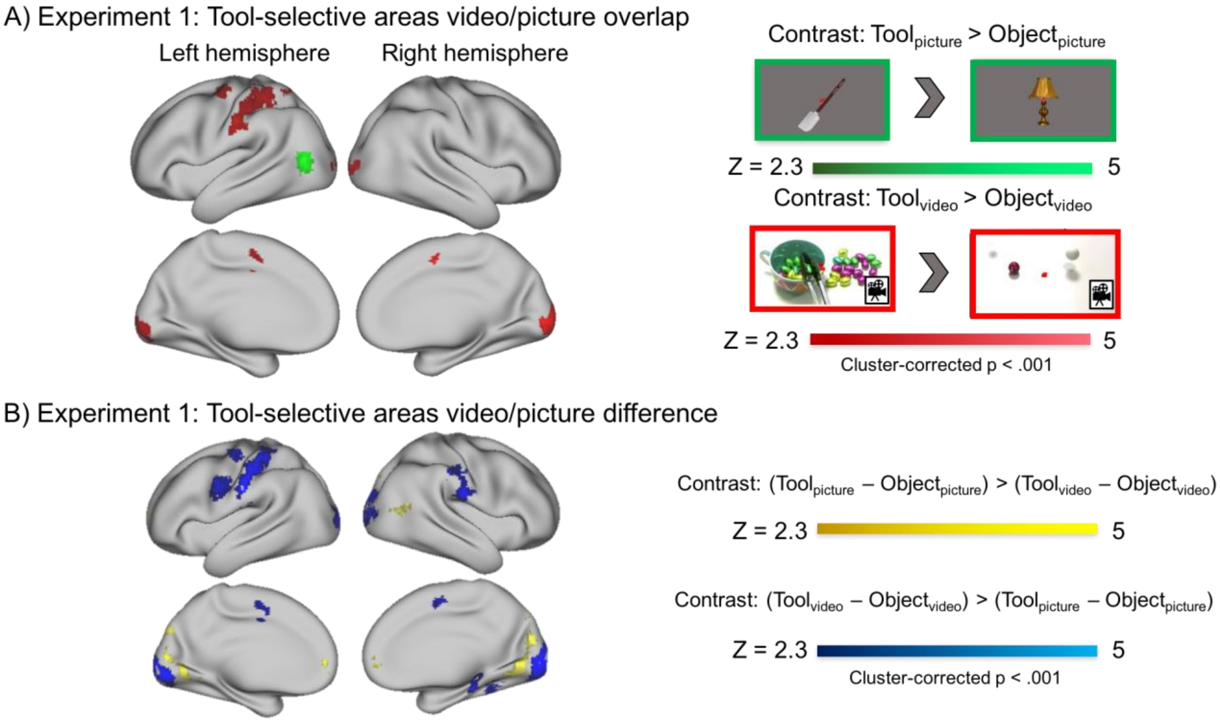
In addition to the object control condition, a second control condition was included to control for differences in low-level features consisting of dismorphed stimuli as a control for pictures and a movie of abstract art for videos. For both pictures and videos, greater tool-selectivity was found in large swaths of cortex compared to dismorphed pictures and low-level visual control videos (respectively). Furthermore, tool-selective areas identified by a contrast against object control stimuli and low-level control stimuli overlapped to a great extent. However, the contrast of tools against low-level control stimuli was more likely to yield tool-selectivity in primary visual areas known to be indifferent to categorical information. Thus, I concluded that objects were a better control condition and focused the rest of the analyses on the differences between tools (and later, hands) versus objects.

3.3.1.2 *Differences* in tool-selectivity for pictures and videos at the group level

Although the initial examination of tool-selectivity in pictures and videos *separately* was suggestive, to determine whether these differences were robust, I next *directly* compared tool-selective activity between formats, as shown in Figure 8B.

Even though the indirect comparison of tool selectivity maps above had revealed greater tool-selectivity for pictures than videos in *left* LOTC, the direct comparison here indicated significantly greater tool-selectivity for pictures than videos only in *right* LOTC. Though these results are somewhat surprising, a likely explanation is that the true differences in tool-selectivity may be effectively bilateral but appear lateralized in the analyses due to the small sample size. As such, only certain comparisons survived corrections for multiple comparisons.

Consistent with suggestions from the indirect comparisons of tool-selectivity between pictures and videos, the direct comparison confirmed that videos activated dorsal visual stream areas more than pictures including areas such as aIPS, aSMG, aSPL, and PMd. In addition, the direct comparison revealed greater tool-selectivity for videos than for pictures in left PMv and right aSMG (see Panel B in Figure 8).


A) Experiment 1: Tool-selective areas video/picture overlap

B) Experiment 1: Tool-selective areas video/picture difference

Figure 8. Tool-selectivity in Experiment 1: (A) Tool-selective areas (as defined by a tool > objects contrast) for videos (in red) and for pictures (in green) in the left and right hemispheres as determined by a mixed effects GLM, and (B) the interaction where tool-selective areas were more selective for videos than pictures (blue) and more selective for pictures more than videos (yellow).

Table 3. MNI coordinates for the peak voxel in group-averaged areas selective for tools over objects in Experiment 1.

EXPERIMENT 1							
TOOL > OBJECT							
PICTURE	***X***	***Y***	***Z***	**VIDEO**	***X***	***Y***	***Z***
Left LOTC	-44	-72	4	Left PMd	-20	-10	60
				Left aIPS	-52	-28	46
				Left aSPL	-30	-42	52
				Left aSMG	-56	-28	30
				Left SMA	-4	0	52
				Right SMA	6	2	54
PICTURE > VIDEO	***X***	***Y***	***Z***	**VIDEO > PICTURE**	***X***	***Y***	***Z***
Right LOTC	44	-64	8	Left PMd	-18	-10	60
				Left PMv	-58	8	30
				Left aIPS	-50	-28	46
				Left aSPL	-42	-32	56
				Left aSMG	-60	-16	30
				Right aSMG	56	-18	30

3.3.1.3 Hand-selectivity for pictures and videos at the group level

As with tools, before *directly* comparing videos to pictures, I searched for hand-selective areas *separately* for pictures and videos.

As shown in Figure 9A, for pictures, hands elicited greater activity than objects in the ventral visual stream in bilateral LOTC. This is in agreement with past research showing hand-selectivity is often bilateral in LOTC (Orlov et al., 2010), in contrast to tool-selectivity, which is more strongly lateralized to the left hemisphere (Lewis, 2006).

Comparatively, for videos, hands elicited greater activity than objects in dorsal visual stream areas in PMv and areas in the left parietal cortex such as aIPS and aSMG consistent with the notion of a left-lateralized network also for hand action control (Gallivan et al., 2013). Videos, in contrast to pictures, recruited more hand-selective areas in the dorsal visual stream suggesting that videos of hands are more effective at conveying action relevant information than pictures of hands. In line with past research (e.g., see Bracci et al., 2012), the results show that hand-selective areas overlap considerably with tool-selective areas.

3.3.1.4 Differences in hand-selectivity for pictures and videos at the group level

Contrasting formats *directly* (as shown in Figure 9B), surprisingly, a greater hand-selectivity for pictures in right LOTC as compared to videos was observed but, as expected, videos demonstrated greater hand-selectivity than pictures in dorsal visual areas including left PMd, left PMv, left aSPL, bilateral SMA, and left insula. As with tool-selective areas, it is likely that hand-selectivity in LOTC is in fact bilateral but the analyses lacked the power to be able to detect activity in both hemispheres.

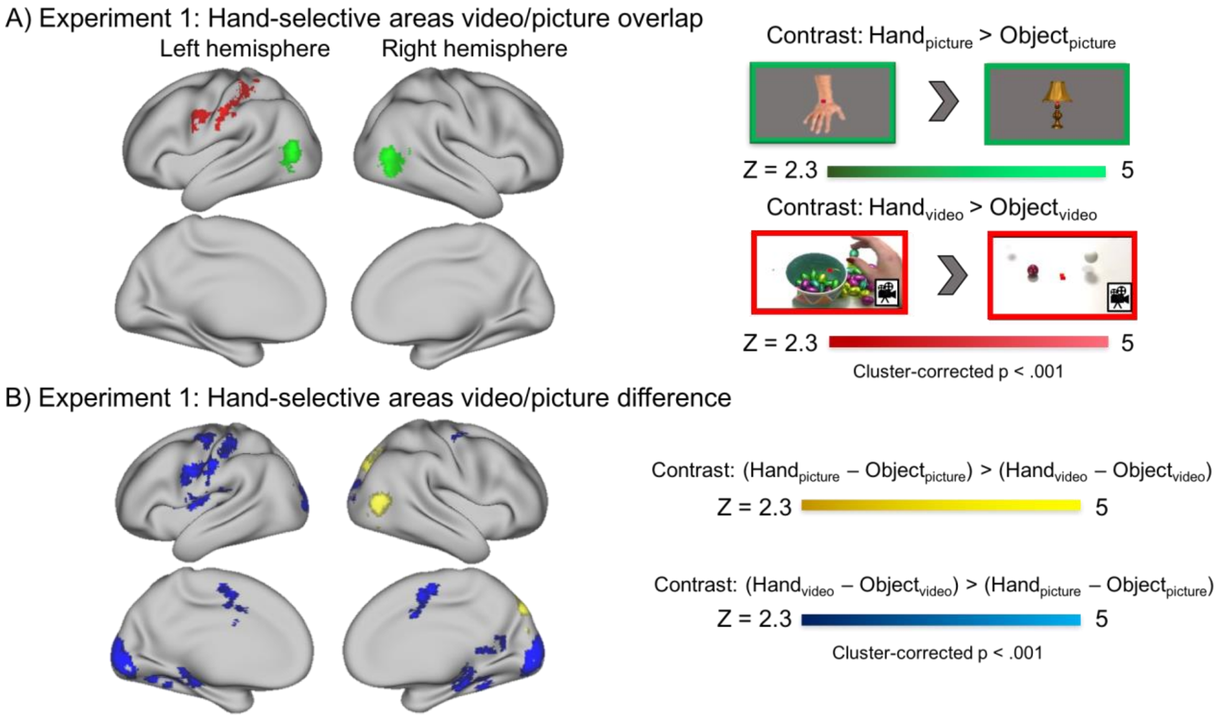
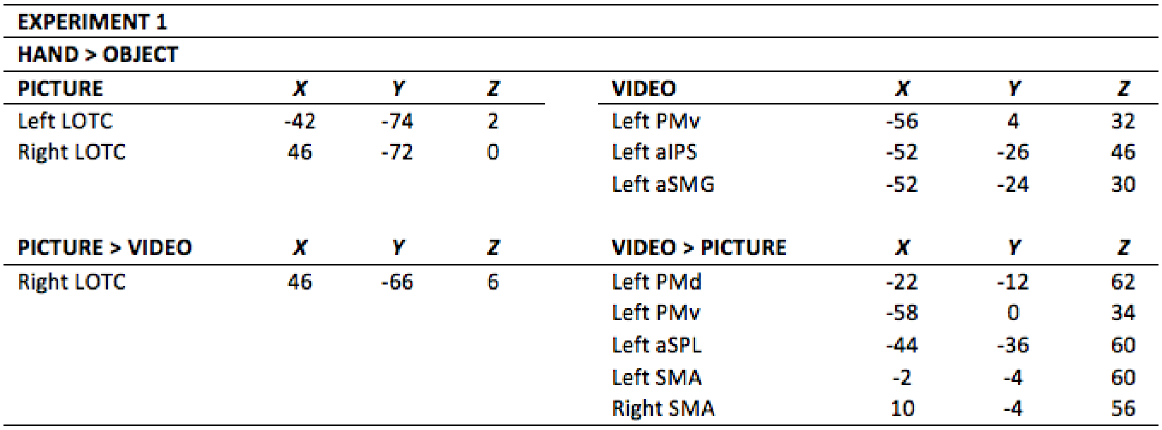


Figure 9. Experiment 1: (A) Hand-selective areas (as defined by a hand > objects contrast) for videos (in red) and for pictures (in green) in the left and right hemispheres as determined by a mixed effects GLM, and (B) interaction where

hand-selective areas were more selective for videos than pictures (blue) and more selective for pictures more than videos (yellow).

Table 4. MNI coordinates for the peak voxel in group-averaged areas selective for hands over objects in Experiment 1.

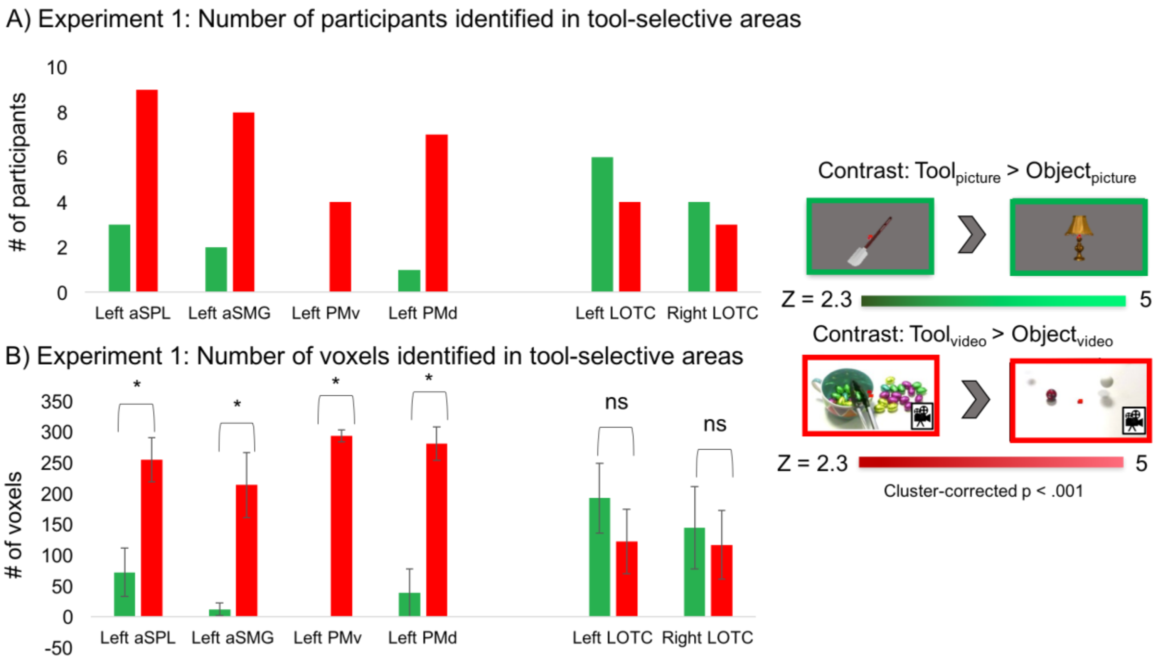


EXPERIMENT 1							
HAND > OBJECT							
PICTURE	**X**	**Y**	**Z**	**VIDEO**	**X**	**Y**	**Z**
Left LOTC	-42	-74	2	Left PMv	-56	4	32
Right LOTC	46	-72	0	Left aIPS	-52	-26	46
				Left aSMG	-52	-24	30
PICTURE > VIDEO	**X**	**Y**	**Z**	**VIDEO > PICTURE**	**X**	**Y**	**Z**
Right LOTC	46	-66	6	Left PMd	-22	-12	62
				Left PMv	-58	0	34
				Left aSPL	-44	-36	60
				Left SMA	-2	-4	60
				Right SMA	10	-4	56

3.3.1.5 Differences in tool- and hand-selectivity at the individual level

One of the primary goals of this study was to compare the *effectiveness* of videos and pictures at localizing tool- and hand-selective areas at the *individual* level. To this end, Z-values were extracted under ROIs involved in visuomotor control generated from Neurosynth maps (see Methods). Specifically, I focused analyses on bilateral LOTC, left aSPL, left aSMG, left PMd, and left PMv (areas also revealed in the group analyses) as they are commonly reported in experiments involving real actions with real tools and hands (Brandi et al., 2014; Gallivan et al., 2013).

To determine whether videos or pictures were more effective at localizing the individual-level ROIs, I first compared the number of participants that showed any significant tool- and hand-selective activity in “action” ROIs (see Figure 7) generated from Neurosynth maps (thresholded at Z = 2.3 and cluster-corrected at p < .001). In line with predictions, tool- and hand-selective ROIs could generally be localized in more participants with videos compared to pictures (see Figures 10A and 11A). Videos were unquestionably more effective than pictures at localizing areas in the dorsal visual stream however pictures marginally out-performed videos in the ventral visual steam specifically in left and right LOTC. An exact McNemar’s test revealed that, after collapsing across all ROIs, the probability of finding significant activation in individual participants differed significantly between videos vs. pictures for tools (*p* = .003) but not for hands (*p* = .5). Although the analysis is only shown for one particular threshold (Z= 2.3), the same trend was also observed at more conservative (Z = 3) and at more liberal thresholds (Z = 2), showing that the effect is robust despite the specific choice of statistical parameters.


