HAPTIC FOUNDATIONS FOR VISUALLY GUIDED ACTION

JENNI M. KARL
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Department of Neuroscience
University of Lethbridge
LETHBRIDGE, ALBERTA, CANADA

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JENNI KARL

Date of Defence: August 1, 2014

Dr. Ian Q. Whishaw Supervisor	Professor	Ph.D.
Dr. Claudia Gonzalez Thesis Examination Committee Member	Associate Professor	Ph.D.
Dr. Masami Tatsuno Thesis Examination Committee Member	Associate Professor	Ph.D.
Dr. Jon Doan Internal Examiner	Associate Professor	Ph.D.
Dr. Jody Culham External Examiner Western University London, Ontario	Professor	Ph.D.
Dr. Robert McDonald Chair, Thesis Examination Committee	Professor	Ph.D.

Dedication

For Mark and my Family

Thesis Abstract

Prehension is proposed to consist of two movements mediated by separate neural pathways – a Reach transports the hand to the target while a Grasp shapes the hand for target purchase – but under vision the two movements appear as a seemless act. The purpose of the present thesis was to examine prehension under conditions of limited visual feedback. Removing vision in adults caused prehension to decompose into an open handed Reach followed by a haptically mediated Grasp, suggesting that haptics also access the Reach and Grasp pathways. That Grasp, but not Reach, formation is equally accurate under haptic versus visual control indicates that the sensory control of the two movements can be differentiated. Finally, young infants perform haptic Reach and Grasp movements before integrating them together under vision. These results suggest that the Reach and the Grasp, with their requisite neural pathways, originate under haptic control with secondary access by vision.

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List of Abbreviations

AIP/aIPS	Anterior intraparietal sulcus
ANOVA	Analysis of variance
AS	Arcuate Sulcus
B	Blueberry
CS	Central sulcus
D	Donut ball
DCN	Dorsal column nuclei
DRG	Dorsal root ganglion
DVC	Dual visuomotor channel
FEF	Frontal eye fields
IPL	Inferior parietal lobe
IPS	Intraparietal sulcus
IRED	Infrared emitting diode
LIP	Lateral intraparietal sulcus
LS	Lateral Sulcus
M1	Primary motor cortex
MIP/mIPS	Medial intraparietal sulcs
MLM	Mixed linear model
MST	Medial superior temporal area
MTG	Middle temporal gyrus
NDI	Norther digital inc.
O	Orange slice
Opt	Parietal area Opt
PE	Parietal area PE
PEa	Parietal area PEa
PEc	Parietal area PEc
PF	Parietal area PF
PFG	Parietal area PFG
PG	Parietal area PG
PLATO	Portable liquid-crystal apparatus for tachistoscopic occlusion
PMd/F2	Dorsal premotor cortex caudal (F2)
PMd/F7	Dorsal premotor cortex rostral (F7)
PMV/F4	Ventral premotor cortex caudal (F4)
PMv/F5	Ventral premotor cortex rostral (F5)
POS	Parietal occipital sulcus
PPC	Posterior parietal cortex
Pre-SMA/F6	Pre-supplementary motor area (F6)
RA	Rapidly adapting
SI	Primary somatosensory cortex
SII	Secondary somatosensory cortex
SA	Slowly adapting
SC	Caudal somatosensory area
SF	Sylvian fissure
SMA/F3	Supplementary motor area (F3)

SPL	Superior parietal lobe
SPOC	Superior parietal occipital sulcus
SR	Rostral somatosensory area
STS	Superior temporal sulcus
V1	Primary visual cortex
V2	Secondary visual cortex
V3A	Visual area 3A
V4	Visual area 4
V6Ad	Visual area 6A dorsal
V6Av	Visual area 6A ventral
VIP	Ventral intraparietal area
VP	Ventroposterior nucleus of the thalamus
VPI	Ventroposterior inferior nucleus of the thalamus
VPS	Ventroposterior superior nucleus of the thalamus

Chapter 1

Introduction

Introduction

Modern theories of brain organization are based on the idea that neural areas are organized according to their functional outputs rather than their sensory inputs. This view was pioneered by visual neuroscientists Mishkin and Ungerleider (1982), who suggested that visual information is processed by two functionally distinct pathways: a dorsal "where" pathway in the parietal lobe that uses visual information to determine the location of an object within the external environment and a ventral "what" pathway in the temporal lobe that uses visual information to perceive, recognize, and remember what those objects are. This dual pathway model was later revised by Milner and Goodale (1995, 2008), who showed that the dorsal "where" pathway is more accurately described as a "how" pathway that uses visual information to guide one's actions in space and to interact with external objects, for example, to reach out and grasp a piece of food. This distinction between the dorsal "vision-for-action" and the ventral "vision-for-perception" pathway is now widely accepted by the majority of the neuroscientific community and has become a foundational concept in the study of brain and behavior.

While this work highlights a clear dissociation within the visual system, it has somewhat paradoxically led to the idea of unification between the visual and motor systems within the dorsal pathway. The idea being that neural processing related to visual inputs vs. motor outputs cannot be dissociated, but rather exist along a visual-to-motor continuum in the occipito-parieto-frontal cortex (Goodale, 1998). Clearly vision plays an important role in our ability to both perceive and interact with our external environment; however, there are at least as many situations where vision is not available to guide action and for many species vision plays a secondary role compared to the alternative sensations of touch, olfaction, and audition. In short, it seems that the cortical motor system must operate independent from vision in order to enable interactions with objects to which our visual system is not directly attuned, i.e., objects in the dark, in peripheral vision, or located on our own body, and for the same reason non-visual systems such as touch and audition must also have access to the cortical motor system.

The purpose of this review is to re-examine the organization of the primate somatosensory system from the perspective of its contribution to dorsal stream action control in the absence of vision, or, “somatosensation-for-action”. Somatosensory processing, which includes both tactile and proprioceptive inputs, is briefly described at the peripheral, subcortical, and cortical levels. I then describe emerging evidence that the cortical motor system consists of a number of partially overlapping parietofrontal circuits related to specific motor acts such as walking, reaching, handling food, and grasping (Kaas et al., 2013). In doing so, I consider the extent to which these circuits process somatosensory and visual inputs for action control. Collectively, the evidence supports emerging theories of sensorimotor control, which propose that functional motor modules can process inputs from a variety of sensory stimuli and achieve optimal action control by re-weighting sensory inputs according to their reliability in a given situation.

Somatosensation in the Peripheral and Central Nervous Systems

It is important to recognize that objects are comprised of a constellation of physical properties, which define the ways in which we may interact with them. For instance, the ability to reach out and grasp a piece of food is largely dependent on the sensorimotor system's ability to recognize an object's extrinsic properties (i.e., location and orientation – to which the hand must reach), and an object's intrinsic properties (i.e, size and shape – to which the digits must open, shape, and close; Jeannerod, 1981, Jeannerod et al., 1995). While some object properties are uniquely derived from a particular sensory modality, i.e., object colour from vision vs. object temperature from somatosensation, the properties of object location, orientation, size, and shape can be directly derived from either vision or somatosensation, insomuch as the object is located within the operational space of each modality.

When we reach out to touch, grasp, or manipulate an object a bidirectional exchange occurs at the interface between the skin of our hand and the surface of the object. Consider reaching to grasp a small round blueberry. When the tip of your digit first touches the blueberry, its surface may yield to the pressure applied by your finger, but the skin of your fingertip is also deformed by reciprocal pressure from the surface of the blueberry. From this dynamic interaction, the peripheral somatosensory system must accurately discriminate the size, shape, density, texture, and curvature of that particular blueberry in order to successfully grasp it. To accomplish this, the somatosensory system has evolved a variety of specialized peripheral receptors, each of which processes information about a specific physical property. Thus, at the moment of contact the peripheral somatosensory system essentially breaks the blueberry apart into a constellation of its physical properties, each of which is analyzed by a separate receptor system.

The task at higher levels of the somatosensory system then, is to piece these disparate physical properties back together into a meaningful whole and/or to activate the appropriate motor actions required to grasp and interact with that blueberry. Here, a parallel can be drawn between the somatosensory system and the visual system (Dijkermann and de Haan, 2007), as the higher visual system must also reconstruct a meaningful whole from a constellation of disparate visual properties like object colour, luminance, shape, and contrast or engage the appropriate sequence of motor actions.

Somatosensory Cells, Afferents, and Receptors

Dorsal Root Ganglion (DRG) Cells. The DRG cell is the functional unit of the peripheral somatosensory system. It consists of a single cell body that has no dendrites and receives no synapses. Instead, it sends out a single axon that almost immediately branches into two. One branch (the primary afferent) projects to the periphery and terminates as a specialized receptor in the muscle, joint, or skin. The second branch projects into the spinal cord where it either synapses with a motor neuron, forming a spinal reflex, or ascends to the brain via the dorsal columns. The dorsal root ganglion system along the spine conveys somatosensory information from the body and limbs, whereas a different, trigeminal ganglion system, conveys somatosensory information from the face and head (Amaral, 2013).