A) Experiment 1: Number of participants identified in tool-selective areas

B) Experiment 1: Number of voxels identified in tool-selective areas

Figure 10. Experiment 1: Number of participants in which any significantly activated tool-selective voxel was detected within the ROIs (Panel A), and the number of significantly activated voxels detected within these ROIs (Panel B). All maps were thresholded at Z = 2.3 (cluster-corrected *p* < .001) before parameter estimates were extracted in MNI space (2 mm isotropic voxels), and error bars represent standard error of the mean.

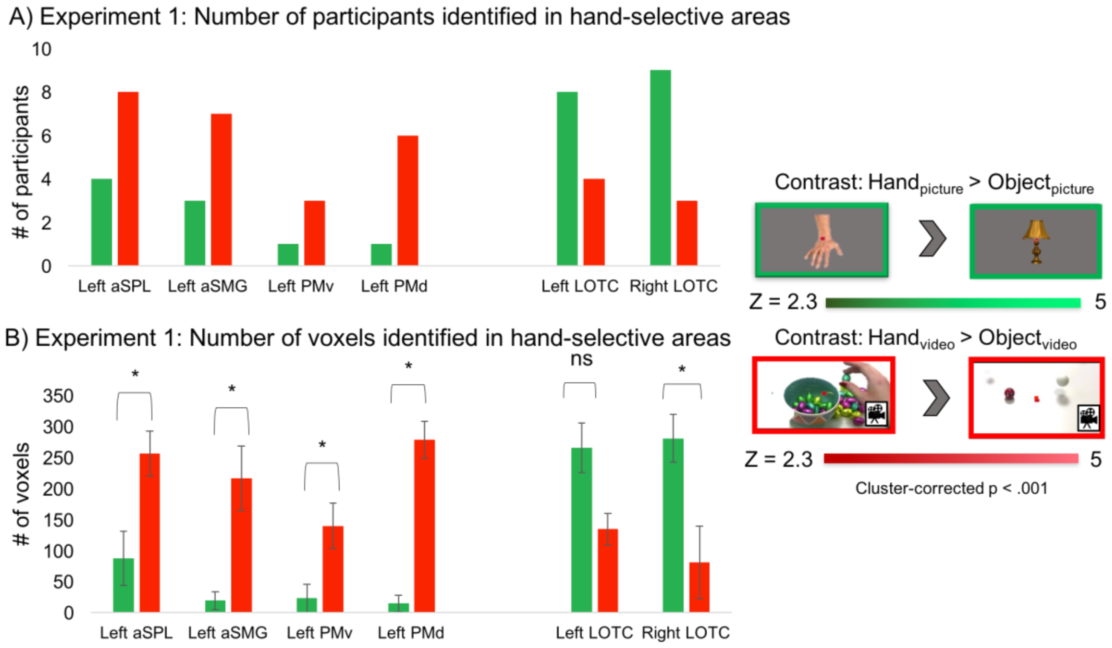


Figure 11. Experiment 1: Number of participants in which any significantly activated hand-selective voxel was detected within the ROIs (Panel A), and the number of significantly activated voxels detected within these ROIs (Panel B). All maps were thresholded at Z = 2.3 (cluster-corrected *p* < .001) before parameter estimates were extracted in MNI space (2 mm isotropic voxels), and error bars represent standard error of the mean

I next compared the *number* of significantly activated voxels (at the individual level) within the ROIs (see Figures 7B and 8B). Only participants who showed activity in the ROIs from the first analysis were included in this second level of the analysis. The results revealed that the participants who showed significant category-selective activation for pictures and videos showed more extensive category-selective activation (i.e., more significant voxels) for videos than pictures in dorsal-stream regions. Had I computed the number of significantly activated voxels for all participants, the difference would have been even more pronounced.

3.3.2 Experiment 2

3.3.2.1 Tool-selectivity for pictures and videos at the group level

As with Experiment 1, before *directly* comparing videos to pictures, I searched for tool-selective areas *separately* for pictures and videos in a mixed-effects GLM analysis on group data. In comparison to Experiment 1, the data for Experiment 2 had a larger sample size (N = 16 vs. N = 10) to increase statistical power. Both pictures and videos were collected in the same design (blocked) using the same scanner protocol (multiband).

As shown in Figure 12A, for pictures, no tool-selectivity was observed. This is in contrast to Experiment 1 where tool-selectivity was found in left LOTC. The discrepancy between experiments could be the result of using different stimuli. In Experiment 1, pictures of tools and objects were isolated on a neutral gray background such that no context was provided. In contrast, in Experiment 2, tools and objects were both presented in the context of a larger real-world scene. Pictures of tools and objects were frames taken from the respective videos such that low-level features were more well matched than they had been in the first experiment.

As in Experiment 1, videos elicited greater tool-selectivity in dorsal visual stream areas including bilateral aIPS, bilateral aSMG, left PMd, left PMv, and left aSPL. In contrast to Experiment 1, where tool-selectivity for pictures but not videos was observed in LOTC, in Experiment 2 the converse was observed, tool-selectivity for videos but not pictures in LOTC. This suggests that the features of the stimuli (such as context and relationship with target stimuli) may be important factors in the ventral-stream areas such as LOTC.

In addition to objects, a second control condition was included to control for differences in low-level features using phase-scrambled stimuli instead of dismorphed pictures or modern art videos. With this second control, both pictures and videos elicited tool-selectivity in greater swaths of cortex compared to the phase-shifted stimuli. As with Experiment 1, the low-level control condition for Experiment 2 evoked activation in primary visual areas that are indifferent to categorical information. This is likely driven by factors such as the differences in the retinotopic distribution of motion therefore I decided to focus on the comparison between tools (and later, hands) vs. objects.

3.3.2.2 Differences in tool-selectivity for pictures and videos at the group level

Contrasting formats *directly* (as shown in Figure 12B), videos revealed greater tool-selectivity in dorsal and ventral visual areas than pictures in both hemispheres including right PMv and bilateral insula. These data, in addition to data from the separate format analysis, confirm that videos are indeed more effective than pictures at localizing tool-selective areas. Consistent with simple subtraction ($\text{Tool}_{\text{picture}} > \text{Object}_{\text{picture}}$), no regions in which pictures localized tool-selective regions better than videos were found.

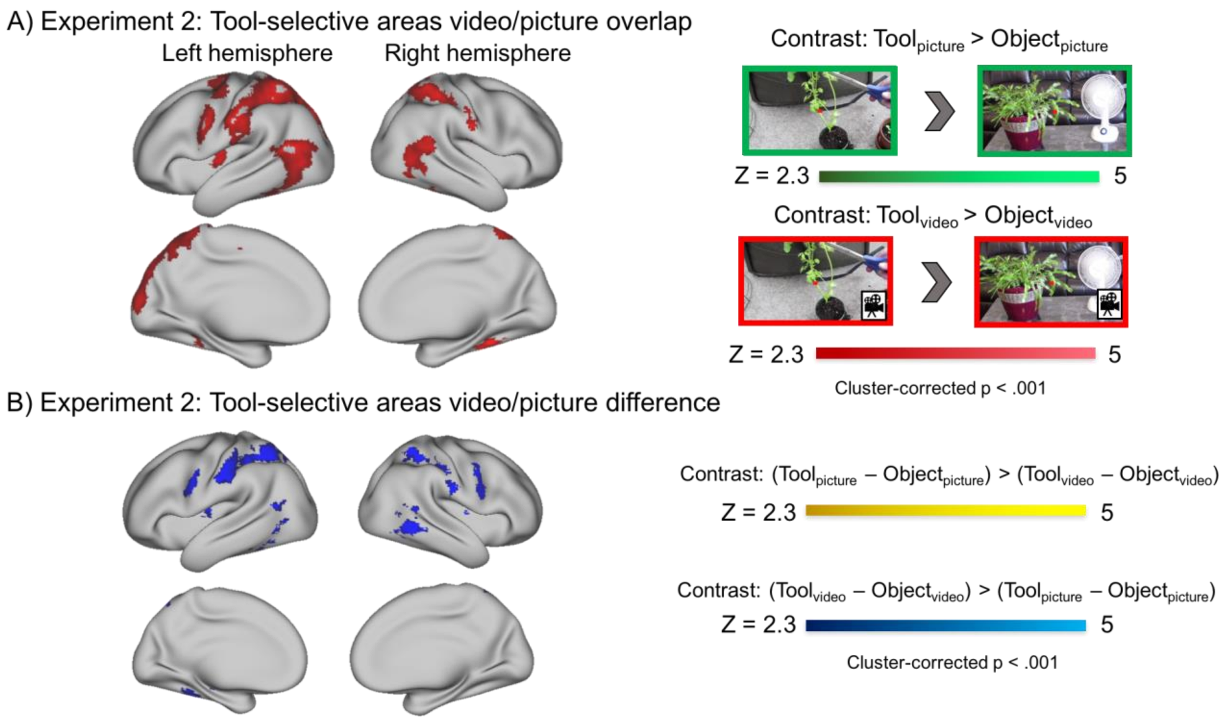


Figure 12. Experiment 2: (A) Tool-selective areas (as defined by a tool > objects contrast) for videos (in red) and for pictures (in green) in the left and right hemispheres as determined by a mixed effects GLM, and (B) interaction where tool-selective areas were more selective for videos than pictures (blue) and more selective for pictures more than videos (yellow).

Table 5. MNI coordinates for the peak voxel in group-averaged areas selective for tools over objects in Experiment 2.

EXPERIMENT 2							
TOOL > OBJECT							
PICTURE	**X**	**Y**	**Z**	**VIDEO**	**X**	**Y**	**Z**
-	-	-	-	Left PMd	-30	-10	60
				Left PMv	-58	8	30
				Left aIPS	-54	-28	38
				Left aSPL	-22	-58	62
				Left aSMG	-54	-28	38
				Left LOTC	-50	-62	10
				Right aSMG	44	-30	38
				Right LOTC	50	-60	2
PICTURE > VIDEO	**X**	**Y**	**Z**	**VIDEO > PICTURE**	**X**	**Y**	**Z**
-	-	-	-	Left PMv	-58	8	28
				Left aIPS	-54	-28	38
				Left aSPL	-32	-58	60
				Left LOTC	-48	-62	12
				Right PMv	54	8	28
				Right aIPS	56	-26	46
				Right aSPL	36	-36	50
				Right aSMG	66	-12	28
				Right LOTC	60	-50	-6

3.3.2.3 Hand-selectivity for pictures and videos at the group level

Looking at activation *separately* for pictures and videos, as shown in Figure 13A, pictures showed hand-selectivity in left LOTC whereas videos elicited greater hand-selectivity in dorsal and ventral visual areas such as left aIPS, left PMd, left PMv, and bilateral aSMG, bilateral aSPL, bilateral LOTC. Hand-selective areas uncovered with videos (but not pictures) overlapped with tool-selective areas uncovered with videos; however, pictures of tools and pictures of hands showed differential activation. This is in contrast to Experiment 1 where hand- and tool-selective areas overlapped considerably irrespective of format.

3.3.2.4 Differences in hand-selectivity for pictures and videos at the group level

Contrasting formats *directly* (as shown in Figure 13B), videos showed greater hand-selectivity than pictures in left aSMG and ventral occipitotemporal cortex.

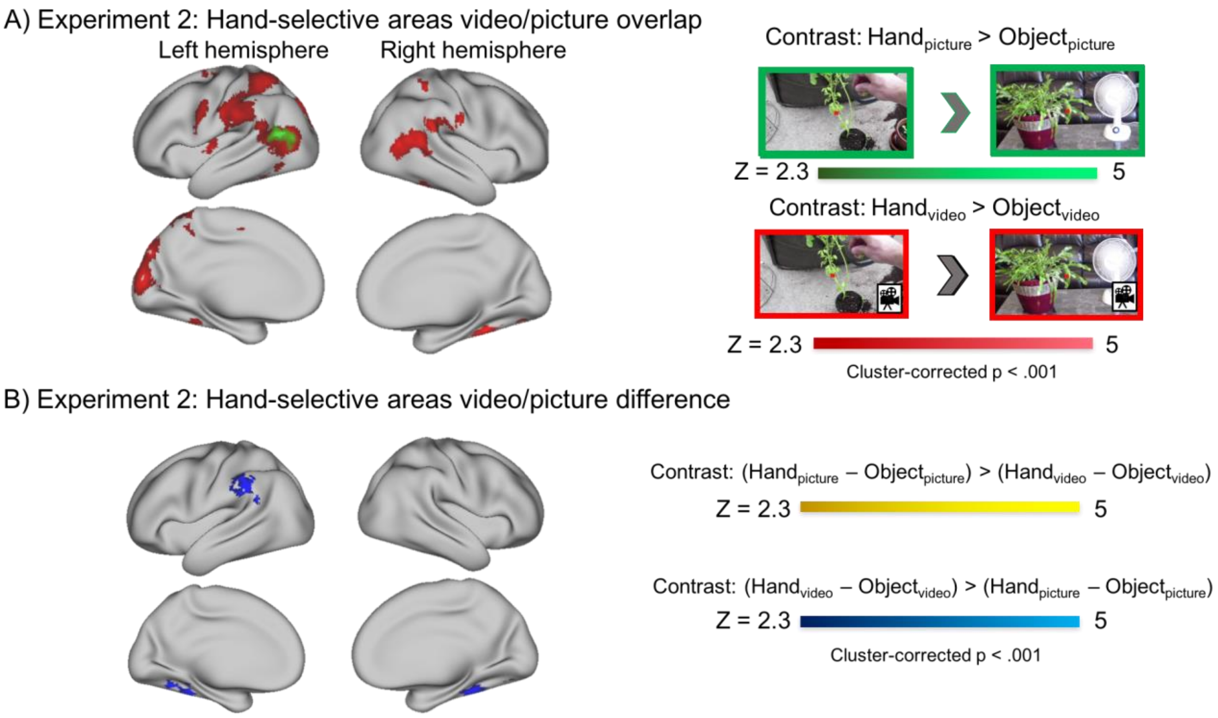
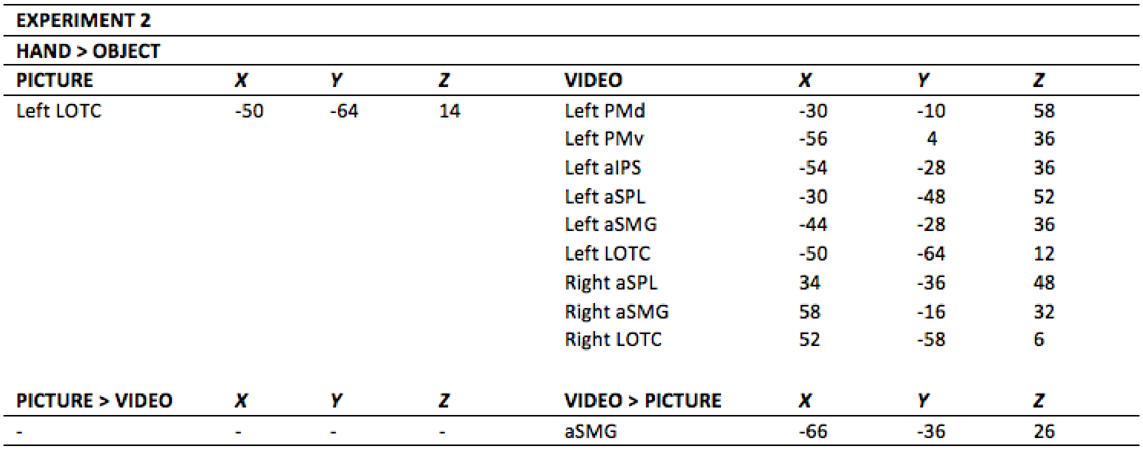


Figure 13. Experiment 2: (A) Hand-selective areas (as defined by a hand > objects contrast) for videos (in red) and for pictures (in green) in the left and right hemispheres as determined by a mixed effects GLM, and (B) interaction where hand-selective areas were more selective for videos than pictures (blue) and more selective for pictures more than videos (yellow).

Table 6. MNI coordinates for the peak voxel in group-averaged areas selective for hands over objects in Experiment 2.



EXPERIMENT 2							
HAND > OBJECT							
PICTURE	***X***	***Y***	***Z***	**VIDEO**	***X***	***Y***	***Z***
Left LOTC	-50	-64	14	Left PMd	-30	-10	58
				Left PMv	-56	4	36
				Left aIPS	-54	-28	36
				Left aSPL	-30	-48	52
				Left aSMG	-44	-28	36
				Left LOTC	-50	-64	12
				Right aSPL	34	-36	48
				Right aSMG	58	-16	32
				Right LOTC	52	-58	6
PICTURE > VIDEO	***X***	***Y***	***Z***	**VIDEO > PICTURE**	***X***	***Y***	***Z***
-	-	-	-	aSMG	-66	-36	26

3.3.2.5 Differences in tool- and hand-selectivity at the individual level

As with Experiment 1, to determine whether videos or pictures were more effective at localizing ROIs and the individual level, I contrasted the number of participants that showed any activity in spheres centered on the peak voxels from the “action” ROIs from Neurosynth.

On average, tool- and hand-selective ROIs could be localized in more participants with videos as compared to pictures (see Figures 14A and 15A). In agreement with this, an exact McNemar’s test revealed that, collapsing across all ROIs, the probability of finding significant activation in individual participants differed significantly between videos vs. pictures for both tools ($p < .001$) and for hands ($p < .001$). Comparing the *number* of significantly activated voxels (at the individual level) within the ROIs for the participants who showed significant activation, again videos out-performed pictures in most tool- and hand-selective regions (see Figures 14B and 15B), except for the left hand- and tool-selective LOTC where pictures out-performed videos.

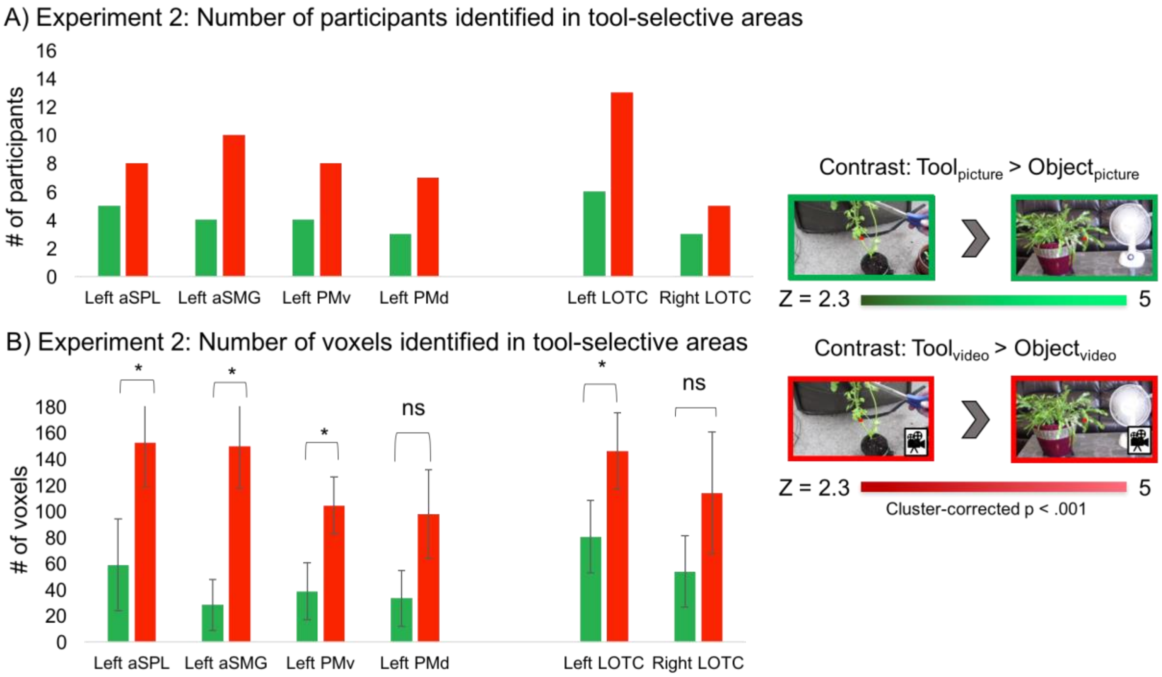


Figure 14. Experiment 2: Number of participants in which any significantly activated tool-selective voxel was detected within the ROIs (Panel A), and the number of significantly activated voxels detected within these ROIs (Panel B). All maps were thresholded at Z = 2.3 (cluster-corrected *p* < .001) before parameter estimates were extracted in MNI space (2 mm isotropic voxels), and error bars represent standard error of the mean.

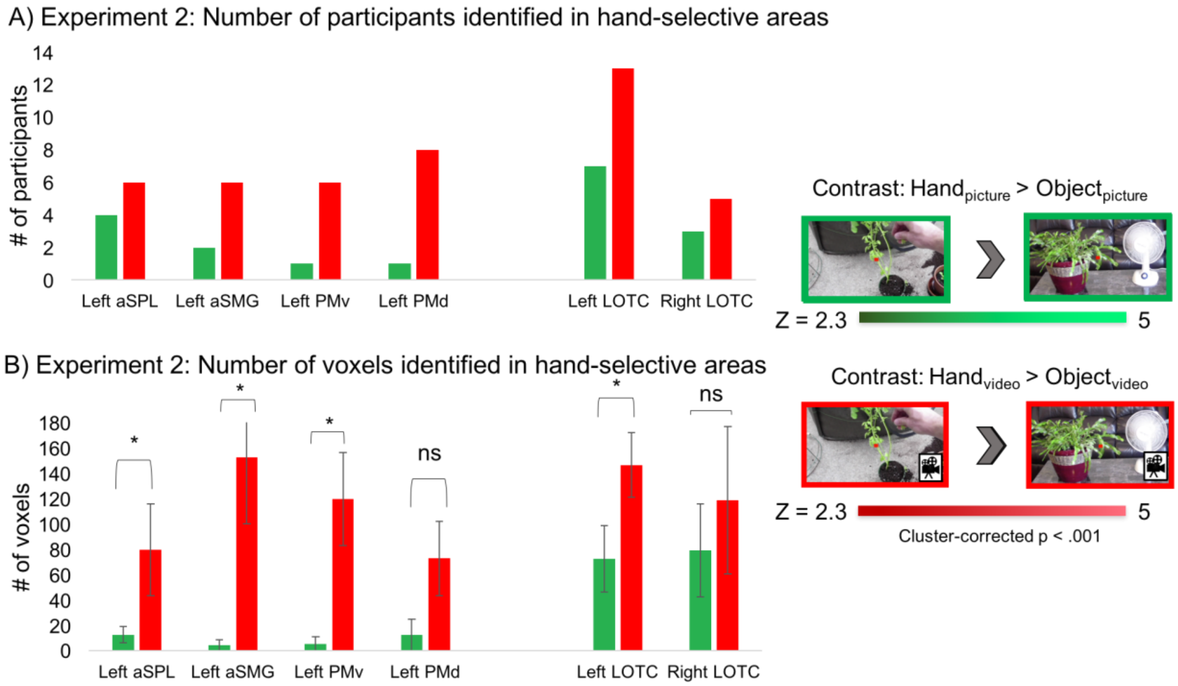


Figure 15. Experiment 2: Number of participants in which any significantly activated hand-selective voxel was detected within the ROIs (Panel A), and the number of significantly activated voxels detected within these ROIs (Panel B). All maps were thresholded at Z = 2.3 (cluster-corrected *p* < .001) before parameter estimates were extracted in MNI space (2 mm isotropic voxels), and error bars represent standard error of the mean.

3.3.3 Experiments 1 and 2: Activation preferences for tools vs. hands at the group level

Although not a central question of the experiment, I also examined whether any regions showed a preference for tools compared to hands or vice versa. Recall that for the video stimuli in both experiments and the pictures only in Experiment 2, hands and tools performed the same actions (e.g., moving dirt with a hand or a shovel) unlike the picture stimuli in Experiment 1, typical of past experiments, in which hands and tools were unrelated and presented out of context. In addition, for regions that showed preferences for tools relative to hands or vice versa, I also examined whether the preference differed for videos vs. pictures.

As shown in Figures 16A and 16B, I *directly* compared tool-selective areas to hand-selective areas using contrast of a (Tool – Hand) and the converse (Hand – Tool) in Experiment 1 and Experiment 2.

For Experiment 1, the right LOTC showed higher activation for pictures of hands vs. tools and pictures of hands vs. the rest baseline [($\text{Hand}_{\text{picture}} > \text{Tool}_{\text{picture}}$) AND ($\text{Hand}_{\text{picture}} > 0$), dark green]. The strength of this hand preference was stronger for pictures than for videos [($\text{Hand}_{\text{picture}} - \text{Tool}_{\text{picture}}$) > ($\text{Hand}_{\text{video}} - \text{Tool}_{\text{video}}$), light green]. No regions showed a Hand > Tool preference for videos. In addition, no regions showed a preference for Tools > Hands in either format. This result agrees with the ($\text{Hand}_{\text{picture}} - \text{Object}_{\text{picture}}$) contrast from Experiment 1 suggesting, again, that parts of the ventral visual stream are perhaps more selective for pictures of hands than other categories of stimuli (including videos of hands and pictures of tools).

For Experiment 2, the right aIPS (extending into the SPL) showed greater activation for videos of tools vs. hands and videos of tools vs. the rest baseline [($\text{Tool}_{\text{video}} - \text{Hand}_{\text{video}}$) AND ($\text{Tool}_{\text{video} >}$ 0), dark red]. This selectivity was more evident for videos than for pictures [($\text{Tool}_{\text{video}} - \text{Hand}_{\text{video}}$) > ($\text{Tool}_{\text{picture}} - \text{Hand}_{\text{picture}}$), light red]. No regions showed a preference for Tool > Hand for pictures. Moreover, no preferential activation was observed preferences for Hand > Tool in either format.

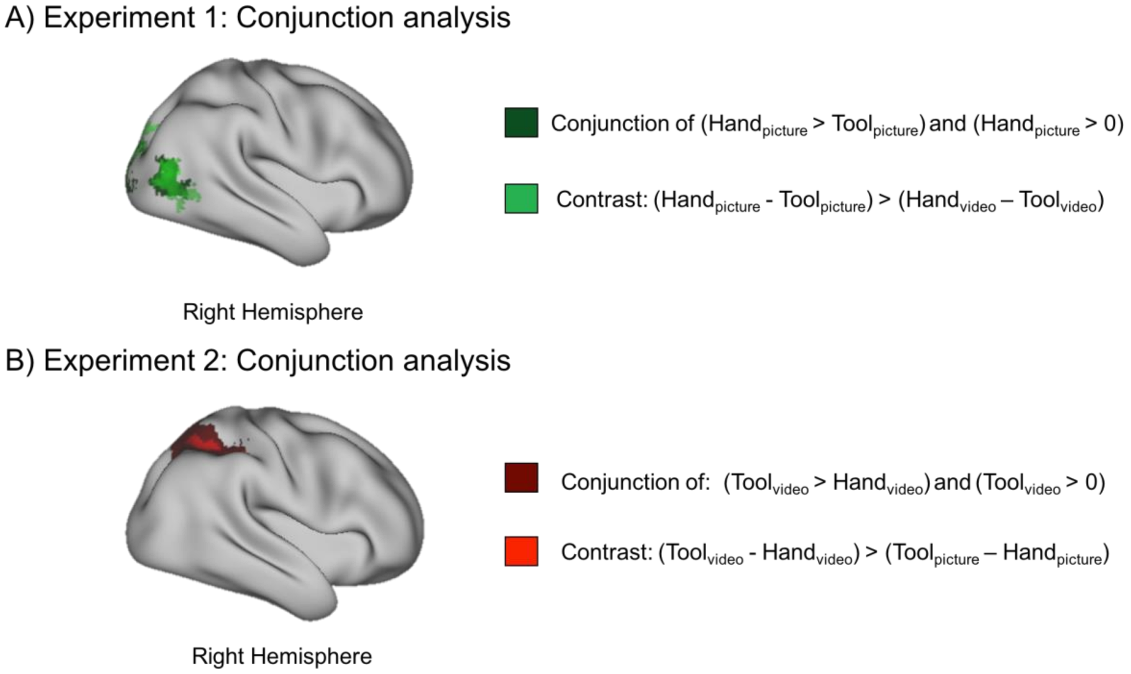


Figure 16. Areas more selective for hands than for tools (Panel A) and vice versa (Panel B). Dark colours indicate category-selective areas whereas bright colours show indicate areas that survived all conjunction analyses whereby activity was greater within format and greater than zero. The MNI coordinate for the peak voxels were as follows: right LOTC in Panel A; X = 42 Y = -70 Z = -4 and right IPS in Panel B; X = 34 Y = -52 Z = 42.

3.4 Discussion

Overall, this study demonstrates that videos out-perform pictures at eliciting tool- and hand-selective activity. The superiority of videos as compared to pictures was unequivocal for many visuomotor regions of the dorsal stream including PMd, PMv, aSMG, and aSPL. Specifically, compared to pictures, videos elicited stronger tool-and hand-selectivity at the group level, along with more reliable activation at the individual level across a range of liberal to conservative thresholds. Importantly, videos were more effective across two experiments despite *numerous* methodological differences. They were better at eliciting category-selective activity both when the picture condition was typical of the approach used in past studies (Experiment 1) and when pictures and videos were well-matched for scene content and complexity (Experiment 2). The effectiveness of videos vs. pictures appeared mixed, however, in the ventral stream, where pictures occasionally out-performed videos at localizing hand-selective LOTC.

Taken together, these results suggest that video stimuli are superior to conventional picture stimuli for localizing category-selective areas, especially for categories with tight links to actions such as tools and hands. I propose that the superiority of videos, especially in the dorsal visual stream, arises from greater invocation of action contexts and goals. Pictures, however, may be more well-suited to tap into semantic constructs for categories such as hands, which are often processed in the ventral visual stream (Hoeren et al., 2013).

3.4.1 Why do videos activate dorsal visuomotor areas more effectively than pictures?

Firstly, videos explicitly convey the interaction between the effector and its target. With picture stimuli, the target object is rarely shown and thus there is no clear interaction between a tool and target. For instance, the purpose of a hammer in a picture is less clear when it is shown in the absence of a nail. In fact, both neurotypical participants and neuropsychological patients perform better when the spatial relationship between a tool and a target are appropriate for the typical tool action (e.g., when a hammer is shown above a nail rather than below; Humphreys et al., 2013). Moreover, in the absence of a context, a participant may not be thinking about the actions that they could perform with the tool or they may be thinking about more than one possible action (e.g., pounding a nail with the hammer’s peen, prying out a nail with the hammer’s claw, or moving the hammer to a shelf). In contrast, by showing a specific action with a video clip, the breadth of possible actions is both guided and constrained. Indeed, there is considerably less variability between participants viewing videos with meaningful vs. meaningless plots (Hasson et al., 2008). Accordingly, meaningful actions are more likely than meaningless actions to recruit visuomotor areas in the action control network (Decety et al., 1997). This is perhaps not surprising as humans, relative to other primates like the macaque monkey, are thought to have a unique ability to understand the meaningful relationship between an effector and its target (Peeters et al., 2009).

Secondly, one obvious but critical benefit videos have relative to pictures is in conveying a tool or hand's characteristic motion. It is perhaps counter-intuitive to study tool- and hand-selectivity using stimuli that are devoid of motion. Using videos is a more ecologically valid approach than using pictures as videos can highlight the motion that is intrinsic to action. The motion associated with tools and hands is unique and its uniqueness cannot be explained solely by the low-level features of motion. For instance, simple point-light displays of tools in motion do not always show the same brain activation profile as in fully depicted tools in motion (Beauchamp et al., 2003). In that same vein, point-light displays of hand motion are also perceived as distinct from displays of random motion or body motion (Bonda, Petrides, Ostry, & Evans, 1996). Using videos of real tool and hand actions, I further validate that the added use of motion is beneficial when studying action control in the visuomotor system. This has been the case in previous studies of tool use (Peeters et al., 2009) and also in studies investigating other categories with defining motion such as faces (Pitcher et al., 2011) and hands (Orlov et al., 2014).

Lastly, one might argue that videos may have out-performed pictures because they are more engaging; however, this difference cannot solely explain the results. Notably, by examining within-format related differences in tool selectivity (e.g., $\text{Tool}_{\text{video}}$ - $\text{Object}_{\text{video}}$ > $\text{Tool}_{\text{picture}}$ - $\text{Object}_{\text{picture}}$) rather than overall activation levels (e.g., $\text{Tool}_{\text{video}}$ > $\text{Tool}_{\text{picture}}$), activation related to viewing videos vs. pictures in general was "subtracted out". Moreover, differences between videos and pictures were still observed even when a task was introduced (Experiment 2).

3.4.2 When may pictures out-perform videos at activating category-selective areas?

Even though videos were, on average, superior to pictures at localizing category-selective areas, pictures were at times more effective at localizing hand-selective LOTC in Experiment 1. This, however, was not the case in Experiment 2, when video and picture stimuli were well-matched and videos continued to out-perform pictures.

It is possible, then, that LOTC may show greater selectivity for pictures of hands in isolation on a neutral background (Experiment 1) than for pictures of hands in the context of scenes and objects (Experiment 2). Because hand-selectivity was defined using the contrast of Hands > Objects, selectivity may have been more pronounced in Experiment 1 where hands were shown in the absence of other objects compared to Experiment 2 where hands were shown amongst other objects.

Alternatively, pictures may have evoked more hand-selectivity than videos because static pictures conveying *implied* motion can activate motion-selective area MT+ within LOTC (Senior et al., 2000; Kourtzi, Bülthoff, Erb, & Grodd, 2002). In Experiment 1, pictures of static hands evoked more implied motion than pictures of static objects whereas videos of hands and objects would not evoke implied motion as they both depict *actual* motion.