Somatosensory Receptors. Compared to the visual and auditory systems, the somatosensory system contains a large number of receptors, each of which processes a different somatosensory modality. For the purposes of this review, we will focus on sensations of fine touch, pressure, and proprioception from the glabrous skin of the primate hand, which are largely conveyed by four tactile receptors (Table 1.1, Johansson and Vallbo, 1983; Johnson, 2001; Johnson et al., 2000), which are described below, and proprioceptive mechanoreceptors, which are described elsewhere (Proske and Gandevia, 2012). Although our focus here is on the tactile feedback from the hand, it has been reported that similar tactile receptors process complex somatosensory stimuli on the face and in the mouth (Trulsson and Johansson, 2002).

Tactile receptors in the glabrous skin of the primate hand can be divided into two groups based on the firing properties of the primary afferent fibers to which they are attached (Johnson 2001). Rapidly adapting (RA) fibers only fire at the onset and offset of a stimulus whereas slowly adapting (SA) fibers continue firing for the entire duration that a tactile stimulus is in contact with the skin. In addition, fibers may be Type 1, meaning that they terminate in the superficial layers of the skin, or Type 2, meaning that they terminate in deeper skin layers. Each type of fiber is associated with a specific type of receptor: Meissner corpuscles (RA1), Merkel disk receptors (SA1), Pacinian Corpuscles (RA2), and Ruffini Endings (SA2).

Type 1 Tactile Receptors. *Meissner corpuscles (RA1)* are located in the superficial layers of the skin and have very small receptive fields. They are the most numerous tactile receptor in the hand and form orderly rows along the dermal ridges of the overlying fingerprint (Bolanowski and Pawson, 2003; Johnson, 2001). They respond to low frequency vibration, tapping, and flutter and they are extremely sensitive to stimuli moving across their receptive field. Thus, they help to signal slippage of an object held in the hand (Macefield et al., 1996).

Table 1.1 Somatosensory Receptor Types*

Receptor Type	Fiber	Modality
Cutaneous and subcutaneous mechanoreceptors		**Touch**
Meissner corpuscle	RA1	Flutter, stroking
Merkel disk receptor	SA1	Pressure, curves
Pacinian corpuscle	RA2	Vibration
Ruffini ending	SA2	Skin stretch

* (adapted from Johnson et al., 2001)

Merkel disk receptors (SA1) are also located in the superficial layers of the skin and are concentrated in the most sensitive parts of the body, the fingertips and lips (van Boven and Johnson, 1994). In rodents they accumulate near the follicles of the whiskers and also on the glabrous skin of the forepaws (Abraira and Ginty, 2013). Merkel disk receptors have very small receptive fields (about 2 to 3 mm in humans), but can resolve spatial detail even finer than this (Johnson, 2001). They have a low activation threshold, which makes them very responsive to light touch or indentation, especially during contact with edges, curves, and corners of objects (Goodwin and Wheat, 1999), which is clearly important for determining object size, shape, and rigidness. The more concentrated the stimulus (i.e. the tip of a nail) the stronger the SA1 fiber responds (creates a sharp feeling). The less concentrated the stimulus (i.e. the side of a glass), the weaker the SA1 fiber responds (creates a smooth feeling; Goodwin et al., 1995; Vega-Bermudez and Johnson, 1999).

The way that Type 1 receptors are organized in the upper layers of the skin is important for a number of reasons (Pare et al., 2002). First, receptor density reflects the sensitivity of a particular body part. As mentioned, Type 1 receptors are most dense in the fingertips and the lips. Thus, the tip of the index finger acts like the somatosensory fovea of the hand, whereas the lips/mouth act as the somatosensory fovea of the face. Using these effectors, one can detect fine tactile details like the braille letter “A” because the individual bumps co-activate discrete Type 1 receptors and their afferents (Phillips et al., 1992). Second, a single receptor may be innervated by axons from several different DRG cells. This is called ‘convergence’ and it allows the somatosensory system to detect very weak stimuli, because although only one receptor may be activated, multiple DRGs are activated; however, high convergence results in low spatial resolution, so if high spatial resolution is required (like on the finger tips) then convergence is low. Third, a single primary afferent fiber (and thus, DRG cell) may receive input from multiple receptors, which may be located across different digits or parts of the hand. This is called ‘divergence’ and it allows the somatosensory system to integrate complex somatosensory stimuli across multiple skin locations. Thus, the receptive fields of Type 1 fibers consist of an array of small hotspots that reflect the branching of the primary fiber to which they are attached (Johansson and Vallbo, 1983).

Type 2 Tactile Receptors. *Pacinian corpuscles (RA2)* are located in the deeper layers of the skin or subcutaneous fat. They are concentrated more in the palm, joints of the fingers, and the wrist rather than in the fingertips. Unlike Type 1 receptors, Pacinian corpuscles have very large receptive fields, sometimes covering the whole hand, which gives them quite low spatial acuity (Johnson et al., 2001). They are extremely sensitive, however, to high frequency vibrations made by an object gripped or manipulated by they hands and they can even discriminate the temporal structure of these high frequency vibrations (Brisben et al., 1999). This allows us to perceive what is going on at the distal tip of a tool that is held in the hand. Thus, Pacinian corpuscles may be especially important for allowing us to manipulate and interact with objects, especially tools, in the absence of vision.

Ruffini endings (SA2) are also located in deep skin layers and have large receptive fields on the skin surface. They are located mainly around the joints of the hand and in the folds of skin on the palm, but they respond to skin stretch (Edin, 1992; Johnson et al., 2000). This allows them to detect hand shape and finger configurations, regardless of whether an object is being held or not. If the hand is held in a fist, the skin of the knuckles is stretched and the ruffini endings there are activated. If the hand is open, the skin on the palm is stretched and the ruffini endings there are activated. Thus, ruffini endings provide more information about the shape of the hand than they do about an external object (Edin and Johansson, 1995), but they can also detect object motion when an object moving across the skin causes the skin to stretch (Olausson et al., 2000).

Type 1 receptive fields are small so they can only detect small portions of an object that is held in the hand. In contrast, the large receptive fields of Type 2 receptors allow them to detect more global features of an object, such as overall size and shape. Thus, activity from all four tactile receptors is important for grasping (Johansson and Flanagan, 2009; Johnson et al., 2000;Westling and Johansson, 1987). RA1 fibers signal the stability of the grasp on the object. They stop firing once the grasp is stabilized, but fire again if the object slips. SA1 fibers signal the amount of force applied by each finger and detect the curvature and edges of the object. RA2 fibers detect the vibrations that are emitted when the object is lifted from or placed on a surface. SA2 fibers signal changes in hand and finger configuration as the object is being grasped. Thus, a loss of this somatosensory information causes deafferented patients to show huge impairments in controlling grip shape and force when trying to grasp and manipulate objects (Darian-Smith and Ciferri, 2005; Hermsdorfer et al., 2008; Sainburg et al., 1993). Even when vision is available, these impairments cannot be fully compensated for, which reveals the tight interdependence of the somatosensory and motor systems in performing precise and dexterous hand movements.

It should be noted that although the majority of somatosensory research has focused on tactile feedback from glabrous skin on the primate hand, almost all other mammals rely much more heavily on a variety of hair mechanoreceptors located across the body in non-glabrous skin, including vibrissae hairs on the face, limbs, and trunk, which can process equally complex somatosensory stimuli (see Abraira and Ginty, 2013; Diamond, 2010; Li et al., 2011; Wu et al., 2012).

Dorsal Column-Medial Lemniscal Pathway

Dorsal Columns. The cell body of a DRG cell is located in a ganglion on the dorsal root of a spinal nerve. Within this ganglion, individual DRG cells may be large or small. Large DRG cells process tactile and proprioceptive information whereas small DRG cells process pain and temperature information (Amaral, 2013). We are concerned with large DRG cells, the fibers of which enter the spinal cord via the dorsal horn where they may terminate or turn upwards and ascend as part of the dorsal columns in the dorsal funiculus. Dorsal column fibers ascending from the feet, legs, and lower trunk are called the *gracile fasiculus* (located medially) whereas fibers ascending from the hands, arms, and upper trunk are called the *cuneate fasciculus* (located laterally, figure 1.1, adapted from Amaral et al., 2013). This mediolateral organization produces a somatopic map of the body across the dorsal columns, with the feet located medially and the hands located laterally (Whitsel et al., 1972).