3.4.3 Tools vs. hands

Previous studies have shown that *pictures* of tools and hands tend to activate similar portions of LOTC even though they are quite visually dissimilar (Bracci et al., 2012; Brandi et al., 2014; Gallivan et al., 2013). Although it was not a central motivation of the study, the fact that the stimuli included tool and hand stimuli performing comparable actions provided the opportunity to examine differences in activation.

The direct comparison between tools and hands revealed that categorical differences, however few, exist. Pictures of hands, in Experiment 1 only, activated ventral-stream areas within LOTC in the right hemisphere more than pictures of tools. This is likely because hands tend to activate LOTC bilaterally whereas tools often only activate LOTC in the left hemisphere (Bracci et al., 2012).

Although pictures of hands yielded higher activation in LOTC than pictures of tools in Experiment 1 (when the stimuli were shown in an isolated context) this effect was absent for videos in Experiment 1 and absent for both pictures and videos in Experiment 2 (when the stimuli were presented in a richer context). That is, the preference for hands as compared to tools was lost once the stimuli were depicted in a richer context when objects were acted upon within scenes. Given that LOTC shows distributed coding for many types of stimuli (e.g., Haxby et al., 2001), it may be that the added complexity from actions, objects, and scenes saturates the activation for hands and tools.

Additionally, videos of tools, in Experiment 2 only, activated dorsal-stream areas along the aIPS (extending into SPL) in the right hemisphere to a greater extent than videos of hands. Several key differences between how the same actions are performed with tool vs. hand could account for these results. For instance, actions with the tool may have looked more natural than actions with the hand, or actions with the tool may have been perceived differently given the added the relationship between the hand movement and the effect upon the acting end of the tool. For example, when lifting an object with tongs, one must factor in the differences between the hand's movements and its consequences on the acting part of the tool. Of note, however, action control typically recruits areas in the *left* hemisphere (Gallivan et al., 2013; Brandi et al., 2014). In this study, areas that responded more for tools than for hands (and vice versa) were in the *right* hemisphere. However, given that the right hemisphere is implicated in spatial transformations (e.g., Króliczak et al., 2007), the right anterior IPS may be recruited more when observing tool actions than hand actions.

3.5 Conclusion

In sum, videos are superior to pictures at revealing category-selective areas. Videos have revealed distinct regions of the brain selective for dynamic faces (Pitcher et al., 2011), bodies (Bonda et al., 1996), and, as shown here, tools and hands. Pictures have only told part of the story thus far.

Even though pictures have successfully identified some category-selective areas also recruited in action control, the content available in pictures is ambiguous and limited, which could make certain visuomotor areas difficult to detect (especially those selective for characteristic motion). Videos, on the other hand, are reliable at activating tool- and hand-selective areas at the individual level as they clearly demonstrate the *interaction* between effector and target, they provide context, and they are more engaging than pictures. Additionally, videos maintain this advantage while still accessing the same action-relevant information that is available in pictures (Hafri, Trueswell, & Epstein, 2017).

Although there are merits to using real actions and real objects in the scanner, especially for the study of visuomotor areas (Snow et al., 2011; Brandi et al., 2014; Freud et al., 2017) this approach is more technically challenging and does not enable use of the full range of real-world actions. For example, limited space in the scanner's narrow bore constrains possible actions, only objects that are non-magnetic can be used, and only certain actions can be performed without inducing motion artifacts. In many cases, videos may provide an optimal solution that brings the study of hand actions and tool use closer to the real world than the use of pictures while still enabling the study of a wide range of naturalistic actions.

Importantly, the benefits of using videos are not limited the study of tool and hand processing. Videos have revealed selectivity for dynamic faces and bodies otherwise undetected if only pictures had been used (Bonda et al., 1996; Pitcher et al., 2011). Videos could also be beneficial for studying other categories in which characteristic motion exists such as scenes, objects, and emotion.

Chapter 4

4 The Impact of Tool Familiarity and Task on Human Visuomotor Areas

4.1 Introduction

The study of tool use provides a window into the evolution of the human brain (Buckner & Krienen, 2013). Arguably, one of the features that distinguishes humans most from other species is the ability to understand and use complex tools. Actions with complex tools and the brain areas that subserve these actions are thought to be unique to humans. Non-human primates, one of the orders that is evolutionarily closest to humans, cannot create compound tools (Frey, 2001) nor do they show the same tool-selective activation that is observed in humans (Peeters et al., 2009).

Neuroimaging researchers have developed clever techniques to study areas selective for tool use using human fMRI. They have adopted strategies influenced by the affordance perspective (Gibson, 1977) whereby the mere passive *observation* of a tool is assumed to activate motor plans in brain areas associated with the actual *use* of that tool. In typical fMRI studies on tool use, participants are presented with pictures of tools and may be required to silently name them, imagine their use, or passively view them (Lewis, 2006). Largely irrespective of task, a network of left-lateralized areas is reliably activated which is comprised of regions that are also recruited when actions are planned and performed with tools (Brandi et al., 2014; Gallivan et al., 2013).

While these results have been suggestive, past research has overlooked an important factor: how *familiarity* with the presented tools impacts areas that guide *functional* actions (e.g., using a hammer to pound a nail into wood) as opposed to non-functional actions (e.g., simply moving a hammer from one location to another). For instance, patients with ideomotor apraxia, individuals who cannot perform tool actions from memory but have intact conceptual knowledge of tools, demonstrate a dissociation between actions in response to familiar and unfamiliar tools. Patients with ideomotor apraxia cannot accurately use familiar tools but perform like neurotypical individuals when asked to use a novel tool (Buxbaum et al., 2003). This suggests that actions in response to familiar tools rely on functional associations whereas actions in response to unfamiliar tools are likely guided by cues provided by the structure of the tool (e.g., center of mass). Unfortunately, many studies investigating the neural correlates of tool use have not assessed the familiarity of the tools presented in their experiments (e.g., Chao & Martin, 2000; Wadsworth & Kana, 2011; Bracci et al., 2012). Neglecting familiarity likely results in a blend of activation associated with mechanisms that either guide actions from functional cues (i.e., for familiar tools) and that guide actions from structural cues (i.e., for unfamiliar tools).

One way to disentangle effects of familiarity on visuomotor areas involved in action control is to examine dissociable responses to familiar and unfamiliar tools when functional and non-functional actions are performed. If functional associations guide actions with familiar tools, visuomotor brain areas should be more active in response to familiar than unfamiliar tools. Critically, familiarity should only mediate activity when functional actions are carried out as opposed to when non-functional actions are executed in which functional associations are less important. Indeed, past research has shown that the visuomotor system processes tools differently depending on the actor’s goal. For instance, latencies are greater when planning to *use* a tool relative to planning to *move* a tool (Valyear et al., 2011; Squires et al., 2016). Accordingly, brain areas involved in visuomotor actions activate to a greater extent when tools are *used* compared to when they are *moved* (Brandi et al., 2014).

Few researchers, however, have considered the extent to which their participants are familiar with the tool actions used in experiments. Moreover, when researchers have considered familiarity, they have often collected normative ratings from a sample separate from those actually tested in their experiment (e.g., Vingerhoets et al., 2011). This is an oversight as repeated execution of an action can alter how that action is processed by the visuomotor system which may lead to different effects across individuals (Weisberg, van Turennout, & Martin, 2007). For example, professional capoeira dancers show different brain activation when they view videos of their own learned dance genre relative to when they view videos of novel dance genres such as ballet (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005). In the same vein, repeated use of a familiar tool can also alter what aspects of the environment draw the attention of the viewer. In cricket, for example, expert batsmen are better able to track a ball with a bat as compared to novice batsmen (Land & McLeod, 2000). Proficient coordination between eye and hand/tool is necessary to make predictive saccades to hit a fast ball pitched by the bowler. Proficiency with tools and certain actions is also accompanied by changes in the brain’s white matter and grey matter. For instance, individuals who learn to juggle show increased functional anisotropy in white matter tracts in the right IPS (Scholz et al., 2009). Likewise, individuals who learn to use chopsticks with their non-dominant hand show changes in functional connectivity between tool-selective regions of the brain (Yoo, Sohn, & Jeong, 2013). These results suggest that familiarity can impact how a tool is processed by the visuomotor system and that special consideration should be given to the individual participants’ familiarity with the tools presented in experiments.

In light of this, the goal of this study was to determine if activation in response to videos of familiar (compared to unfamiliar) tools interacts with activity evoked when videos of functional (i.e., a tool being used) as opposed to non-functional (i.e., a tool being moved) actions are viewed. Specifically, I predict that the combination of viewing a familiar tool and viewing a functional action will be supra-additive in visuomotor regions that guide actions with commonly used tools. Importantly, to measure effects of familiarity, ratings from the participants in the experiment will be used as opposed to using normative ratings.

4.2 Methods

4.2.1 Participants

Sixteen right-handed healthy adults (nine women) with normal or corrected-to-normal vision provided informed consent to be scanned and were compensated $25/hour. Experimental protocol was approved by Western University’s Health Sciences Research Ethics Board.

4.2.2 Questionnaire

A questionnaire (see Appendix A) was given to each participant to familiarize them with the stimuli before going into the scanner and to acquire their individual familiarity ratings for each tool. These ratings were used in the analyses to classify the tools as either familiar or unfamiliar.

4.2.3 fMRI design and task

In a 2 (Task) x 2 (Familiarity) event-related design (see Figure 17), 4-s videos of nine different tools either being moved or used were presented. The tools were selected in such a way that they would span a spectrum of familiarity from completely novel to very familiar (selected based on pilot results). The tools included a pen, an eject tool for a SIM (subscriber identity module) card of a mobile phone, scissors, a tire lever, a spoon, a seam ripper, a tire iron, a ratchet, and a staple remover (see Appendix A). Videos were played at 24 frames/s and were viewed on a back-projection screen at a resolution of 854 x 480 pixels (43 cm from the participant's head) via a tilted mirror setup. The display area had a visual size of 11 cm width x 8 cm height, subtending a visual angle of 36° x 26°. Each condition (e.g., a video of a pen being moved) was repeated three times in each of the eight runs for a total of 24 repetitions across the session. A one-back task was also employed with the goal of maintaining attention across task and familiarity. Participants made a button press with their right hand when a video was repeated twice in a row (repetitions occurred three times per run). Participants fixated centrally throughout the entire session including baseline. The ITIs were jittered between 4-16 s (with optseq2; https://surfer.nmr.mgh.harvard.edu/optseq/), with the majority of the ITIs being between 4 and 6 s. Each eight-minute run began with a 12-s baseline and was repeated eight times. The total duration of the session was 64 minutes.

Figure 17. A 2 (Task) x 2 (Familiarity) event-related design was employed whereby participants viewed video clips of familiar and unfamiliar tools (familiarity determined by the participant) either being used (functional action) or moved (non-functional action).

4.2.4 Data acquisition

Functional and anatomical volumes were acquired using a 3-Tesla Siemens Prisma MRI scanner at the Robarts Research Institute with a 32-channel head coil. Functional T2*-weighted fMRI volumes with a 3-mm isotropic resolution were collected using a multiband (MB4; no iPAT acceleration) pulse sequence with interleaved slice acquisition (TR = 1000 ms; TE = 30 ms; FA = 70º; 44 slices). Anatomical T1-weighted fMRI volumes with a 1-mm isotropic resolution were collected using a gradient-echo EPI pulse sequence (TR = 2300 ms; TE = 2.98 ms; FA = 9º; 176 slices).

4.2.5 Data preprocessing

All imaging data were processed using FSL 6.0 (www.fmrib.ox.ac.uk/fsl). Prior to analyses, all functional runs were screened for large motion spikes with FSL's Motion Outliers tool. A confound matrix was generated for time points where a motion spike exceeded 1 mm, and these time points were modeled in the GLM to remove their influence on other parameter estimates. Following this, functional data underwent linear motion correction with FMRIB's Linear Image Registration Tool (MCFLIRT; Jenkinson et al., 2002), brain-extraction using BET (Smith, 2002), spatial smoothing using a Gaussian kernel (FWHM of 5 mm), mean-based intensity normalization, and high-pass filtering with a 100-s cut-off. Time-series statistical analysis was carried out using FILM with local autocorrelation correction. Functional data were aligned to structural images (within-subject) initially using linear registration (FLIRT), then optimized using Boundary-Based Registration (Greve & Fischl, 2009). Structural images were transformed to standard MNI space using a non-linear registration tool (FNIRT), and the resulting warp fields applied to the functional statistical summary images.

4.2.6 Data analysis

Functional data were analyzed with FEAT (version 6.00), and explanatory variables were convolved with a gamma function. First-level GLMs were computed for each subject with FEAT, and higher-level analyses GLMs for grouped data were computed using FEAT's mixed effects (Flame 1). A cluster threshold was applied to correct for multiple comparisons, and activity was thresholded at $Z < 2.3$ and corrected against a cluster probability threshold of $p < .001$. Volumetric statistical maps in MNI space (MNI 152; 2-mm isotropic voxels) were rendered in surface space using FreeSurfer v5.3 (surfer.nmr.mgh.harvard.edu) on surfaces downloaded from the human connectome project (unrelated 20 subjects beta 0.83; www.humanconnectomeproject.org). Surface activation maps were verified to ensure they accurately reflected volumetric activation maps.

4.3 Results

Before analyses were carried out, tools were classified as either familiar and unfamiliar for each participant separately by grouping the four tools they rated as most and least familiar in the questionnaire. This approach is in contrast with methods used in past research in which normative ratings (Vingerhoets, 2008) or ratings averaged across participants (Vingerhoets et al., 2011) were used to determine familiarity.

Next, the main effects of familiarity and task were examined separately across the whole brain. This was followed by another whole-brain analysis and an ROI analysis to determine in which regions familiarity and task interacted. Specifically, I was interested in the regions in which effects of viewing a familiar tool was greater than effects of viewing an unfamiliar tool when the tools were being used (as opposed to moved). Both a whole-brain analysis and an ROI analysis were carried out to test this interaction as a whole-brain analysis can reveal regions outside of areas in which *a priori* predictions were made (i.e., tool-selective regions); conversely, an ROI analysis can test predictions in specific tool-selective regions using more statistical power than is available in a whole-brain analysis.

4.3.1 Videos of familiar vs. unfamiliar tools

To analyze effects of familiarity, a whole-brain analysis was carried out collapsed across task to compare activity when videos of familiar tools were viewed to when videos of unfamiliar tools were viewed (and vice versa). Familiarity was defined by collapsing across the four most and four least familiar tools (respectively) as determined by the individual ratings.

As shown in Figure 18, a handful of visuomotor regions activated more for familiar tools than for unfamiliar tools including left PMd, left SPL, left pLOTC, and right IPS. In comparison, unfamiliar tools recruited the right SPL, right pLOTC, and medial early visual areas more than familiar tools. That said, areas in the right hemisphere have not typically been associated with *familiar* tool processing (Lewis, 2006).

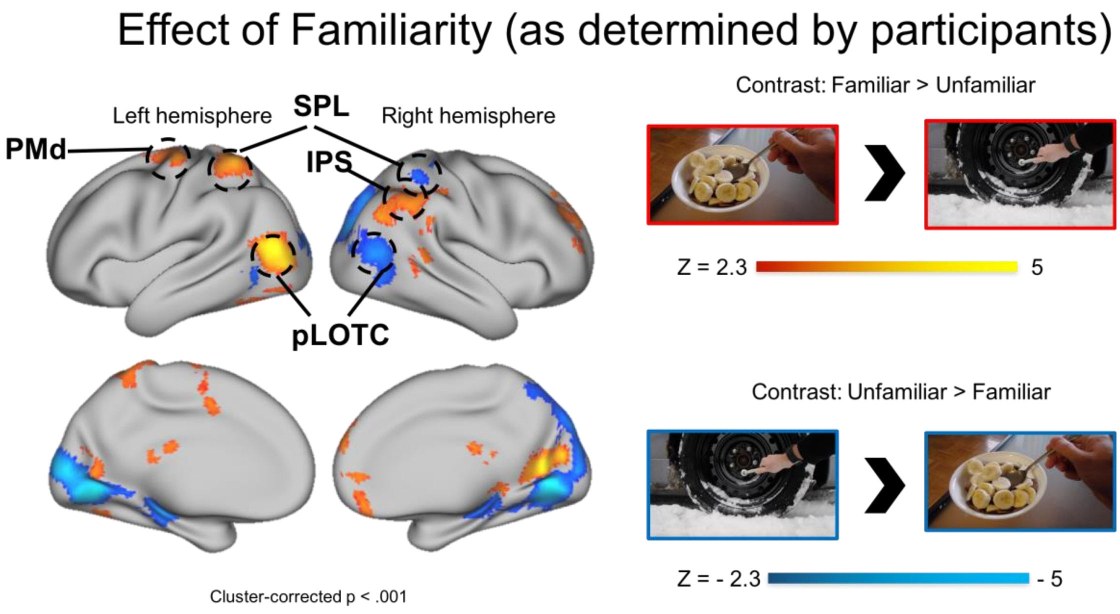
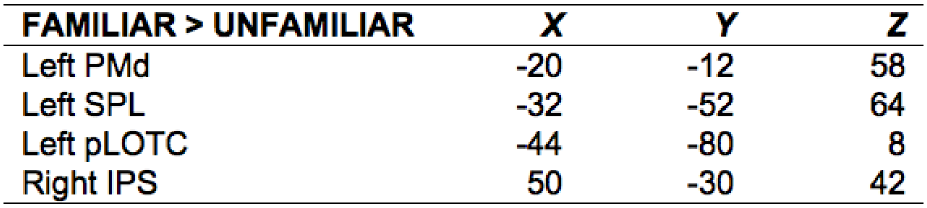
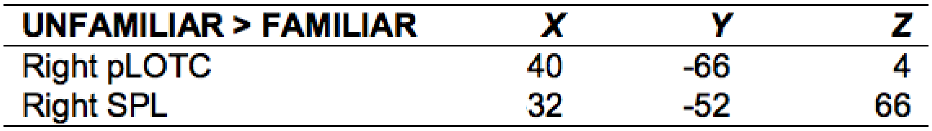


Figure 18. Areas selective for videos of familiar tools over videos of unfamiliar tools (red/orange) and vice versa (blue) collapsed across task in the left and right hemispheres as determined by a mixed effects GLM.