Dorsal Column-Trigeminal Complex. Upon reaching the lower medulla, the dorsal column fibers and fibers from the trigeminal ganglion system synapse with their respective dorsal column nuclei: the *gracile nucleus* (lower body), the *cuneate nucleus*

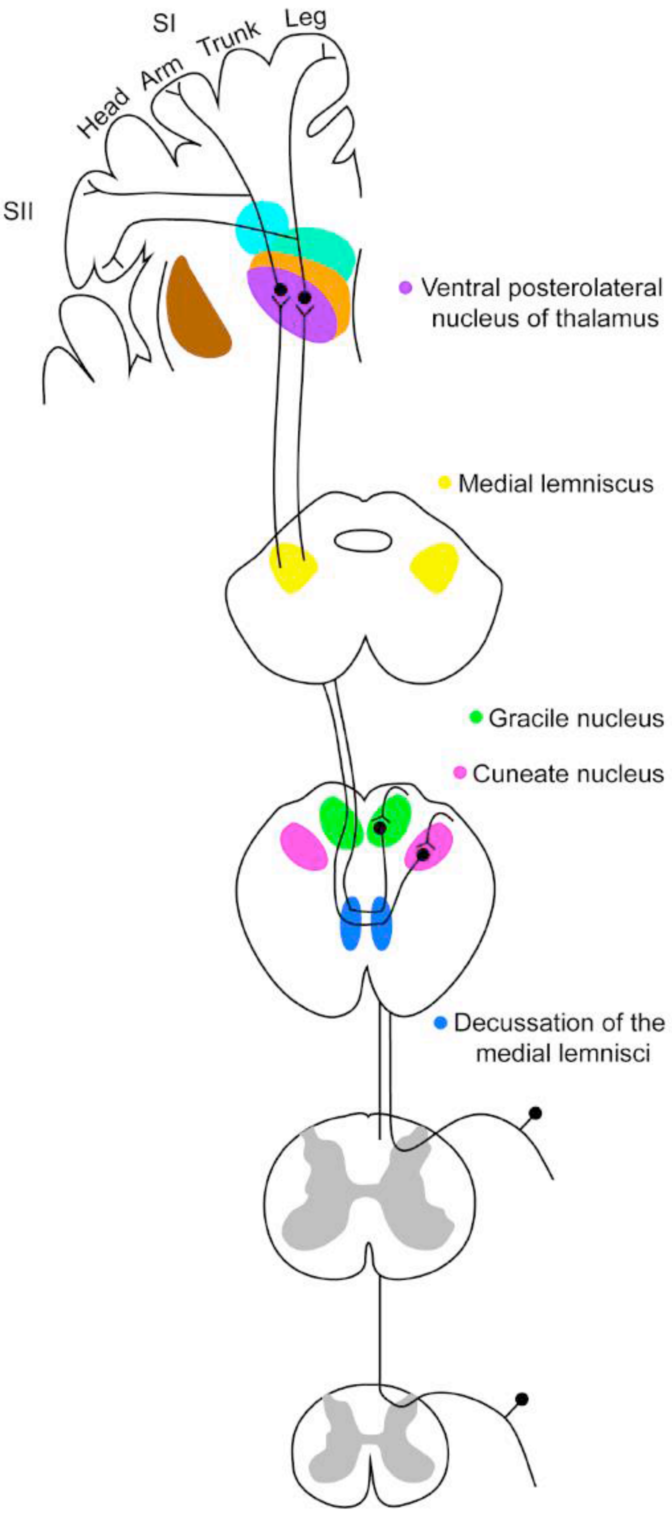


Figure 1.1 The dorsal column-medial lemniscal pathway (adapted from Amaral et al., 2013).

(upper body), and the *principal trigeminal nucleus* (face and head). These three nuclei, in addition to adjacent cells that receive proprioceptive input from muscle spindles and joint receptors, make up the *dorsal column-trigeminal complex* (Kaas, 2008). Here, the somatotopic map of the body is maintained but the tactile and proprioceptive inputs are segregated. The majority of outgoing projections then cross the midline of the medulla and ascend in a fiber bundle called the *medial lemniscus*, which maintains the mediolateral somatotopic map of the body, and projects to the *ventroposterior complex* of the contralateral thalamus (figure 1.1). However, a small minority of fibers, carrying information about the mouth, lips, and teeth, also projects to the ipsilateral ventroposterior complex (Jones et al., 1986). The majority of the inputs to the ventroposterior complex are excitatory, but about 30% are inhibitory and may act to limit the size of the receptive fields of neurons in the these nuclei (Schwark et al., 1999; Wang and Wall, 2006).

Ventroposterior Complex of the Thalamus

The thalamus acts as a selective filter for information passing between subcortical structures and the cortex. It may enhance or prevent the transfer of specific information depending on a person's behavioural state. The somatosensory thalamus (the *ventroposterior complex*) consists of 3 major nuclei (Kaas, 2008): the *ventroposterior nucleus* (VP), which relays primarily tactile information, the *ventroposterior superior nucleus* (VPS), which relays primarily proprioceptive information, and the *ventroposterior inferior nucleus* (VPI), which relays primarily pain and temperature information. Here, we will consider only VP and VPS.

The majority of inputs to VP are tactile (Kaas, 2008; Kalil, 1981). Thus, VP contains a somatotopic map of the contralateral body, but it is the mirror image of the map found in the dorsal columns and medial lemniscus with the head located medially and the feet laterally. Bands devoid of cells separate different body parts, like the head from the rest of the body, and in primates the forelimb representation is separated from the hindlimb representation. Smaller bands separate individual fingers and parts of the face and mouth (Kaas, 2008; Rausell and Jones, 1991). These cell-free bands are thought to represent body areas (or spaces between body parts) that lack somatosensory receptors. The majority of VP outputs project to area 3b of the primary somatosensory cortex, but a minority also project to areas 1 and 2 of SI as well as the hand and face areas in posterior parietal cortex (Cusick et al., 1985; Kaas, 2008; Pons and Kaas, 1985). These projections are generally somatotopic with hand regions in VP projecting to hand areas of cortex.

The VPS, which processes proprioceptive information is located just dorsal to VP and receives projections from the proprioceptive nuclei in the dorsal column-trigeminal complex (Boivie and Boman, 1981). Its outgoing projections are directed to areas 3a and 2 in primary somatosensory cortex (Cusick et al., 1985; Darian-Smith and Darian-Smith, 1993). A substantial number of these projections (up to ~40%) may split and simultaneously project to homotopic areas in both area 3b and 2 (Cusick et al., 1985).

A number of additional thalamic nuclei receive somatosensory inputs and project to somatosensory regions in the parietal cortex. These nuclei may be involved in processing higher-level somatosensory information and include; the *anterior pulvinar*, which has reciprocal connections with anterior, posterior, and lateral parietal cortex (Pons and Kaas, 1985); the *medial pulvinar*, which has reciprocal connections with somatosensory and multisensory posterior parietal areas, including those involved in reaching and grasping (Kaas, 2008); the *lateral posterior nucleus* which connects to posterior and lateral parietal cortex (Padberg and Krubitzer, 2006); and the *basal ventral medial nucleus,* which receives tactile inputs from the mouth and projects to the tongue representation in area 3b of SI (Kaas et al., 2006).

Axons leaving the thalamus to the cortex project via the *internal capsule*, but there are many more projections moving in the opposite direction, from the cortex to the thalamus and also to the dorsal column-trigeminal complex. In general, these corticothamalic connections are somatotopic, meaning that cortical areas representing the hand tend to project to thalamic areas also representing the hand; however, some projections are mismatched (Kaas, 2008). These cortical to subcortical projections appear to regulate the size of the receptive fields of the cells in the thalamic nuclei (Wang and Wall, 2006) and may help to spread somatosensory information across different parts of the cortex. Ultimately, these connections appear to modulate the responsiveness of the thalamic nuclei to different somatosensory stimuli, depending on behavioural state.

Primary Somatosensory Cortex (SI)

Primary somatosensory cortex (SI) is located on the anterior parietal cortex and extends from the caudal region of the central sulcus into the postcentral sulcus. It consists of 4 separate somatotopic representations of the opposite side of the body; areas 3a, 3b, 1, and 2 progressing from rostral to caudal (Kaas et al., 1979). In all four areas, the feet are represented medially and the hands and head are represented laterally. As mentioned, the majority of VPS and VP projections are directed towards areas 3a and 3b, respectively. Thus areas 3a and 3b appear to be engaged in simpler forms of somatosensory processing compared to areas 1 and 2. The ability to process more complex somatosensory stimuli appears to be related to differences in receptive field size and complexity between the different SI areas.

According to extensive neuroanatomical and electrophysiological work by Kaas and colleagues (Huffman & Krubitzer, 2001; Kaas,1984, 2004; Qi et al., 2008; Qi and Kaas, 2004) each SI area processes a different set of somatosensory inputs. Area 3b receives tactile inputs from VP and is generally considered the ancestral form of SI, which is present in all mammals (Kaas, 2004). It contains two types of modules. As in the thalamus, bands lacking cells separate individual body parts such as the head vs. body, individual digits, and different parts of the face, mouth, and teeth (Kaas, 2004; Qi and Kaas, 2004). These body-specific modules are most obvious in area 3b, but are also present in areas 3a, 1, and 2. Within these body-specific modules, alternating patches of cortex (~0.5mm wide) receive selective inputs either from SA or RA tactile receptors (Chen et al., 2001), thereby forming mini modality-specific modules within each body part representation. Higher somatosensory cortical areas may also consist of a similar modular organization, but it is not clear how the modules and mini-modules are defined, but it is likely by more complex features than body or receptor type. Area 3a receives proprioceptive inputs directly from VPS and appears to respond only to position sense. It likely corresponds to the rostral somatosensory area (SR) located rostral to SI in non-primate mammals. Area 1 processes tactile inputs, which it receives directly from VP, but also indirectly via area 3b. Area 2 receives both tactile inputs from 3b and 1 and proprioceptive inputs from 3a and VPS. Together, areas 1 and 2 may correspond to the caudal somatosensory area (SC) located caudal to SI in non-primate mammals. All of the primary somatosensory areas project to SII and the posterior parietal cortex (PPC).

Iwamura and colleagues (1993, 1994) studied the receptive fields of cells in SI. They found that SI receptive fields are larger than the receptive fields of individual sensory afferents that project there. For instance, a single 3b cell will have a receptive field that represents about 300 incoming somatosensory afferents. As you move to higher cortical areas the receptive fields get larger and more complex. Thus, receptive fields in area 3b might cover the tip of a single digit, area 1 receptive fields may span multiple digit tips, and area 2 receptive fields may span multiple digits. The receptive field of a single cell in area 1 or 2 is comprised of a number of area 3b receptive fields arranged in a particular spatial pattern. As discussed further below, the receptive fields in SII and PPC are often discontinuous and cover multiple body parts, like the hand and the mouth, and are often bilateral.

Differences in receptive field size and complexity means that different S1 areas process stimuli of differing complexity (Ageranioti-Belanger and Chapman, 1992). The electrophysiological properties of neurons in areas 3a and 3b are relatively simple. Neurons in 3b have small and precise receptive fields, thus 3b activity recreates the topographic locations of tactile events on the skin surface. But as information flows to higher somatosensory areas, more complex stimuli are needed to excite the neurons. For instance, area 1 cells respond to specific tactile patterns or textures (Tremblay et al., 1996) whereas area 2 cells respond to the orientation of edges, the surface curvature of objects, and the direction of motion across the hand. Area 2 neurons fire most strongly when the hand grasps an object, and individual area 2 neurons are specific to the shape of the object grasped, i.e., a round ball or a long narrow rod (Iwamura and Tanaka, 1978).

The organization of these complex receptive fields is somewhat dynamic, as they change throughout development and can be modified in response to experience or injury (Merzenich and Jenkins, 1993). Lesions to SI produce impairments on relatively simple, but specific somatosensory tasks. Lesions to area 3b impair one's ability to detect tactile stimuli on certain parts of the body, lesions to area 1 impair one's ability to detect changes in textural patterns on the skin, and lesions to area 2 impair one's ability to detect the size and shape of an object held by the hand (Hikosaka et al., 1985).

Secondary Somatosensory Cortex (SII)

SII is located on the upper bank of the lateral sulcus, but its organization is not well understood. In macaques, SII is thought to consist of at least 4 regions (Eickhoff et al., 2006) including at least 3 hand maps (Fitzgerald et al., 2004). SII receives both tactile and proprioceptive inputs from SI and the thalamus (Kaas, 1984; Cusick et al., 1989; Krubitaer and Kaas, 1990; Qi et al., 2002; Coq et al., 2004) and some neurons process both types of input (Fitzgerald et al., 2004). Neurons in SII have larger and more complex receptive fields than are found in SI. SII receptive fields may be bilateral, cover multiple parts of the hand, multiple parts of the hand and face, half the body, or the whole body (Fitzgerald et al., 2004; Ishida et al., 2013). SII appears to play an important role in being able to recognize objects through touch (Hsaio, 2008) and in producing haptic exploration movements with the hands. Lesions to this area impair manipulatory hand movements (tactile apraxia; Valenza et al., 2001; Roland, 1987) and the ability to discriminate the shape of an object held in the hand (tactile agnosia; Caselli, 1991) despite normal performance on simpler tactile discrimination tasks.

Posterior Parietal Cortex (PPC)

Traditionally, significant debate existed concerning the extent to which the PPC of human and non-human primates was homologous. This made neuroanatomical comparisons between the two groups especially difficult and conclusions drawn from such research were generally conservative. However, functional neuroimaging (Culham et al. 2006; Grefkes and Fink 2005), in addition to recent anatomical and functional connectivity studies (Mars et al., 2011; Margulies et al., 2009) suggest that the organization of functional parietal areas, as well as parietofrontal connectivity, is more similar between human and non-human primates than previously thought. Human vs. non-human differences appear to be most pronounced in the medial inferior parietal lobe, with humans displaying greater connectivity between this region and anterior prefrontal cortex compared to macaques (Mars et al., 2011).

In both humans and macaques the PPC is divided into two lobes. The superior parietal lobe (SPL) is located dorsal to the intraparietal sulcus (IPS) and extends from the medial lip of the IPS onto the medial surface of the longitudinal fissure. The inferior parietal lobe (IPL) is located ventral to the IPS and extends from the lateral lip of the IPS to the sylvian fissure. Figure 1.2 (adapted from Caminiti et al., 2010) illustrates the various terminologies used to describe subregions of the PPC in macaques and humans.

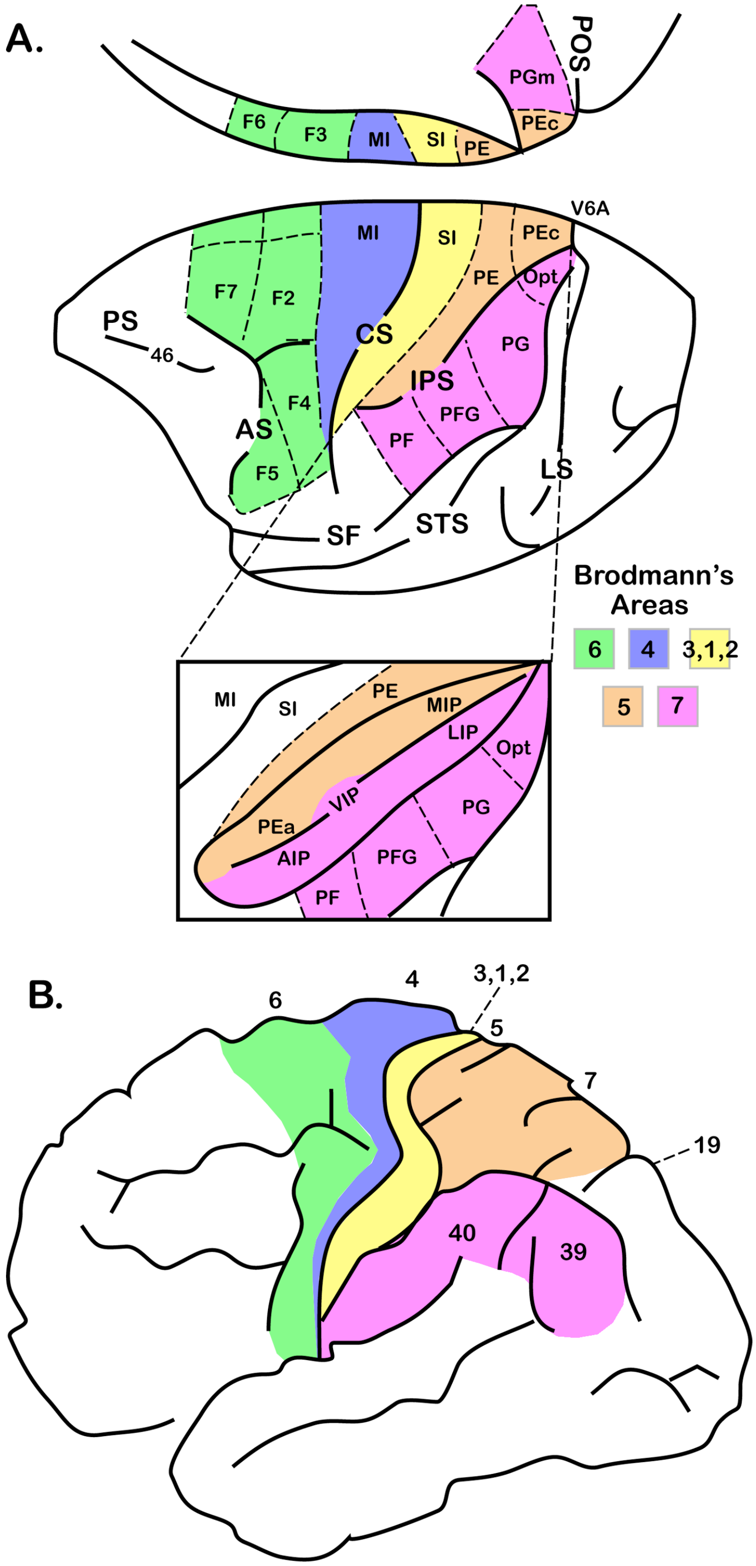


Figure 1.2 Cortical regions of posterior parietal cortex in the macaque (A) and human (B) brain (adapted from Caminiti et al., 2010).