Table 7. MNI coordinates for the peak voxel in group-averaged areas selective for familiarity.



FAMILIAR > UNFAMILIAR	X	Y	Z
Left PMd	-20	-12	58
Left SPL	-32	-52	64
Left pLOTC	-44	-80	8
Right IPS	50	-30	42



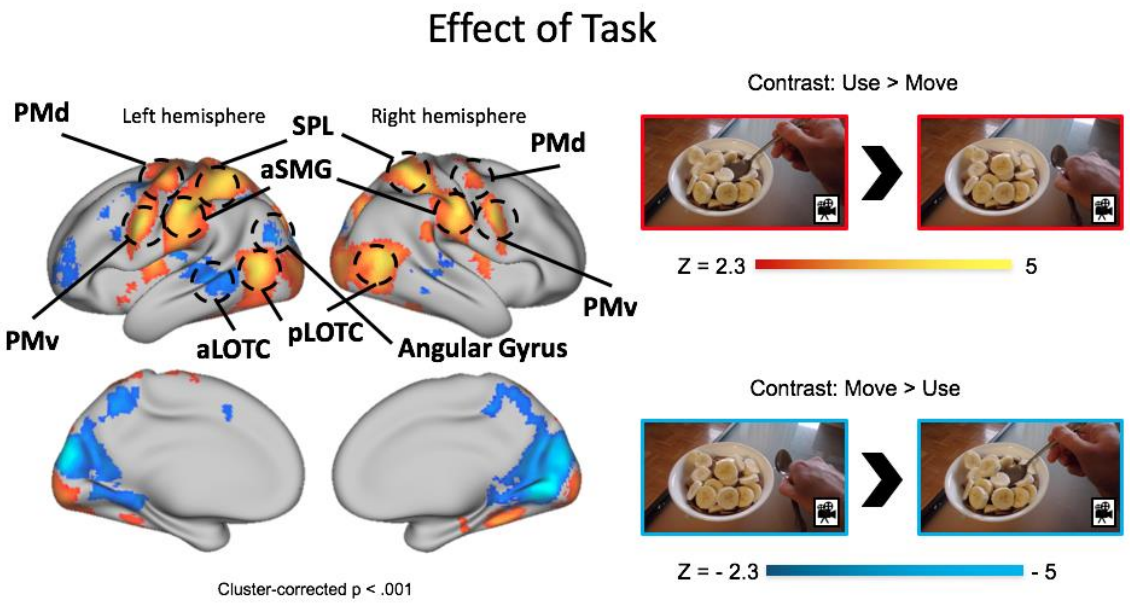
UNFAMILIAR > FAMILIAR	X	Y	Z
Right pLOTC	40	-66	4
Right SPL	32	-52	66

4.3.2 Videos of tools being used vs. moved

To analyze effects of task, a whole-brain analysis was carried out collapsed across familiarity to compare activity when videos of tools being used were viewed to when videos of tool being moved were viewed (and vice versa).

As shown in Figure 19, videos of tools being used activated visuomotor regions to a greater extent than videos of tools being moved. Specifically, tool use videos activated dorsal-stream regions such as bilateral PMd, bilateral PMv, bilateral aSMG, bilateral SPL, and ventral-stream regions such as bilateral pLOTC as well as bilateral insula and parahippocampal cortex. Notably, videos of tools being used recruited regions that were also more active for familiar tools as compared to unfamiliar tools such as the left PMd, left SPL, and left pLOTC.

Tools being moved, on the other hand, did not activate many visuomotor areas relative to tool being used. The areas that were selective for tools being moved included left anterior LOTC (aLOTC), left angular gyrus, inferior frontal cortex, and medial early visual areas.


Effect of Task

Cluster-corrected p < .001

Figure 19. Areas selective for videos of tools being used over videos of tools being moved (red/orange) and vice versa (blue) collapsed across familiarity in the left and right hemispheres as determined by a mixed effects GLM.

Table 8. MNI coordinates for the peak voxel in group-averaged areas selective for task.

USE > MOVE	***X***	***Y***	***Z***
Left PMd	-28	-14	58
Left PMv	-58	8	32
Left SPL	-32	-52	62
Left aSMG	-52	-20	34
Left pLOTC	-44	-70	2
Right SPL	34	-50	70
Right PMv	60	12	32
Right SPL	34	-50	70
Right aSMG	60	-18	36
Right pLOTC	46	-62	6

MOVE > USE	***X***	***Y***	***Z***
Left aLOTC	-54	-40	-4
Left Angular Gyrus	-42	-72	22
Left Parahippocampal Cortex	-24	-46	-8
Right Parahippocampal Cortex	22	-48	-8

4.3.3 The interaction between familiarity and task

Lastly, to determine the brain areas in which activity in response to videos of *familiar* (compared to unfamiliar) tools interacts with videos of tools being *used* relative to tools being *moved*, the interaction between contrasts [(Familiar$_{\text{use}}$ – Unfamiliar$_{\text{use}}$) > (Familiar$_{\text{move}}$ – Unfamiliar$_{\text{move}}$)] was tested on statistical maps of the brain. The resulting statistical map from this interaction was then masked with the statistical map from the contrast (Familiar$_{\text{move}}$ – Unfamiliar$_{\text{move}}$) to ensure that differences were not solely driven by differences between the move conditions. The results from this whole-brain analysis revealed no visuomotor areas showing an interaction between familiarity and task.

Lastly, an ROI analysis was carried out to also test the interaction between familiarity and task in specific visuomotor regions as opposed to across the whole brain. Regions of interest were identified using the peak voxels from use- and move-selective areas. To create the ROIs, a sphere (9-mm radius) was centered on the voxel with peak activation from move- and use-selective areas based on the contrasts (Move > Use) and (Use > Move), respectively, collapsed across familiarity. Parameter estimates (Z-scores) were then extracted for each level of familiarity and task (for instance, Z-scores associated with activation in response to a familiar tool being moved) using the ROIs as masks. Z-scores were then submitted to a 2 (Task) x 2 (Familiarity) repeated-measures ANOVA and paired samples t-tests were used to test differences between conditions when the interaction reached significance. Importantly, it should be noted effects related to task, but not familiarity, are redundant in this analysis as ROIs were selected based on their activation in the earlier analysis on task.

As seen in Figure 20, among use-selective areas, only the left and right SPL showed a significant interaction between familiarity and task. The nature of this interaction was such that a supra-additive effect was present driving greater activation for familiar relative to unfamiliar tools in the use condition but not in the move condition. Surprisingly, the right SPL also showed supra-additive effects whereby activation was greater for unfamiliar tools relative to familiar tools in the move condition but not in the use condition.

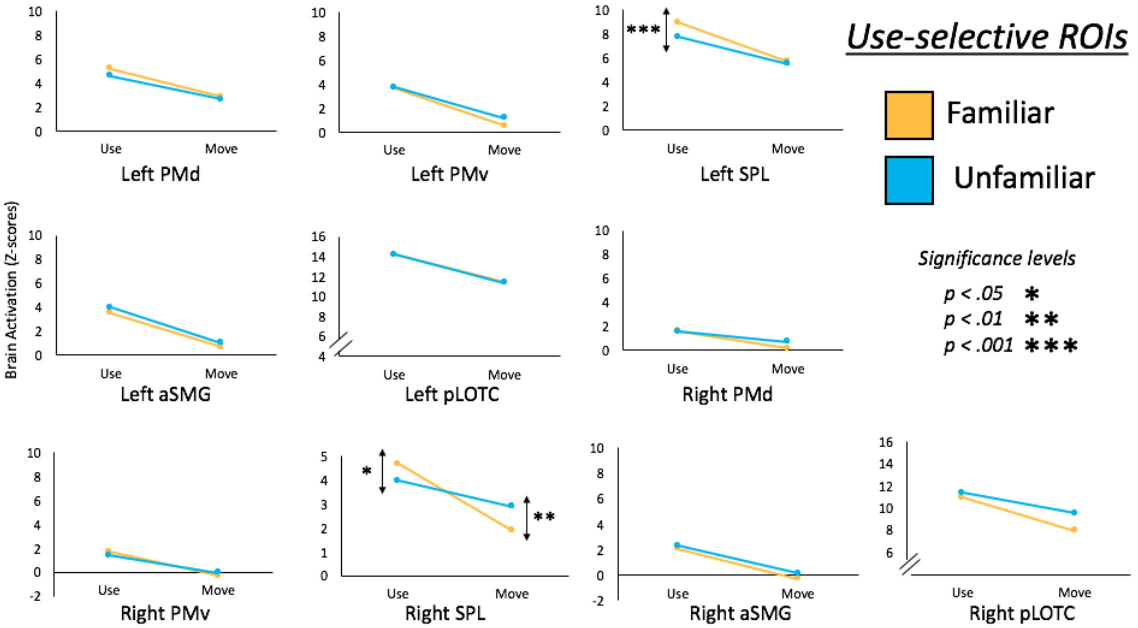


Figure 20. Parameter estimates extracted underneath use-selective ROIs to test the interaction between familiarity and task.

As can be seen in Figure 21, in move-selective areas the left aLOTC showed a significant interaction between familiarity and task. The nature of this interaction was similar to that of the interaction observed in use-selective right SPL whereby activation was greater for unfamiliar tools relative to familiar tools in the move condition but not in the use condition. That said, this interaction is difficult to interpret with confidence as it is the result of differences in negative activation.

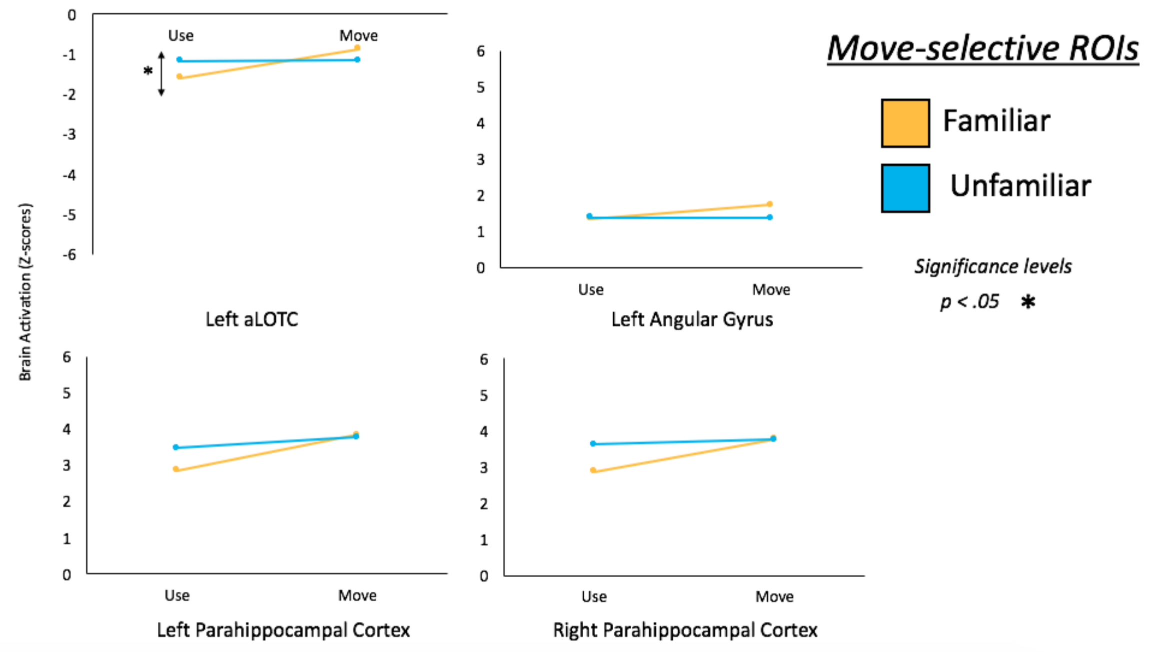


Figure 21. Parameter estimates extracted underneath move-selective ROIs to test the interaction between familiarity and task.

4.4 Discussion

The key findings from this study are 1) that activation in response to videos of familiar tools overlaps to a great extent with activation in response to videos of tools being used (namely in the left PMd, left SPL, and left pLOTC), and 2) that SPL is particularly selective for familiar tools (relative to unfamiliar tools) when the actions are functional (e.g., “use” actions) but not when the actions are non-functional (“move” actions).

4.4.1 Familiarity mediates activity in SPL when tools are *used*

This finding corroborates past research on patients with lesions to left SPL resulting in neuropsychological disorders such as ideomotor apraxia. Patients with ideomotor apraxia are impaired at performing actions with a tool but can nonetheless recognize a tool’s function (Frey, 2004). They have difficulty pantomiming in response to *familiar* tools but, tellingly, perform like healthy controls when pantomiming in response to *unfamiliar* tools (Buxbaum et al., 2003). This suggests that, in areas like the left SPL, functional associations guide actions with familiar tools whereas other factors such as structural cues likely guide actions with unfamiliar tools (Goldenberg & Hagmann, 1998).

Familiarity guides functional actions with tools as it can provide the ability to detect the functional associations (Frey, 2004). Comparatively, familiarity is less relevant when non-functional actions (e.g., simply moving a tool) are carried out. One explanation for this is that familiarity facilitates predictions regarding the interaction between a tool and its target. This would entail making sensorimotor predictions required to manipulate the tool and functional predictions about the relationship between tool and target (Reynaud, Lesourd, Navarro, & Osiurak, 2016). Of course, when a familiar tool is simply moved (as opposed to used), there is no interaction between the tool and a target thus no functional predictions can be made.

Surprisingly, in contrast to the left SPL, familiarity and task interacted in the right SPL in the move condition as well as in the use condition. In the use condition, the right SPL responded like the left SPL whereby it activated more strongly to familiar tools being used as compared to unfamiliar tools being used. In the move condition, however, the right SPL responded more strongly to unfamiliar tools being moved relative to familiar tools being moved. The same interaction was also observed for move-selective region aLOTC. While speculative, it is possible that the context provided by the videos suggested that a “use” action was more appropriate than a “move” action. The interaction between an unfamiliar tool and a move action could be the result of a semantic violation created by the expectation of a use action combined with the presence of an unfamiliar tool with few functional associations.

4.4.2 The role of familiarity in action control

To make predictions about a familiar tool being used, access to functional knowledge is required. Accordingly, the regions that activated both in response to the videos of familiar tools and to videos of tools being used are also involved in goal-directed actions (PMd; Gallivan et al., 2013), the ability to manipulate tools (as evidenced by lesions to SPL; Frey, 2004), and action semantic knowledge (pLOTC; Buxbaum et al., 2014). This is in agreement with previous studies in which novel tools activated semantic ventral areas such as pLOTC to a greater extent after the tools became repeatedly associated with actions over short training periods (Weisberg, van Turennout, & Martin, 2007). Likewise, past research has also shown that tools which are familiar to certain individuals (e.g., cigarettes for smokers vs. non-smokers) activate visuomotor regions such as the left PMd and left SPL to a greater extent (Yalachkov, Kaiser, & Naumer, 2009).

Surprisingly, effects of familiarity were not observed in other areas that underlie semantic action knowledge such as areas lesioned in patients with ideational apraxia. Patients with ideational apraxia can accurately perform actions with a tool but do so in incorrect contexts (e.g., eating food with a toothbrush). The lesions associated with ideational apraxia are typically found around the intersection of the temporal, parietal, and occipital lobes (posterior to the lesions observed in patients with ideomotor apraxia; Frey, 2004). While no effects of familiarity were observed at this intersection, effects were observed in pLOTC which is an area also associated with retrieval of semantic action knowledge (Buxbaum et al., 2014). This suggests that even though familiarity does not mediate activity in areas associated with ideational apraxia, familiarity likely impacts activity in other areas that subserve semantic (e.g., left pLOTC) as well as manipulative action knowledge (e.g., left SPL).

4.4.3 Defining tool familiarity

The effect of familiarity on tool-selective activation has often been overlooked in past research. In the few studies that have considered familiarity with tools, normative ratings as opposed to participant ratings have typically been collected to divide tools into familiar and unfamiliar bins (Vingerhoets, 2008). While the results from such studies have been suggestive, familiarity determined by the participants who were tested is likely a more powerful approach for two reasons: 1) no assumptions need to be made regarding the participants' history with the tools, and 2) effects of familiarity are less likely to be confounded by low-level features as the videos within the familiar and unfamiliar conditions are different for each participant. A video of a ratchet, for instance, may be coded as familiar for one participant but as unfamiliar for another.

Accordingly, the results from the familiarity analysis in this study are only in partial agreement with past studies exploring the effects of familiarity on tool processing. This discrepancy between studies could be explained by differences in how familiarity ratings were collected. For example, in one study by Vingerhoets et al. (2008) in which normative ratings were used, familiar tools recruited several regions that were also recruited in current study (left PMd, left SPL, and left pLOTC). However, when activity in response to familiar tools was *directly* compared to activity in response to unfamiliar tools in the Vingerhoets et al. (2008) study, only activity in the left inferior parietal lobule (IPL; Vingerhoets et al., 2011), left SMG, and left precuneus was observed. In contrast, the direct comparison between familiar and unfamiliar tools in the current study revealed that left PMd, left SPL, and the left pLOTC activated more strongly in response to familiar than to unfamiliar tools. Indeed, the overlap in activation for familiar and unfamiliar tools in the Vingerhoets (2008) study suggests that some of their unfamiliar tools may have in fact been familiar. This suggests that there is merit to assigning familiarity individually as was done in the current study.

4.4.4 Task-dependent effects

The visuomotor system differentially processes stimuli depending on the required motor output. For instance, if the desired output is a button press, low-level features near the point of fixation are most salient. In contrast, if the desired output is a grasp, functional cues become most relevant (Pavese & Buxbaum, 2002). Moreover, some actions require additional sensorimotor computation relative to other actions. Using a tool, for instance, is more complex than simply moving a tool (Valyear et al., 2011) as using a tool requires input from brain areas involved in high-level cognition such as those that process goal (Gallivan et al., 2013).

The results from this study partially replicate and extend previous work investigating the neural correlates of *real* use and move actions. The dorsal visual stream (namely PMd and SPL), as well as pLOTC, are reported as being involved in *real* use actions as compared to *real* move actions especially in the left hemisphere (Brandi et al., 2014). Results from the current study, using videos of actions instead of real actions, reveal additional use-selective areas in the dorsal stream such as PMv and aSMG. Moreover, these areas were bilaterally recruited in the current study as opposed to left lateralized. Historically, the network of regions selective for actions and tools is reported as lateralized to the left hemisphere. That said, most experiments have utilized pictures or artificial tasks such as pantomiming or passive viewing to study tool-selective activation (Lewis, 2006). It is possible that videos are more effective than pictures and pantomimes at identifying tool- and action-selective activation in both hemispheres (as seen in Chapter 3). This may be the case as videos are more engaging, they can depict an action from start to finish, and they demonstrate the characteristic motions associated with tools.

4.5 Conclusion

In sum, this study reveals that familiarity guides functional actions with tools especially in visuomotor regions such as SPL. Tools are a unique class of stimuli with strong ties to goal prediction and reasoning (Osiurak et al., 2010). When tools are unfamiliar or when the goal of manipulating the tools is not functional (e.g., simply moving the tool), less predictions can be made about the tool and target and therefore visuomotor areas are recruited to a lesser extent relative to with familiar tools or functional actions.

Chapter 5

5 General Discussion

The overarching goals of my thesis were, 1) from a methodological perspective, to determine whether different proxies for studying tool use were more effective than using pictures but less technically challenging than using real actions on real tools; and 2) from a theoretical perspective, to determine what these proxies could reveal about complex tool processing, particularly in brain regions involved in visuomotor control. To this end, in three projects I presented real tools, pictures of tools, and videos of tools to determine how format presentation affects complex tool processing. Moreover, I investigated how different tasks such as simply viewing a tool, using a tool, and moving a tool differentially impact what features of the tools are salient.

In Chapter 2, elongated *real* tools and elongated non-tools were *passively viewed* while manipulating which hand the tool handle was directed towards. While this method was moderately challenging to adopt, it was quicker than asking participants to act on real tools and it circumvented issues related to motion artifacts. Crucially, this method was also more likely to evoke affordances than the conventional approach of presenting pictures of tools because real tools afford the opportunity for an action whereas pictures of tools do not. Using this method, I revealed two new characterizations of tool-selective regions: 1) these regions remain selective for real tools as compared to non-tools even after low-level properties such as elongation, real-world size, and manipulability have been matched, and 2) these regions do not show preferential activation to real tool handles directed towards or away from the hand.

In Chapter 3, *videos* of tools and *pictures* of tools were presented. Using videos and pictures was less likely to evoke affordances relative to passively viewing *real* tools, however presenting videos provided the opportunity to depict the characteristic motion of tool actions including the interaction between the tools and their target. Using this method, I discovered that videos, which provide information about the context and the goal of the actor using the tool, are more effective than pictures at activating tool-selective areas, particularly in dorsal-stream brain areas that support real actions.

In Chapter 4, *videos* of tools were used to determine if tool-selective regions show a stronger response to familiar than unfamiliar tools that are depicted in functional actions (e.g., a hammer being used to pound a nail into wood) or in non-functional actions (e.g., a hammer simply being moved from one location to another). To this end, videos of familiar and unfamiliar tools being used or moved were presented. Using this method, I identified two new components of tool-selective regions: 1) areas that are selective for familiar tools are also selective for functional actions, and 2) familiar tools activate areas such as SPL to a greater extent than unfamiliar tools when a functional action is carried out.

Taken together, this thesis suggests that presenting videos of familiar tools performing functional actions may be an optimal proxy to studying tool use in human fMRI relative to using pictures or real actions on real tools. Videos provide context to stimuli, they depict the characteristic motion associated with tools, and they are easy to implement in experiments. Through evaluating the effectiveness of different formats and task on tool-selective activation, this thesis also provides novel characterizations of tool-selective regions revealing that these regions are selective for the functional associations afforded by tools (Chapter 2), for the defining motion associated with tools (Chapter 3), and for familiar tools for which functional associations are well-established (Chapter 4).

More importantly, however, the results from this thesis reveal the importance in providing *context* when studying tool-selective regions. In Chapter 2, these regions activated more in response to real tools than to non-tools of which the latter do not provide contextual information with regards to possible functions. In Chapter 3, videos of tools evoked more activity in these regions as compared to pictures of tools because videos are more effective at depicting context through goal-directed actions and characteristic tool motion. Lastly, in Chapter 4, the effect of context was directly assessed by contrasting activation in these regions in response to videos of tools performing functional and non-functional actions. Here, the differences between using stimuli with and without context was most striking as functional actions evoked widespread bilateral activation across tool-selective regions as compared to non-functional actions. This is likely because context changes the perceived “toolness” of an object. A shoe, for instance, is not typically considered a tool however it may be perceived as a simple tool if its heel is used to pound a nail. It is especially important to provide context, such as task, to tool stimuli when using proxies to study tool use. As revealed in the last project, the task that is depicted (e.g., using a tool vs. moving a tool) can also alter how a tool is processed. A functional task (e.g., using a tool) is more likely to draw attention to the semantic and functional properties of an object which can affect its perceived “toolness”. In the case of moving a tool, for instance, semantic and functional properties become less relevant as compared to cues such as center of mass which determine where the object will be grasped to transport it from one location to the another.

Tellingly, even though the experiments in each chapter used different stimuli and tasks (not to mention that data were collected using different designs, on different fMRI scanners, and analyzed by different software packages), commonly reported tool-selective regions were nonetheless consistently activated (see Figure 22).

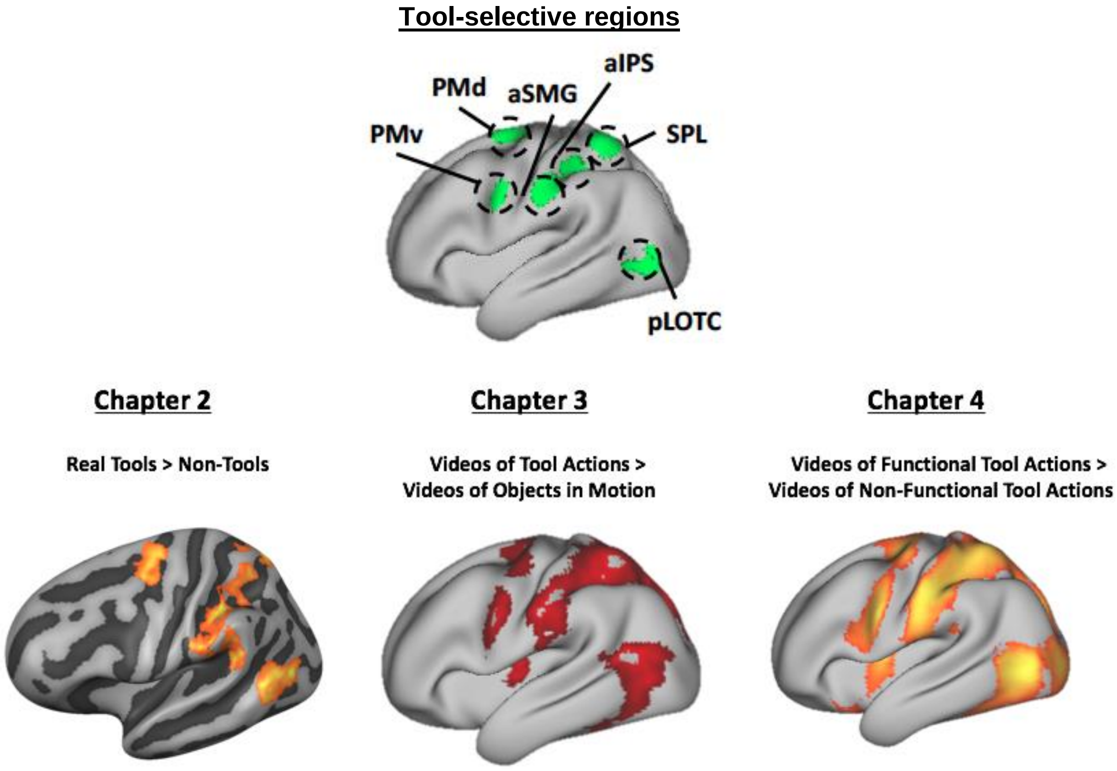


Figure 22. Tool-selective areas activated across all three chapters.

5.1 Affordances in tool-selective regions

Though tool-selective regions were activated despite no actions ever being carried out, the data from this thesis does not offer *complete* support to Gibsonian perspective whereby every aspect of your environment automatically potentiates an action (Gibson, 1977). Instead, the data from Chapters 3 and 4 suggest that motion, task, and familiarity mediate activity in tool-selective regions. Regardless, the results from Chapters 2 and 3 demonstrate that tools are indeed a unique class of objects and that tools, in comparison to non-tool objects, are more likely to create a potential for a novel action by qualitatively changing the function of the hand (e.g., hands using scissors to cut paper). Conversely, graspable non-tool objects, like a desk lamp, do not activate tool-selective regions to the same degree because a desk lamp cannot extend or transform the current functional capabilities of the hand in the same way as a tool.

Surprisingly, the results from Chapter 2 also showed that tool-selective regions do not activate preferentially to tool handles oriented away or towards the hand. This result contradicts the seminal experiment by Tucker and Ellis (1998) whereby the direction of the tool's handle facilitated a response with the hand that it was directed towards. Instead, my results suggest that even though tools are more effective than non-tools at evoking a potential for action, the prospective action does not map to a specific hand. Representing action information independent of hand could explain why upper-limb amputees, for instance, show preserved grip selection to graspable objects (Philip & Frey, 2011) even though they cannot physically grasp the objects.

5.2 What does *viewing* tools as proxy to *using* tools reveal about tool-selective regions?

In agreement with past research, the results from this thesis suggests that there is overlap in the brain areas that activate when a tool is *viewed* and when a tool is *used*. Even though this comparison was not directly tested, the results from my experiments as well as other experiments suggest that a real tool, even when passively viewed, activates similar areas relative to when an actual tool is used (Gallivan, et al., 2013). This is the case irrespective of whether real tools, videos of tool use, or pictures of tools are presented and regardless of task such as passive viewing, detecting repetitions in the stimuli (e.g., a one-back task), and detecting changes to low-level features such as frame brightness. It should be noted, however, that areas in primary sensorimotor cortex and the cerebellum were not often reported as being tool-selective across these projects even though they are recruited during the motor control of real actions (Schmahmann, 2010; Paccioco, McLean, & Culham, 2012; Gallivan et al., 2013).

There are several reasons why simply presenting a tool can activate many similar regions as those activated when a tool is *actually* used. Firstly, from a Gibsonian perspective, viewing a tool may automatically evoke the affordances and the potential for action associated with that tool (Gibson, 1977). This perspective argues that the motor system is primed for tool use even though the viewer has no intention to use the tool (Tucker & Ellis, 1998; Grezes et al., 2003). While this framework is perhaps extreme (and hotly contested; see Cho & Proctor, 2010), results from Chapter 2 suggest that passively viewing real tools is sufficient to activate areas of the brain that are also recruited when a tool is used. That said, results from Chapter 4 reveal that task (e.g., using a tool vs. moving a tool) mediates activity in visuomotor areas therefore I cannot conclude that affordances evoked by tools are the only driving factor in tool-selective regions. The end goal of the tool is considered when actions are primed.

Secondly, when a tool is viewed it is possible that the motor system simulates actions that could be performed with that tool leading to overlap with tool use areas (Caramazza, Anzellotti, Strnad, & Lingnau, 2014). Simulation could account for why greater activity was observed for tools as compared to non-tools in Chapter 2 as well as for familiar relative to unfamiliar tools in Chapter 4. Of course, it is not possible for a viewer to simulate an action that is unknown to them. Novel tools only activate tool-selective regions after repeated use when they are no longer novel (Weisberg et al., 2007). That said, it is unclear why visuomotor areas would activate more in response to viewing a tool being used as compared to viewing a tool being moved (Chapter 4) if simulation was the only driving factor behind activation in tool-selective regions. Moreover, if actions were simulated when a tool was viewed, different tool-handle orientation should have mediated activity in visuomotor areas in Chapter 2 which they did not.

Thirdly, the overlap in brain activation for viewing compared to using tools could be due to the low-level visual similarity between the tools presented in both view and use conditions. In other words, the overlap in activation could be driven by visual neurons exclusively without input from motor neurons. This too, however, is unlikely considering that videos of tools and still frames of the videos differentially activate tool-selective regions. Moreover, past research has shown that congenitally blind patients show activation in tool-selective areas upon hearing spoken words corresponding to tools (Mahon, Schwarzbach, & Caramazza, 2010). Vision alone could not have driven tool-selective activity in these patients.

Lastly, and most likely, activation is similar when a tool is viewed and used because when a tool is viewed predictions can be made about the physical interaction between tool and target (Reynaud et al., 2016). This prediction could include estimates for end state comfort of the hand (Wood & Goodale, 2011) as well as transformations required to convert a hand action into a tool action. In a sense, activation of tool-selective regions upon viewing a tool mimics the preparatory response that occurs before an action occurs. Indeed, regions that activate when an action with a tool is performed also show increased activation when the tool is previewed *and* when the action with a tool is planned before movement onset (Gallivan et al., 2011).

5.3 Comparing approaches to study tool use

This thesis has reviewed a number of proxies to studying tool use ranging from methods that are more likely to potentiate an action (e.g., presenting *real* tools) to conventional methods that are artificial but practical (e.g., presenting *pictures* of tools; Lewis, 2006). In the middle of this range, however, the results from this thesis suggest that there is perhaps an optimal proxy to studying tool use: presenting *videos* of *familiar* tools being *used*.

With videos, there is no ambiguity as to what action could be performed on the tool as compared to with pictures of tools in which there are many possible actions. Videos are also more effective than pictures at demonstrating the meaningful interaction between the tool and its target. Moreover, using videos circumvents many of the issues unique to experiments that use real actions on real tools. With videos, any action can be depicted, any tool can be used, and any context can be provided to the stimuli (e.g., scene, location, etc.). Comparatively, with real actions on real tools, actions must be very slow and constrained as to avoid motion artifacts, all stimuli must be free of ferrous metal, and context is difficult to provide as actions in the scanner are often inconsequential (e.g., aimlessly turning a plastic screw into a platform; Brandi et al., 2014).

That said, there is no "one size fits all" method to studying tool-selective regions and the preferred method largely depends on the aspects of tools that are of interest to researchers. For instance, neuroimaging researchers interested in studying tool *cognition* as opposed to the *visuomotor* aspects of tools have less to gain from using videos of tools or real tools. Conversely, it goes without saying that researchers interested in best approximating the neural correlates of real tool use should use real actions on real tools. If real actions cannot be used, however, the next best method is to simply present real tools. At a minimum, real tools afford the opportunity for an action to be carried out. Tellingly, results from Chapter 2 show that passively viewing a real tool is sufficient to recruits areas to that are also recruited when that tool is used.