It is generally accepted that the parietal lobes contain a rostrocaudal gradient with somatosensory information processing dominating in anterior PPC and gradually transitioning to predominantly visual processing in posterior PPC (Filimon, 2010).

Motor Modules in PPC

Classic work by Mountcastle et al. (1975) and Rizzolatti et al. (1988) showed that neurons in both frontal and parietal cortex fire in response to particular ethologically-relevant movements such as grasping with the hand, grasping with the mouth, reaching to a location in external space, and bringing the hand toward the mouth. Subsequent electrical stimulation studies by Graziano (2006) and Kaas et al. (2013) have confirmed that electrical stimulation applied for an ethologically-relevant length of time to interconnected regions of anterior PPC and motor cortex can elicit these same complex movements. Even more recently, studies using long-train stimulation of motor cortex have elicited complex forelimb movements, some of which also resemble reach, grasp, and hand-to-mouth movements in rodents (Bonazzi et al., 2013; Harrison et al., 2012). Together, this work suggests that interconnected modules in primate parietofrontal cortex are dedicated to specific motor actions and that at least the frontal aspects of these modules are retained from the common ancestor of rodents and primates, with some investigators proposing that action-specific processing is also a conserved feature of rodent PPC (Whitlock, 2014). In the following sections I describe four primate parietofrontal pathways that appear to mediate walking, reaching, grasping, and hand-to-mouth food handling behaviours as well as the visual and somatosensory inputs that they process.

Locomotion

Neural recording (Brevelieri et al., 2008; Drew et al., 2008), electrical stimulation (Graziano, 2006; Kaas et al., 2013), and neuroanatomical (Bakola et al., 2010, 2013) studies in non-human mammals, along with human neuropsychological (Della Sala et al., 2002; Evans et al., 2013) and neuroimaging studies (Abdollahi et al., 2013; Heed et al., 2011) converge to suggest that interconnected regions of the superior parietal lobe and medial frontal cortex are involved in producing complex locomotor behavior in mammals. In primates, this locomotor network appears to include the supplementary motor area (SMA/F3) and parietal areas PE, PEc, and V6A (Table 1.2).

Supplementary Motor Area (SMA). SMA/F3 is a cortical motor area located on the medial surface of the longitudinal fissure, just dorsal to PMd/F2, and sends projections to both the cervical and lumbrosacral regions of the spinal cord (Murray and Coulter, 1981). Short train stimulation of SMA produces a rough somatotopic map of the body with the forelimbs located in the middle, the face and mouth rostrally, and the hindlimbs caudally (Fried et al., 1991). The majority of movements evoked from SMA involve proximal limb joints or complex movements involving more than one joint (Fried et al., 1991; Luppino et al., 1991). The majority of SMA neurons respond to somatosensory stimuli, but visual responses are rare (Matsuzaka et al., 1992). Monkeys with lesions to SMA show a disruption of bimanual coordination in that they are unable

Table 1.2 Monkey cortical regions proposed to be involved in locomotion and their somatosensory and visual inputs

	Somatosensory or Somatomotor		Visual	
Area	**Inputs**	**References**	**Inputs**	**References**
V6A/SPOC	MIP PEc PG VIP MST PMd /F7	Bakola et al., 2010, 2013; Gamberini et al., 2009, 2011; Marconi et al., 2001	V2 V3 V4 V6 VIP MST	Gamberini et al., 2009, 2011; Passarelli et al., 2011; Shipp et al., 1998;
PEc	PE PEci MIP SI (2) SII PMd/F2 SMA/F3 MI	Bakola et al., 2010; Luppino et al., 1991 Mitz and Wise, 1987; Petrides and Pandya,1984;	V6Ad	Bakola et al., 2010
PE	PEc PEci PEa PF PG MIP SI (2) SII SMA/F3 M1 PMd/F2 PMV/F4	Bakola et al., 2013; Gerbella et al., 2011; Petrides and Pandya,1984; Pons and Kaas, 1986;	PG	Bakola et al., 2013
SMA/F3	PE PEa PEci SII PFop, PGop PMd/F2/F7 PMv F4/F5 MI	Jones et al., 1978; Luppino et al., 1991,1993; Petrides and Pandya, 1984;		

to produce coordinated actions with two hands. Instead, both hands consistently perform the same action (Brinkman, 1981). Bilateral SMA lesions in humans, produce gait ataxia (Della Salla, 2002), an inability to initiate or stop walking, which is often accompanied by disturbances in other coordinated behaviors, like rolling over in bed, walking backwards, or sitting down and standing up from a chair. A recent functional imaging study in healthy participants has also confirmed increased activity in SMA when people watch videos of others walking and stepping over obstacles (Wang et al., 2009). This work suggests that SMA processes primarily somatosensory inputs in order to produce coordinated movements of the forelimbs, hindlimbs, and torso, especially those involved in locomotion.

Parietal Area PE. PE is located in the SPL just posterior to SI and is also proposed to be involved in producing complex locomotor behavior in mammals. Ethologically relevant trains of stimulation applied to medial PE elicit complex forelimb and hindlimb movements reminiscent of running, leaping, or climbing in monkeys (Kaas et al., 2013). Human PE neurons (area 5 and precuneous) are activated during both the execution and observation of arm and leg movements involved in reaching, pointing, or climbing (Abdollahi et al., 2012; Filimon et al., 2009; Heed et al., 2011) and appear to code arm movements in both postural and retinal coordinates depending on whether or not vision is available (Bernier and Grafton, 2010; Bremner and Andersen, 2012; Filimon et al., 2010). The feline homologue of primate PE is involved in the production of skilled forelimb stepping movements over complex and uneven terrains (Drew et al., 2008; Marigold and Drew, 2011).

In primates, PE contains a rough somatotopic map of the contralateral side of the body with the feet at the midline and the face and hands located on the lateral surface, although the hand representation is largely over represented (Padberg et al., 2007). Bakola et al. (2013) report that 60% of the inputs to PE are from other parietal areas that process somatosensory stimuli, mostly SI and SII, with another 30% arriving from frontal cortex; M1 and SMA/F3. PE neurons respond most strongly to proprioceptive stimulation of the limbs, rather than to tactile or visual stimulation (Hyvarinen, 1982). Medial PE regions, which represent the legs, receive inputs from homotopic leg regions in the somatosensory and motor cortices whereas lateral PE, which represents mostly the arms, receives both homotopic and heterotopic inputs. PE is directly connected to dorsal MIP and PEc, but not ventral MIP (MIP-proper) or AIP, regions known to be involved in reaching and grasping. Interestingly, while direct inputs from visual areas and prefrontal cortex are almost completely absent, PE is well connected to mesial cortical areas involved in navigation (Bakola et al., 2013).

Parietal Area PEc. PEc is located just caudal to PE in the SPL and responds to passive joint manipulation and tactile stimulation of the skin on the arms and, to a lesser extent, the legs (Breveglieri et al., 2006, 2008). Bakola et al. (2010) showed that the majority of PEc neurons receive inputs from somatosensory areas PE, dorsal MIP, SI (area 2), and SII. PEc also receives inputs from motor areas that process somatosensory information about the hindlimbs such as PMd/F2 and SMA (Bakola et al., 2010; Luppino et al. 1991). These somatosensory and motor inputs seem to be most prominent in rostral PEc. Visual inputs to caudal PEc originate mostly from V6Ad, but also from cortical areas involved in optic flow, eye movements, and navigation (Bakola et al., 2010), which suggests that the visual information that PEc does process may be related to the animal's movement through the environment (Breveglieri et al., 2008).

Breveglieri and colleagues (2008) also show that the somatosensory receptive fields of neurons in PEc are organized in a non-topographic manner and are mostly anchored to proximal limb regions, while the visual receptive fields of the same neurons are large, respond only to complex visual stimuli, and do not anchor to the same location as the corresponding somatosensory receptive field. The authors propose that this lack of topography and somatosensory/visual field convergence implicates a role for PEc in coordinating various body parts as the animal moves through a complex visual environment. The majority of PEc outputs are directed towards somatosensory responsive regions of dorsocaudal PMd/F2 and to SMA/F3 (Matsuzaka et al., 1992).

Visual Area 6A (V6A). V6A, the most caudal cortical area implicated in locomotor behaviour, consists of two subregions, V6Ad and V6Av (Gamerbini et al., 2011). The vast majority of neurons in both regions respond to arm reaching and pointing movements (Galletti et al., 1997), but V6Ad cells respond more vigorously to reaching movements in the dark whereas V6Av cells respond more vigorously to reaching movements in the light (Gamberini et al., 2009). Reaching or pointing movements with the legs and feet have not been investigated in monkeys; however, the human homolog of V6A (SPOC) is activated during pointing movements made with both the hand and the foot (Heed et al., 2011) and lesions to SPOC disrupt both visually-guided reaching and stepping movements (Cavina-Pratesi et al., 2013; Evans et al., 2013).

While just less than half of the inputs to V6Ad are somatosensory, only about a quarter of the inputs to V6Av are somatosensory (Gamberini et al., 2011). Bimodal cells that respond to both visual and somatosensory inputs are only located in V6Ad. V6Av receives strong inputs from early visual areas (Passarelli et al., 2011), whereas the visual inputs that do project to V6Ad appear to originate from higher visual areas such as VIP, which processes visual stimuli approaching the face, and MST, which processes optic flow information generated by self motion through the environment (Bakola et al., 2010; Gamberini et al., 2009).

Reaching

Extensive human and non-human primate studies have consistently implicated a role for the SPL in generating visually-guided reaching movements (for reviews see Andersen et al., 2014; Culham and Valyear, 2006; Vesia and Crawford, 2012). The most prominent evidence is derived from studies in human and non-human primates showing that lesions localized to the caudal pole of the SPL produce impairments in visually guided reaching (Cavina-Pratesi et al., 2010a, 2013; Desmurget et al., 1999; Hwang et al., 2012; Karnath and Perenin, 2005; Perenin and Vighetto, 1988), but may leave grasping intact (Cavina-Pratesi et al., 2010a). The parietofrontal areas involved in reaching partially overlap with those previously described for locomotion and include PMd/F2, PE, PEc, PG, and V6A (Table 1.3). Recent studies (Blangero et al., 2007; Filimon et al., 2010; Reichenback et al., 2014), suggest that in addition to visually guided reaching, these parietofrontal areas may also play an important role in processing proprioceptive inputs for reaching without vision.

Table 1.3 Monkey cortical regions proposed to be involved in reaching and their somatomotor and visual inputs

	Somatosensory or Somatomotor		**Visual**	
Area	**Inputs**	**References**	**Inputs**	**References**
V6A/SPOC	MIP PEc PG VIP MST PMd /F7	Bakola et al., 2010, 2013; Gamberini et al., 2009, 2011; Marconi et al., 2001	V2 V3 V4 V6 VIP MST	Gamberini et al., 2009, 2011; Passarelli et al., 2011; Shipp et al., 1998;
PEc	PE PEci MIP SI (2) SII PMd/F2 SMA/F3 MI	Bakola et al., 2010; Luppino et al., 1991 Mitz and Wise, 1987; Petrides and Pandya,1984;	V6Ad	Bakola et al., 2010
PE	PEc PEa PF PG MIP SI (2) SII SMA/F3 M1 PMd/F2 PMV/F4	Bakola et al., 2013; Gerbella et al., 2011; Pons and Kaas, 1986;	PG	Bakola et al., 2013
PG	PEc MIP AIP SII	Murata et al., 2000; Johnson et al., 1996; Rozzi et al., 2006	V6Ad Opt	Rozzi et al., 2006
MIP	DCN/VPS SI (3a)	Prevosto et al., 2011	V6A LIP Cerebellum Thalamus	Galletti et al., 2001; Prevosto et al., 2009, 2010;
PMd/F2	PE PEc PF MIP VIP PMV/F5 SMA	Caminiti et al., 1999; Johnson et al., 1996; Matelli et al., 1998; Tanne-Gariepy et al., 2002;	V6A MIP VIP	Johnson et al., 1996; Matelli et al., 1998; Tanne-Gariepy et al., 2002

Dorsal Premotor Cortex (PMd/F2). PMd/F2 is located rostral to the superior portion of M1. It receives both proprioceptive and visual information from three main SPL regions: MIP, V6A/SPOC, PEc and fewer projections from mesial areas of the SPL (Matelli et al., 1998). A number of non-human primate studies have identified PMd/F2 as a region that processes signals related to reach direction (Cisek and Kalaska, 2005; Scott et al., 1997), reach orientation (Scott et al., 1997), reach distance (Messier and Kalaska, 2000), and reach correction (Lee and van Donkelaar 2006). PMd/F2 cells may encode reaching movements in both retinal and postural coordinates (Batista et al., 2007) and long-train electrical stimulation of this region elicits reaching movements to different regions of peripersonal space (Gharbawie et al., 2011; Graziano, 2006). PMd may influence reaching movements through direct projections to the spinal cord, or indirectly via connections with M1.

Parietal Areas PE, PEC, and V6A. The relevant neurophysiological properties of PE, PEc and V6A have been largely covered in the above section on locomotion. To summarize, significant somatosensory inputs project to anterior SPL regions (PE and rostral PEc), which are engaged during both visually and proprioceptively guided reaching movements (Filimon et al., 2010; Bernier and Grafton, 2010). In contrast, caudal regions (caudal PEc and V6A) receive additional visual inputs and appear to play a specialized role in reaching to grasp visual targets. Both areas, however, may be capable of representing reach targets in both retinal and postural coordinates depending on whether or not vision is available (Bernier & Grafton, 2010; Beurze et al., 2010).

Medial Intraparietal Sulcus (MIP). Selective lesions to monkey MIP produce reaching impairments while leaving saccadic eye movements unimpaired (Hwang et al., 2012; Trillenberg et al., 2007) and MIP has been proposed to play a specialized role in guiding reaching movements both with and without vision (Reichenback et al., 2014). Using retrograde tracers, Prevosto et al., (2011) found that macaque MIP receives dense proprioceptive inputs from both the dorsal column nuclei (via the VPS and the anterior pulvinar), and area 3a in SI. Direct inputs from area 3a originate mostly from the arm, shoulder and neck representation, with a small input originating from the more lateral 3a hand representation. The majority of inputs from both 3a and the dorsal column nuclei are almost entirely proprioceptive, rather than tactile, which likely explains why it is easy to elicit neural activity from MIP during passive arm movements, but not so much in response to cutaneous stimuli (Burbaud et al., 1991). This also supports the proposition that neural activity in MIP is much more related to multi-joint arm movements during reaching than to grasping and/or manipulatory hand actions (Prevosto et al. 2011; Crawford et al., 2004). MIP also receives visual inputs from V6A and LIP.

Parietal Area PG. PG is located in the IPL and is strongly connected with higher visual areas also involved in reaching such as MIP, V6Ad and Opt, as well as SII (Rozzi et al., 2006). Electrophysiological recordings from PG show that many of the neurons respond to reaching movements (Battaglia-Mayer et al., 2007; Blum, 1985; Rozzi et al., 2008), with fewer neurons also responding to eye movements (Rozzi et al., 2008). Early reports suggested that PG neurons responded equally to reaching in the light and dark, but later studies suggest that PG reaching neurons in PG respond more strongly to visually-guided reaching (Rozzi et al., 2008).

Summary of Locomotion and Reaching

Together neuroanatomical and electrophysiological studies in primates suggest that anterior SPL (PE and rostral PEc) receives somatomotor inputs related to both hindlimb and forelimb movements whereas posterior SPL (caudal PEc and V6A) receives additional visual and motor inputs related to forelimb movements. Thus, anterior SPL regions may specialize in coordinating hindlimb and forelimb movements for locomoting in nonvisual environments, whereas additional activity from the posterior SPL could mediate locomotion in a visual environment. As suggested by Bakola et al., (2013), anatomical and physiological differences in anterior and posterior SPL could underlie sensorimotor specializations for the arms (reaching to visual targets) vs. the legs (stepping, usually in the absence of direct visual guidance) in primates. Neural commands related to locomotor activity appear to ultimately reach the spinal cord via reciprocal connections between SPL, and frontal motor areas SMA/F3, PMd/F2, and M1, whereas neural commands related to forelimb reaching may be mediated by connections between the SPL and PMd/F2.

As an aside, it should be noted that the majority of primate studies have examined subjects whose heads were locked in a fixed position. This has obviously limited the extent to which cortical contributions to locomotor control have been directly investigated in primates and contrasts significantly with studies of PPC in freely moving cats and rodents, which have strongly implicated a role for PPC in navigational (Wilber et al., 2014), locomotor (Whitlock et al., 2014), and forelimb placing tasks (De Ryck et al., 1992). Thus, future studies using unrestrained primates should help to bridge the current gap between non-primate and primate research concerning cortical contributions to locomotion.