5.4 A note on ecological validity and studying "tool use without tool use"

As researchers, there is a need to consider more ecologically valid ways of studying tool use. Initial research on tool use using pictures as proxies has been suggestive however the results from this thesis argue that an artificial representation of a tool (such as a picture) is not the ideal proxy to study tool use. Indeed, past research has shown that real objects evoke different activation than pictures of objects (Snow et al., 2011), real actions recruit different regions than pantomimed actions (Króliczak et al., 2007), and real objects are visually explored differently relative to pictures of objects (Gerhard et al., 2016). Especially in the case of tools, creating the potential for action is important. Pictures of objects are not equated in graspability relative to real objects and the areas that are involved in visually-guided grasping respond to the difference (Freud et al., 2017).

5.5 Conclusion

To conclude, this thesis has demonstrated that presenting videos of familiar tools performing functional actions is an optimal proxy to study tool use in human fMRI. This approach outperforms conventional yet artificial methods of using pictures of tools and ecologically valid yet technically challenging methods of using real actions on real tools. Importantly, in testing these different methods, this thesis also provides novel characterizations of tool-selective regions revealing that these regions are selective for the function afforded by tools, for the defining motion associated with tools, and for familiar tools of which functional associations are well-established.

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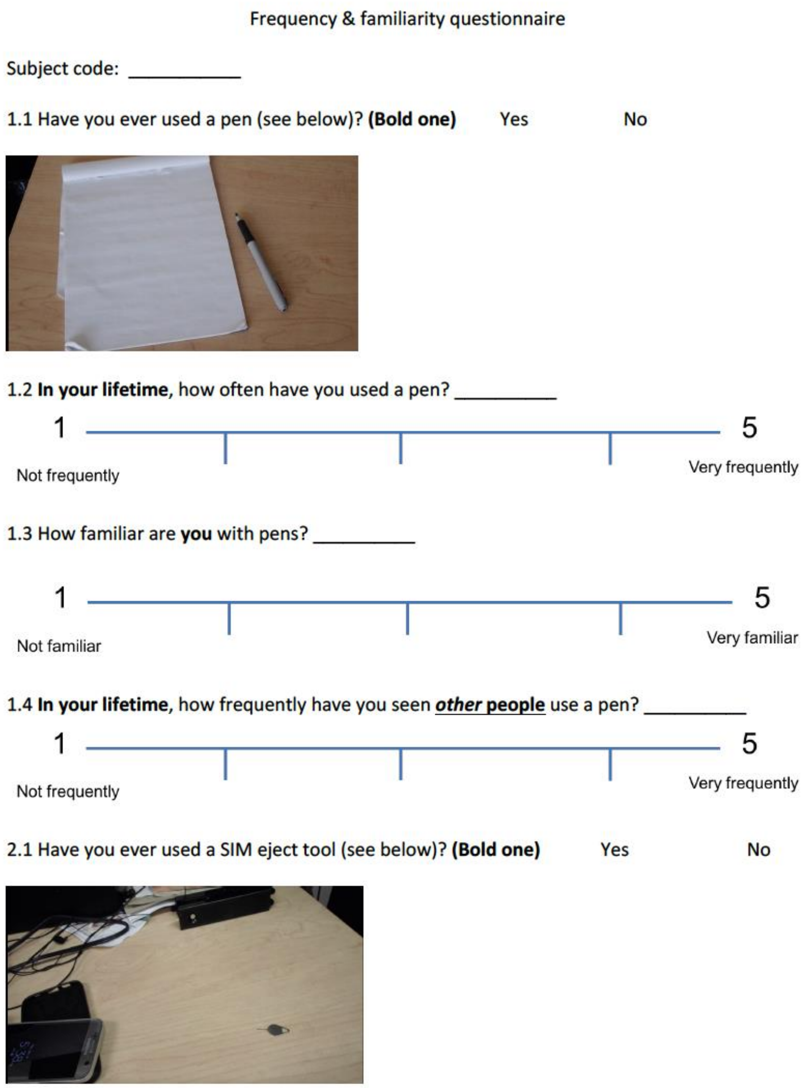
Appendices

Appendix A: Frequency and Familiarity questionnaire given to participants in the fMRI experiment from Chapter 4.



Frequency & familiarity questionnaire

Subject code: ___________

1.1 Have you ever used a pen (see below)? **(Bold one)** Yes No

1.2 **In your lifetime**, how often have you used a pen? __________

1 5

Not frequently Very frequently

1.3 How familiar are **you** with pens? __________

1 5

Not familiar Very familiar

1.4 **In your lifetime**, how frequently have you seen ***other* people** use a pen? __________

1 5

Not frequently Very frequently

2.1 Have you ever used a SIM eject tool (see below)? **(Bold one)** Yes No

2.2 **In your lifetime**, how often have you used a SIM eject tool? __________

1 5

Not frequently Very frequently

2.3 How familiar are **you** with SIM eject tools? __________

1 5

Not familiar Very familiar

2.4 **In your lifetime**, how frequently have you seen ***other* people** use a SIM eject tool? __________

1 5

Not frequently Very frequently

3.1 Have you ever used scissors (see below)? **(Bold one)** Yes No

3.2 **In your lifetime**, how often have you used scissors? __________

1 5

Not frequently Very frequently

3.3 How familiar are **you** with scissors? __________

1 5

Not familiar Very familiar

3.4 **In your lifetime**, how frequently have you seen ***other* people** use scissors? __________

1 5

Not frequently Very frequently

4.1 Have you ever used a tire lever (see below)? **(Bold one)** **Yes** **No**

4.2 **In your lifetime**, how often have you used a tire lever? __________

1 5

Not frequently Very frequently

4.3 How familiar are **you** with tire levers? __________

1 5

Not familiar Very familiar

4.4 **In your lifetime**, how frequently have you seen ***other* people** use a tire lever? __________

1 5

Not frequently Very frequently

5.1 Have you ever used a spoon (see below)? **(Bold one)** Yes **No**

5.2 **In your lifetime**, how often have you used a spoon? __________

1 5

Not frequently Very frequently

5.3 How familiar are **you** with spoons? __________

1 5

Not familiar Very familiar

5.4 **In your lifetime**, how frequently have you seen ***other* people** use a spoon? __________

1 5

Not frequently Very frequently

6.1 Have you ever used a seam ripper (see below)? **(Bold one)** Yes No

6.2 **In your lifetime**, how often have you used a seam ripper? __________

1 5

Not frequently Very frequently

6.3 How familiar are **you** with seam rippers? __________

1 5

Not familiar Very familiar

6.4 **In your lifetime**, how frequently have you seen ***other* people** use a seam ripper? __________

1 5

Not frequently Very frequently

7.1 Have you ever used a tire iron (see below)? **(Bold one)** Yes No

7.2 **In your lifetime**, how often have you used a tire iron? __________

1 5

Not frequently Very frequently

7.3 How familiar are **you** with tire irons? __________

1 5

Not familiar Very familiar

7.4 **In your lifetime**, how frequently have you seen ***other* people** use a tire iron? __________

1 5

Not frequently Very frequently

8.1 Have you ever used a ratchet (see below)? **(Bold one)** Yes No

8.2 **In your lifetime**, how often have you used a ratchet? __________

1 — 5

Not frequently — Very frequently

8.3 How familiar are **you** with ratchets? __________

1 — 5

Not familiar — Very familiar

8.4 **In your lifetime**, how frequently have you seen ***other* people** use a ratchet? __________

1 — 5

Not frequently — Very frequently

9.1 Have you ever used a staple remover (see below)? **(Bold one)** Yes No

9.2 **In your lifetime**, how often have you used a staple remover? __________

1 5

Not frequently Very frequently

9.3 How familiar are **you** with staple removers? __________

1 5

Not familiar Very familiar

9.4 **In your lifetime**, how frequently have you seen ***other* people** use a staple remover?
____

1 5

Not frequently Very frequently

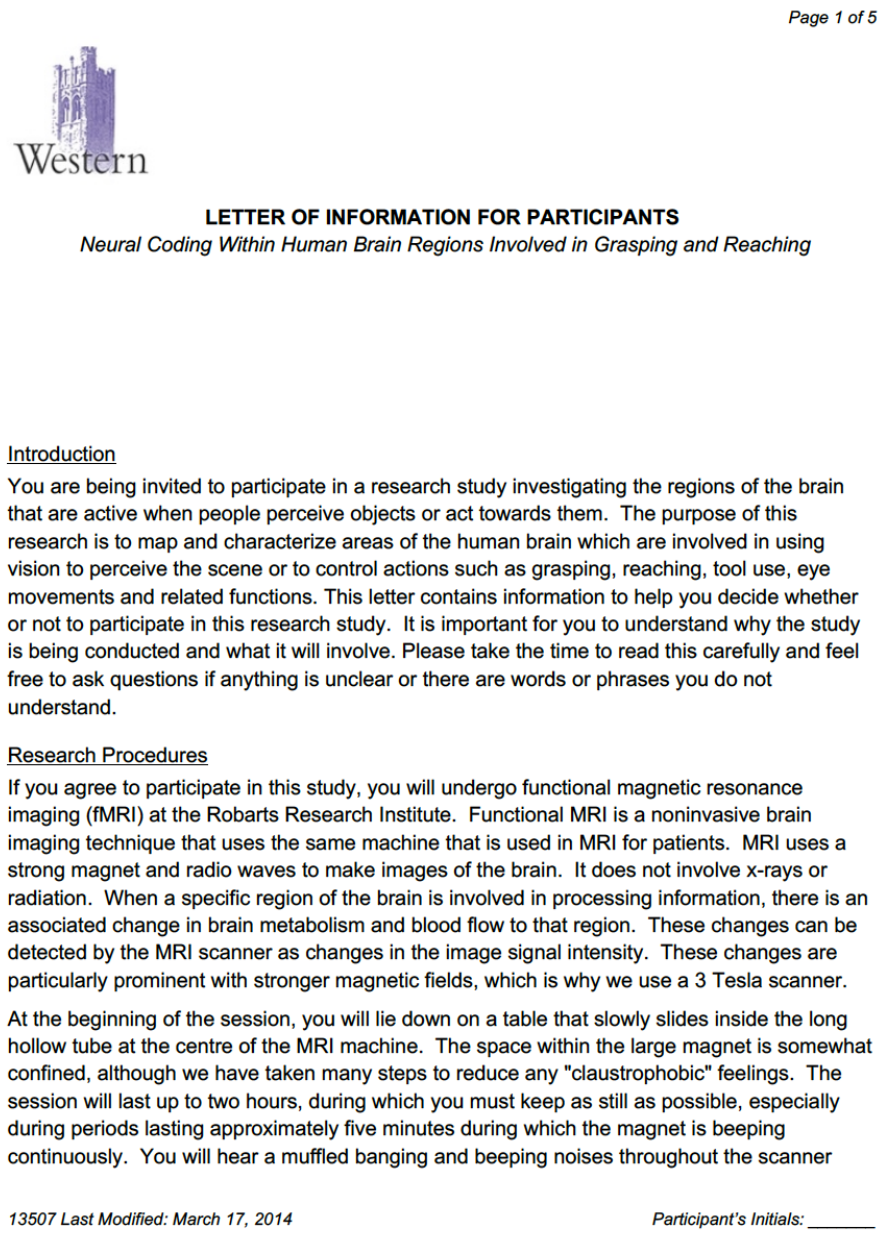
Rank your ***frequency of use*** with the following tools: **Pen, SIM eject tool, Scissors, Tire Leaver, Spoon, Seam Ripper, Tire Iron, Ratchet, Staple Remover**

1. (most frequent) ________________________
2. ________________________
3. ________________________
4. ________________________
5. ________________________
6. ________________________
7. ________________________
8. ________________________
9. (least frequent) ________________________

Rank your ***familiarity*** with the following tools: **Pen, SIM eject tool, Scissors, Tire Leaver, Spoon, Seam Ripper, Tire Iron, Ratchet, Staple Remover**

1. (most familiar) ________________________
2. ________________________
3. ________________________
4. ________________________
5. ________________________
6. ________________________
7. ________________________
8. ________________________
9. (least familiar) ________________________

Appendix B: Letter of Information, Consent Form, and Ethics Approval for experiments in Chapters 2-4.



Western

LETTER OF INFORMATION FOR PARTICIPANTS

Neural Coding Within Human Brain Regions Involved in Grasping and Reaching

Introduction

You are being invited to participate in a research study investigating the regions of the brain that are active when people perceive objects or act towards them. The purpose of this research is to map and characterize areas of the human brain which are involved in using vision to perceive the scene or to control actions such as grasping, reaching, tool use, eye movements and related functions. This letter contains information to help you decide whether or not to participate in this research study. It is important for you to understand why the study is being conducted and what it will involve. Please take the time to read this carefully and feel free to ask questions if anything is unclear or there are words or phrases you do not understand.

Research Procedures

If you agree to participate in this study, you will undergo functional magnetic resonance imaging (fMRI) at the Robarts Research Institute. Functional MRI is a noninvasive brain imaging technique that uses the same machine that is used in MRI for patients. MRI uses a strong magnet and radio waves to make images of the brain. It does not involve x-rays or radiation. When a specific region of the brain is involved in processing information, there is an associated change in brain metabolism and blood flow to that region. These changes can be detected by the MRI scanner as changes in the image signal intensity. These changes are particularly prominent with stronger magnetic fields, which is why we use a 3 Tesla scanner.

At the beginning of the session, you will lie down on a table that slowly slides inside the long hollow tube at the centre of the MRI machine. The space within the large magnet is somewhat confined, although we have taken many steps to reduce any "claustrophobic" feelings. The session will last up to two hours, during which you must keep as still as possible, especially during periods lasting approximately five minutes during which the magnet is beeping continuously. You will hear a muffled banging and beeping noises throughout the scanner

13507 Last Modified: March 17, 2014

Participant's Initials: _______

operation, but the hearing protection will reduce the sound level to an acceptable level. If you find the sound uncomfortably loud, notify the operator immediately.

During the functional scans, you will look at images or real objects. You may be asked to look at the displays passively, to make perceptual judgments about the displays, and/or to interact with them by moving your eyes or reaching out to touch or grasp them. Specific instructions will be given for each task before you begin.

Because the MRI scanner uses a very strong magnet that will attract metal, we must be certain that you have no metal in or on your body when you go into the scanner. Prior to participating, you will be asked to fill out a screening checklist to evaluate whether you meet the eligibility criteria for participation in this fMRI study. These include precautions to ensure you have no metal in your body and, if you are female, that you are not pregnant or at risk of conceiving a child. You will also be asked to remove any metallic personal effects (jewellery, watch, hair clips, wallet) to be stored in a safe place while you are being scanned.

You will be in voice contact with the operator between scans (of approximately five minutes apiece). You will also be given a squeeze ball to alert the operator during a scan. You may ask the operator to end the experiment at any time.

Voluntary Participation

Participation in this study is voluntary. You may refuse to participate, refuse to answer questions or withdraw from the study at any time with no effect on your academic or employment status. You should ask to stop the experiment if you feel uncomfortable, claustrophobic or tired.

You have no obligation to participate in concurrent or future studies. At a future date, we may ask whether you would be willing to participate in an additional study from our lab or institute. If you would like to be contacted for potential participation in future studies, please initial the box below. In the event that you are contacted to participate in a future study, you will be given another letter of information pertaining to that study. Initialing this form does not in any way hold you accountable for future participation, only to be contacted for a participation request.

☐

In the event that you are contacted to participate in a future study, you will be given another letter of information pertaining to that study. Initialing this form does not in any way hold you accountable for future participation, only to be contacted for a participation request.

Compensation

You will be compensated $25 per hour to compensate you for your time, parking and the inconveniences associated with participating in the study.

Benefits

There is no direct benefit to you from participating in this study. The results from this study may help us to better understand the brain regions underlying human vision and action.

Risks

The Food & Drug Administration (USA) has indicated that for clinical diagnosis an ‘insignificant’ risk is associated with human MRI exposure at the intensities used in this project. Current Canadian guidelines follow the USA guidelines. Although very rare, injury and deaths have occurred in MRI units from unsecured metal objects being drawn at high speeds into the magnet or from internal body metal fragments of which the subject was unaware or had not informed MRI staff. To minimize this latter possibility it is essential that you complete a screening questionnaire. Other remote but potential risks involve tissue burns and temporary hearing loss from the loud noise inside the magnet. The latter can be avoided with ear protection that also allows continuous communication between you and the staff during the study.