Feeding

Clinical studies have described brain injured patients that are impaired at performing coordinated eating and drinking behaviours (Jackson, 1870; Holmes, 1918) and a few monkey studies show that certain PPC lesions may impair visually guided reaching to external objects while leaving the ability to bring the hand to the mouth intact (Ettlinger and Wegener, 1958; Bates and Ettlinger, 1960). In addition, single neuron recording (Rizzolatti et al., 1988; Taoka et al., 2013; Yokochi et al., 2003) and microstimulation studies (Desmurget et al., 2014; Graziano, 2006; Kaas et al., 2013) in humans and non-human primates have implicated at least 3 parietofrontal areas that might contribute to the production of hand-to-mouth and feeding movements in primates. These are PMv/F5, PF/PFG, and SII (Table 1.4).

Ventral Premotor Cortex (PMv/F5). PMv/F5 is located in the rostrolateral region of premotor cortex, ventral and caudal to the arcuate sulcus. It is strongly interconnected with somatosensory areas of the parietal cortex like SI, SII, and PF/PFG and higher-order visual/somatomotor areas like AIP and VIP (Tanne-Gariepy et al., 2002; Luppino et al., 1999). Recording from this area, Rizzolatti and colleagues (1988) discovered "grasping-with-the-hand-and-the-mouth" neurons, which fired whenever the monkey grasped a piece of food with it's mouth, left hand, or right hand, but not during coordinated actions between the hand and the mouth. About one half of these neurons responded to passive somatosensory stimuli on the arms, mouth, or face, and about one fifth responded to visual stimuli. They also described another subset of "hand-to-mouth" neurons that fired when the monkey brought a grasped piece of food towards the mouth

Table 1.4 Monkey cortical regions proposed to be involved in feeding or hand-to-moth behaviour and their somatomotor and visual inputs

	Somatomotor		**Visual**	
Area	**Inputs**	**References**	**Inputs**	**References**
SII	SI DCN/Thalamus	Kaas, 2008		
PF/PFG	PE SI (2) SII AIP VIP PMv/F4/F5	Gharbawie et al., 2011; Rozzi et al., 2006; Cavada and Goldman-Rakic, 1989a,b;	STS PG VIP MST	Rozzi et al., 2006;
AIP	PF/PFG SII PMv (F5)	Borra et al., 2008;	LIP STS MTG VIP FEF	Borra et al., 2008;
PMv/F5	SI SII AIP VIP PF/PFG PEa Pre-SMA/F6 PMv/F4	Cavada and Goldman-Rakic, 1989a,b; Gerbella et al., 2011; Luppino et al., 1999; Tanne-Gariepy et al., 2002;	AIP VIP Pre-SMA/F6	Gerbella et al., 2011; Luppino et al., 1999; Tanne-Gariepy et al., 2002;

with the hand. The majority of these hand-to-mouth neurons did not display visual or tactile receptive fields, but the ones that did responded to visual stimuli moving towards the mouth and tactile stimuli on or near the mouth. In a more recent study, approximately one third of the mouth neurons recorded in PMv/F5 also showed mirror response properties in that they fired when the monkey observed another animal making feeding or communicative movements with the mouth (Ferrari et al., 2003). Graziano (2009) found that he could elicit hand-to-mouth movements in monkeys by stimulating the anterior PMv and a recent study has found that long-train stimulation of rostral M1 regions can also elicit hand-to-mouth movements in humans (Desmurget et al., 2014).

Another subset of neurons in human M1 were found to generate arm/hand movements, but processed somatosensory inputs from the mouth (Desmurget et al., 2014). The authors propose that these neurons may, "constitute a hardwired feedback loop suited to bind oral sensory inputs with upper limb motor commands, for guiding hand movements according to mouth sensations". The authors suggest that this feedback loop would support perioral behaviours in young infants; however, it is conceivable that such a mechanism might also subserve food-handling behaviours, where the hands lift, shape, and grasp a food item already held in the mouth in order to manipulate it or modify it for consumption. The number of sites sampled by Desmurget et al. (2014) was small, but they did not find evidence of the reverse type of neurons, that process sensory inputs from the hand and also generate mouth movements, suggesting that sensory inputs from the mouth tend to guide actions of the hand and not the reverse. Perhaps this is why young infants engage in perioral exploration – haptic feedback from the mouth may help to train manipulatory actions made with the hand.

Parietal Area PF/PFG. Yokochi et al. (2003) describe “face-hand” neurons in areas PF and PFG in the rostral IPL, which were later confirmed by Rozzi et al (2008). These neurons have unique somatosensory receptive fields that are large, bilateral, and discontinuous, covering both the hand (83% covered the whole hand) and part of the face (96% covered the mouth). Some face-hand neurons responded to uncoordinated face and hand actions (similar to the first set of neurons described by Rizzolatti et al. (1988) in PMv). These were intermingled in the anterior tip of the IPS. Other neurons responded to self-generated synergistic movements between the hand and the face, i.e., bringing the hand to the mouth during eating. These neurons fired more strongly during coordinated eating behaviours than they did when hand and mouth movements were made in isolation, or when the hand and mouth receptive fields were passively stimulated. Yokochi et al. (2003) localized these neurons to rostroventral regions of PF, whereas Rozzi et al. (2008) localized them to PFG. Interestingly, PFG may be the only area in the IPL that sends projections to the spinal cord (Rozzi et al., 2006). Similar neurons, called bimanual or intrapersonal coordination neurons, were previously described by Leinonen and Nyman (1979) and Leinonen et al. (1979). Approximately one quarter of Yokochi’s face-hand neurons also responded to complex visual stimuli, usually when the monkey observed the experimenter performing an action that coordinated with the monkey’s own behavior. For example, one neuron began firing as the experimenter moved a piece of food, held in his hand, towards the monkey and stopped firing after the monkey took the piece of food in his mouth and ate it. These were not mirror neurons, as they required action by the monkey in order to fire.

Secondary Somatosensory Cortex (SII). More recently Taoka et al. (2013) have described hand-mouth neurons located at the border between face neurons and hand neurons in rostral SII. These neurons become active when the monkey retrieves food with the hand, puts the food in the mouth, and closes the mouth to chew. About 60% of these neurons have discontinuous somatosensory receptive fields on the face and hands, whereas the remaining neurons have receptive fields only on the hands, only on the face, or no receptive fields at all. Hand-mouth neurons in SII could be either phasic or tonic. Phasic hand-mouth neurons fired during specific actions – when the monkey grasped the food, when the monkey transferred the food from one hand to the other, and when the monkey closed his mouth to chew. Thus, similar to a subset of neurons found in PMv/F5 these neurons fired when the monkey grasped the food item, regardless of the body part used (right hand, left hand, or mouth). The authors conclude that these neurons might encode the goal of the action (to grasp the object) rather than the effector used to execute the action. Tonic hand-mouth neurons started firing when the monkey began to reach towards the food and peaked when the monkey put the food in its mouth, stopping when the monkey began chewing. Hand-mouth neurons in SII almost never responded to initial tactile contact between the monkey's hand and the object in the experimenter's hand, suggesting that they process information related to proprioceptive/motor control rather than tactile feedback.

Grasping

A plethora of neural recording (Mountcastle et al., 1974; Rizzolatti et al., 1988), electrical stimulation (Gharbawie et al., 2011; Graziano, 2006; Kaas et al., 2013), lesion (Fogassi et al., 2001; Gallese et al., 1994) and neuroanatomical tracing (Borra et al., 2008; Tanne-Gariepy et al., 2002) studies in monkeys, combined with human neuropsychological (Binkofski et al., 1998), neurostimulation (Cohen et al., 2009) and neuroimaging (Binkofski et al., 1998; Cavina-Pratesi et al., 2010; Culham et al., 2003; Konen et al., 2013) studies have identified four parietofrontal areas that appear to be consistently involved in the production of grasping and/or manipulatory actions made with the hand. In monkeys, this circuit largely overlaps with the cortical areas involved in feeding behavior and include SII, PF/PFG, AIP, and PMv/F5, all of which are strongly interconnected (Table 1.5). Real or virtual lesions to one or more of these areas may impair grasping and/or manipulatory hand movements, with little or no impairment in reaching (Binkofski et al., 1998; Gallese et al., 1994; Fogassi et al., 2001; Rice et al., 2006; Tunik et al., 2005).