Participant Exclusion Criteria

The most important safety concern with MRI is to avoid having any metal in your body that is deemed unsafe in a strong magnetic field. Prior to participating, you will be asked to fill out a screening checklist to evaluate whether you meet the eligibility criteria for participation in this fMRI study. These include precautions to ensure you have no unsafe metal in your body and, if you are female, that you are not pregnant or at risk of conceiving a child. If you have any history of head or eye injury involving metal fragments, if you have ever worked in a metal shop or been a soldier, if you have some type of implanted electrical device (such as a cardiac pacemaker), if you have severe heart disease (including susceptibility to arrhythmias), you should not have an MRI scan. Some surgical implants (e.g., hip or joint replacements) are made of alloys (e.g., titanium) that are non-magnetic and are therefore safe in the MRI scanner. To certify that your surgical implant is safe for the MRI, we must have documentation from your physician before you will be able to participate in the experiment.

Incidental Findings

The MRI experiments carried out for this study are performed solely for scientific purposes. The data which is collected is not optimized to make clinical diagnoses, and the research team involved in these experiments are not trained to make medical evaluations. By participating, you agree that the experimenters are not expected to arrive at a clinical interpretation of the data collected.

Nevertheless, there is a small possibility that a potential abnormality might be observed – otherwise known as an incidental finding. If this occurs you will be notified of the issue by the principal investigator of the study who will assist you with your options for following up.

Investigators are not responsible for the outcome of medical follow-up or for any incurred costs during medical follow-up. By participating, you agree to the possibility of being informed about a potential incidental finding, according to the above-described procedure. If you do not agree to the potential risk of an incidental finding you should not participate in this study.

Confidentiality

Any information obtained from this study will be kept confidential. Any data resulting from your participation will be identified only by case number, without any reference to your name or personal information. The data will be stored on a secure computer in a locked room. Both the computer and the room will be accessible only to the experimenters. After completion of the experiment, data will be archived on storage disks and stored in a locked room for five years, after which they will be destroyed.

Representatives of the University of Western Ontario Health Sciences Research Ethics Board may require access to your study-related records or may follow up with you to monitor the conduct of the study.

Estimate of participant's time and number of participants

Each experiment will last approximately two hours. Each experiment within the project will involve approximately 15 subjects. The entire research project will involve approximately 400 subjects.

Contact Information

If you would like to receive a copy of the overall results of the study, please print your name and address on a blank piece of paper and give it to the experimenter.

If you have any questions about your rights as a research participant or the conduct of the study you may contact:

The Office of Research Ethics The University of Western Ontario

You do not waive any legal rights by signing the consent form. You will be provided with a copy of this letter of information and the consent form.

CONSENT FOR RESEARCH STUDY

Neural Coding Within Human Brain Regions Involved in Grasping and Reaching

I have read the letter of information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

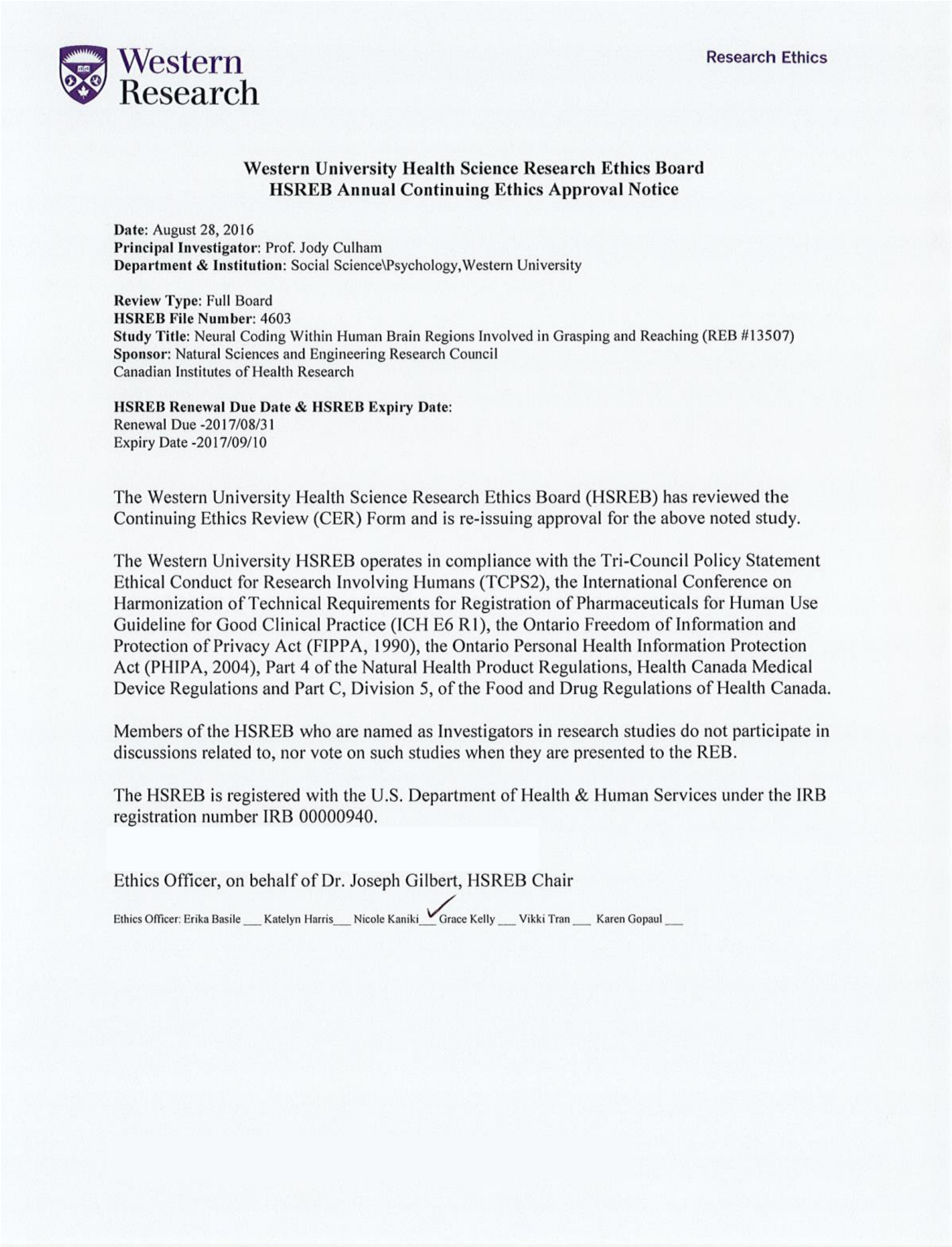
Dated in London, Ontario, this__________ day of________________,20______.

________________________________	________________________________
Name of Participant (Please print)	Name of Principal Investigator
________________________________	________________________________
Signature of Participant	Signature of Principal Investigator

Name of Person Responsible for Obtaining Consent: ______________________________
(Please print)

Signature of Person Responsible for Obtaining Consent: ______________________________

Dated in London, Ontario, this__________ day of________________, 20______.



Western Research

Research Ethics

Western University Health Science Research Ethics Board
HSREB Annual Continuing Ethics Approval Notice

Date: August 28, 2016
Principal Investigator: Prof. Jody Culham
Department & Institution: Social Science\Psychology,Western University

Review Type: Full Board
HSREB File Number: 4603
Study Title: Neural Coding Within Human Brain Regions Involved in Grasping and Reaching (REB #13507)
Sponsor: Natural Sciences and Engineering Research Council
Canadian Institutes of Health Research

HSREB Renewal Due Date & HSREB Expiry Date:
Renewal Due -2017/08/31
Expiry Date -2017/09/10

The Western University Health Science Research Ethics Board (HSREB) has reviewed the Continuing Ethics Review (CER) Form and is re-issuing approval for the above noted study.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice (ICH E6 R1), the Ontario Freedom of Information and Protection of Privacy Act (FIPPA, 1990), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Ethics Officer, on behalf of Dr. Joseph Gilbert, HSREB Chair

Ethics Officer: Erika Basile ___ Katelyn Harris___ Nicole Kaniki_✓_ Grace Kelly ___ Vikki Tran ___ Karen Gopaul ___

Curriculum Vitae

EDUCATION

University of Western Ontario, London, Ontario
PhD in Neuroscience
Degree in-progress – diploma expected August 2017
Supervisor: Dr. Jody Culham

Mount Allison University, Sackville, New-Brunswick
Honours in Psychology (BA)
Degree completed – diploma received May 16th, 2011
Supervisor: Dr. Geneviève Desmarais

SCHOLARSHIPS AND AWARDS

Ontario Graduate Scholarship (OGS) – $15,000
Western Graduate Research Scholarship (WGRS) – $7,400
Neuroscience Travel Award - $500

MANUSCRIPTS PUBLISHED

Hahamy, A., **Macdonald, S. N.**, van den Heiligenberg, F., Kieliba, P., Emir, U., Malach, R., Johansen-Berg, H., Brugger, P., Culham, J. C., & Makin, T. R. (2017). Representation of multiple body parts in the missing-hand territory of congenital one-handers, *Current Biology.*

Freud, E., **Macdonald, S. N.**, Chen, J., Quinlan, D. J., Goodale, M. A., & Culham, J.C. (2017). Getting a grip on reality: Grasping movements directed to real objects and images rely on dissociable neural representations, *Cortex.*

Squires, S. D., **Macdonald, S. N.**, Culham, J. C., & Snow, J. C. (2016). Priming tool actions: Are real objects more effective primes than pictures? *Experimental Brain Research,* 234(4), 963-76. doi: 10.1007/s00221-015-4518-z

Macdonald, S. N., Richards, E. D., & Desmarais, G. (2016). Impact of semantic similarity in novel associations: direct and indirect routes to action, *Attention, Perception, & Psychophysics,* 78(1), 37-43. doi:10.3758/s13414-015-1041-z

Macdonald, S. N., & Culham, J. C. (2015). Do human brain areas involved in visuomotor action show a preference for real tools over similar non-tools and does orientation matter? *Neuropsychologia,* 77, 35-41. doi:10.1016/j.neuropsychologia.2015.08.004

MANUSCRIPTS SUBMITTED

van den Heiligenberg, F.M.Z., Orlov, T., **Macdonald, S. N.**, Duff, E. P., Slater, D. H., Beckmann, C., Johansen-Berg, H., Culham, J. C., & Makin, T. R. Artificial limb usage shapes visual representations, *Nature Neuroscience*.

MANUSCRIPTS IN PREPARATION

Macdonald, S. N., van den Heiligenberg, F.M.Z., Makin, T. R., & Culham, J. C. Videos are more effective than pictures at activating tool- and hand-selective areas in human neuroimaging.

Macdonald, S. N., & Culham, J. C. The impact of tool familiarity and task on human visuomotor areas.

SUPERVISION OF TRAINEES

Undergraduates

Emma Bluemke	2016 - present
Tya Vine	2016 - present
Nathan Katz	2015 - 2016
Scott Squires	2013 - 2014
Marina Borja	2012 - 2013
Mark Trainor	2013 - 2014

Research Assistants & Volunteers

Marissa Donnelly	2016 - present
Jocelyn Goldhawk	2012 - 2013
Stefan Poirier	2013 - 2014
Leanne Zive	2013 – 2014

RELATED WORK EXPERIENCE

FMRIB, University of Oxford, United-Kingdom
Intern

Mount Allison University
Research Assistant

Mount Allison University
Tutor

University of Waterloo
Research Assistant

TEACHING ASSISTANT EXPERIENCE

University of Western Ontario, London, Ontario
Psychology Honours Seminar

University of Western Ontario, London, Ontario
Neuroimaging of Cognition

University of Western Ontario, London, Ontario
Sensation and Perception

University of Western Ontario, London, Ontario
Introduction to Psychology

Mount Allison University, Sackville, New-Brunswick
Biopsychology course and lab

Mount Allison University, Sackville, New-Brunswick
Human neuropsychology course and lab

Mount Allison University, Sackville, New-Brunswick
Introduction to Psychology

CONTRIBUTIONS

London Brain Bee Head Organizer

Dorchester Penitentiary Volunteer (Shepody Psychiatric Unit)

Lab coordinator (Mount Allison University)

PEER REVIEW

Reviewer, Experimental Brain Research
Co-reviewer, Restorative Neurology and Neuroscience
Co-reviewer, Trends in Cognitive Sciences
Co-reviewer, Neurophysiology
Co-reviewer, Experimental Brain Research
Co-reviewer, Neuron
Co-reviewer, Cerebral Cortex
Co-reviewer, Journal of Experimental Psychology: General
Co-reviewer, Psychological Science

INVITED TALKS

Macdonald, S. N., van den Heiligenberg, F.M.Z., Culham, J. C., & Makin, T. R. (2015).

Localizing tool and hand-selective areas with fMRI: Comparing video and picture stimuli. Talk presented at the 9th Annual Canadian Neuroscience Satellite Meeting, Vancouver, BC.

Macdonald, S. N., Cardinali, L., & Culham, J. C. (2015). The plasticity of hand and prosthesis representation in the brain. Keynote speaker at the 32nd Annual Meeting of the Ontario Association of Amputee care.

CONFERENCE PRESENTATIONS

Macdonald. S, van den Heiligenberg, F., Culham, J. C., Makin, T, & Culham, J. C. (2015). Localizing tool- and hand-selective areas with fMRI: Comparing video and picture stimuli. Poster presented at the Society for Neuroscience, Chicago, Illinois.

Macdonald. S, van den Heiligenberg, F., Culham, J. C., Culham, J. C., & Makin, T. (2015). Localizing tool- and hand-selective areas with fMRI: Comparing video and picture stimuli. Poster presented at the Vision Sciences Society in St. Pete Beach, Florida.

van den Heiligenberg, F., **Macdonald. S.**, Duff, E., Slater, D. H., Culham, J. C., Johansen- Berg, H., & Makin, T. (2014). Prosthesis representation in the visual cortex of upper-limb amputees. Poster presented at the annual Oxford Neuroscience Symposium, Oxford, UK.

Squires, S., **Macdonald, S.,** Quinlan, D. J., Paccioco, J. U., Culham, J. C., & Snow, J. C. (2014). Do real tools prime hand actions more than photographs of tools? Poster presented at the 2014 annual meeting of the Canadian Society for Brain, Behaviour, and Cognitive Science, Toronto, Ontario.

Squires, S., **Macdonald, S.,** Quinlan, D. J., Paccioco, J. U., Culham, J. C., & Snow, J. C. (2014). Do real tools prime hand actions more than photographs of tools? Poster presented at the annual Southern Ontario Neuroscience Association conference, Toronto, Ontario.

Macdonald, S., & Culham, J. C. (2013). Do human brain areas involved in visuomotor actions show a preference for real tools over visually similar non-tools. Poster presented at the Society for Neuroscience, San Diego, California.

Macdonald, S., & Culham, J. C. (2013). Do human brain areas involved in visuomotor actions show a preference for certain tool orientations? Poster presented at the Canadian Association for Neuroscience, Toronto, Ontario.

Macdonald, S., & Culham, J. (2012). The effect of tool handle orientation on fMRI activation. Talk presented at the 2012 annual meeting of the Collaborative Research and Training Experience (CREATE) Computational Approaches to

Neuroscience – Action Control and Transformations (CAN-ACT) Retreat in Toronto, ON.

Macdonald, S., & Desmarais, G. (2011). The Transfer of Action Control from a Semantic to a Structural System after Repeated Exposure. Poster presented at the 2011 annual meeting of the Canadian Society for Brain, Behaviour, and Cognitive Science in Winnipeg, MN.

Macdonald, S., & Desmarais, G. (2011). The Transfer of Action Control from a Semantic to a Structural System after Repeated Exposure. Talk given at the 2011 annual meeting of the Atlantic Provinces Council of the Sciences in Halifax, NS.

Macdonald, S., & Desmarais, G. (2011). The Transfer of Action Control from a Semantic to a Structural System after Repeated Exposure. Talk given at Mount Allison University's 2011 Research Day in Sackville, NB.

Macdonald, S., & Desmarais, G. (2010). The Impact of Semantic Information on Action Production and Action Identification. Talk given at McMaster University's 2010 SOMBS in Hamilton, ON

Macdonald, S., & Desmarais, G. (2010). The Impact of Semantic Information on Action Production and Action Identification. Poster presented at the 2010 annual meeting of the Canadian Society for Brain, Behaviour, and Cognitive Sciences in Halifax, NS.

Macdonald, S., & Desmarais, G. (2010). The Impact of Semantic Information on Action Production and Action Identification. Poster presented at Mount Allison University's 2010 Research Day in Sackville, NB.

Macdonald, S., & Desmarais, G. (2009). The Impact of Semantic Information on Action Production. Poster presented at the 2009 Annual Theoretical & Experimental Neuropsychology Conference in Montreal, QC.

Macdonald, S., & Desmarais, G. (2009). The Impact of Semantic Information on Action Production. Poster presented at the 2009 annual meeting of the Atlantic Provinces Council of the Sciences in Halifax, NS.

Macdonald, S., & Desmarais, G. (2009). The Impact of Semantic Information on Action Production. Poster presented at the 2009 annual meeting of the Atlantic Provinces Council of the Sciences in Halifax, NS.

Macdonald, S., & Desmarais, G. (2009). The Impact of Semantic Information on Action Production. Poster presented at Mount Allison University's 2009 Research Day in Sackville, NB.