Ventral Premotor Cortex (PMv/F5/F4). As mentioned above, Rizzolatti and colleagues (1988) also describe “grasping-with-the-hand” neurons in monkey PMv. Specific PMv neurons fire when a monkey forms a particular grip configuration or when the monkey makes other hand actions like tearing, holding, or manipulating, regardless of whether or not vision is available (Raos et al., 2006). The authors conclude that, “…the activity of F5 grasping neurons is not related to individual finger movements, but to the grasping action as a whole. The brain uses motor schemata/grasp categories to simplify the control of the many degrees of freedom of the hand…” Thus, PMv appears to contain a “vocabulary” of hand shapes that can be used to grasp and interact with different

Table 1.5 Monkey cortical regions proposed to be involved in grasping and their somatomotor and visual inputs

	Somatosensory or Somatomotor		**Visual**	
Area	**Inputs**	**References**	**Inputs**	**References**
SII	SI DCN/Thalamus	Kaas, 2008;		
PF/PFG	PE SI (2) SII AIP VIP PMv/F4/F5	Gharbawie et al., 2011; Rozzi et al., 2006;	STS PG VIP MST	Rozzi et al., 2006;
AIP	PF/PFG SII PMv (F5)	Borra et al., 2008;	LIP STS MTG VIP FEF	Borra et al., 2008;
PMv/F5	SI SII AIP VIP PF/PFG PEa	Gerbella et al., 2011; Luppino et al., 1999; Tanne-Gariepy et al., 2002;	AIP VIP	Luppino et al., 1999; Tanne-Gariepy et al., 2002;

objects. While all “grasping” neurons fire when a grasping action is actually executed, about half also fire when the monkey simply looks at a graspable object (Murata et al., 1997; Raos et al., 2006). These neurons usually encode visual objects and grip configurations that are compatible. That these neurons are really “grip” rather than “shape” selective is confirmed by evidence that the same neuron fires when using a similar grip to grasp different shaped objects (Raos et al., 2006). Reversible inactivation of PMv disrupts the ability to form the appropriate grip configuration and to place the grasping digits at appropriate contact points on the object in both monkeys and humans (Fogassi et al., 2001; Davare et al., 2006).

Parietal Areas PF/PFG. Grasping neurons, similar to those described in PMV/F5 were discovered even earlier in the anterior IPL by Vernon Mountcastle (Mountcastle et al., 1975). Some PF/PFG neurons fire during grasping in both the light and the dark, some fire more strongly in the light compared to the dark, and some fire only in the light. Subsequent investigations by Rozzi and colleagues (2008) localized the majority of hand grasping neurons to area PFG. Similar to PMV/F5 and AIP (as described below) PFG neurons that respond to both motor acts and visual inputs appear to encode visual object shapes and grip configurations that are compatible (Rozzi et al., 2008).

Anterior Intraparietal Sulcus (AIP). Grip selective neurons have also been found in monkey AIP (Murata et al., 2000; Sakata et al., 1997; Taira et al., 1990) and functional neuroimaging studies have attributed grasp selective activity to the human AIP region (Begliomini et al., 2007; Binkofski et al., 1998; Cavina-Pratesi et al., 2010; Culham et al., 2003; Frey et al., 2005; Konen et al., 2013). AIP is located at the intersection of the rostral tip of the intraparietal sulcus and postcentral sulcus. In monkeys, this region receives strong somatosensory inputs from area 2 in primary somatosensory cortex (Gharbawie et al., 2011a,b), SII (Borra et al., 2008) and PF/PFG. It also receives visual inputs from both the dorsal (LIP, VIP) and ventral (STS) streams (Borra et al., 2008). Grasp selective neurons in this region may respond to grasping in the dark, grasping in the dark and in the light, or viewing of graspable objects. Thus, AIP is engaged during the grasping and manipulation of both visual and non-visual targets (Binkofski, 1998; Murata et al., 2000). In humans the more anterior region of human AIP may encode the somatosensory and motor aspects of grasping, whereas the posterior regions may additionally encode the visual aspects (Culham et al., 2006).

Secondary Somatosensory Cortex (SII). Ishida and colleagues (2013) recently described "hand-manipulation" neurons in SII that fire in relation to grasping or exploratory hand movements made in both the light and the dark. Many of these neurons also show grip-selectivity, similar to PMv/F5 and AIP grasping neurons. Some SII hand-manipulation neurons appear to encode motor, rather than somatosensory, parameters as they tend to fire before and after contact with the target and rarely in response to passive somatosensory stimuli. The authors suggest that SII neurons that do respond to somatosensory stimuli may detect hand-object interaction and trigger the appropriate motor command for subsequent exploration and manipulation of the object. Binkofski et al. (1999a, 1999b) showed that SII co-activates with AIP and PMV when humans manipulate a 3D object and this may be related to SII's role in processing somatosensory information related to active hand movements (Valenza et al., 2001).

Feeding and Grasping Summary

The studies reviewed above suggest that either a single, or two overlapping networks involving SII, PF/PFG/AIP, and PMv/F5 contribute to the production of hand-to-mouth, hand grasping, and mouth grasping movements regardless of whether or not vision is available. While neuroanatomical (Stepniewska et al., 2009) and behavioural work (Edwards et al., 2005; Karl et al., 2012b) suggest that forelimb hand-to-mouth movements are mediated almost exclusively by somatosensation, additional work suggests that the grasping network preferentially processes somatosensory inputs (Gharbawie et al., 2011a), but also processes grasping related visual information from both the dorsal and ventral streams (Gharbawie et al., 2011a; Borra et al., 2008).

Human feeding behavior has not been studied to the same extent as reaching or grasping. There are difficulties associated with attempting hand-to-mouth movements in an MRI scanner; however, future work employing virtual lesions of these cortical areas should further elucidate the specific contribution of each to feeding, as well as other coordinated hand and mouth movements, in humans. Complex feeding behavior has been well documented in rodents (Whishaw and Coles, 1996) and is dependent on the corticospinal system (Whishaw et al., 1992). Nevertheless, additional lesion and/or electrophysiological work is needed to ascertain whether or not PPC contributes to feeding behavior in rodents.

Intermodule Connectivity

Although the emphasis in this review is on the differences between the parietofrontal pathways that mediate different actions, it is important to note that a number of smaller connections exist between most of these cortical areas (Borra et al., 2008; Gamberini et al., 2009; Gharbawie et al., 2011) and that these pathways likely work together in a coordinated manner to produce meaningful behaviour. As such, almost all of the cortical areas mentioned above can be found to contain neurons that respond to actions other than the one to which they are primarily attuned. For instance, "reach area" PMd/F2 is connected to "grasp area" PMv/F5 and "reach area" V6A is connected to "grasp area" AIP. Thus, traditional reach areas PMd/F2 and V6A also contain some neurons that respond to grasping movements (Raos et al., 2003, 2004; Fattori et al., 2010).

As has been previously suggested (Cavina-Pratesi et al., 2010b; Karl and Whishaw 2013), it is likely the case that simpler tasks can be accomplished by a single parietofrontal pathway acting in relative isolation, but more complex tasks, such as combined reach-to-grasp movements may require significant interaction between multiple pathways at the same time. In support of this, Raos et al (2004) found that visually modulated grasp selective neurons in PMd/F2, but not PMv/F5 (Raos et al., 2006), lose their grip selectivity when reaching to grasp an object in the dark. The authors suggest that these PMd/F2 neurons might combine grip information from PMv/F5 with visual "reaching" information from MIP, V6A, and MST in order to "continuously update the configuration and orientation of the hand as it approaches the object to be grasped". In other words, SPL regions with privileged access to the dorsal visual areas may also serve to integrate the reach and the grasp together under visual control. A similar role has been proposed for SPL area V6A (Fattori et al., 2010).

Motor Intentions

The existence of common and interconnected motor representations in both parietal and frontal cortices raises questions about redundancy. A recent study by Desmurget et al. (2009) suggests that one unique contribution of the movement representations in PPC is that they are coupled to conscious *intention* and *awareness*, whereas the action representations in frontal cortex are not.

Desmurget et al. (2009) stimulated anterior PPC and frontal cortex in awake patients undergoing brain surgery. Patients reported that moderate stimulation of the IPL induced a strong desire or intention to move specific body parts like the arm, foot, or mouth. When IPL stimulation was increased, patients reported that they had actually made the desired movements, even though they had not, which was confirmed with EMG. When stimulation was applied to the premotor cortex patients actually made specific movements with the arms, legs, and mouth, but when asked, they denied that they had moved at all. These results suggest that conscious intention and awareness of executed movements are dependent on the neural processing that takes place in PPC prior to movement initiation (Desmurget et al., 2009).

That PPC uniquely encodes movement *intentions* is further illustrated by a serendipitous observation made by Graziano (2009) when stimulating the premotor cortex of an awake monkey for the first time. Upon stimulation, the monkey’s arm reached out in front of him, an act that appeared to surprise the monkey as much as it did the experimenters! Upon completion of the stimulation the monkey promptly retrieved his extended arm and hand and proceeded to sit on it for the remainder of the testing session, clearly indicating that he had certainly not *intended* to make that reaching movement.

The dissociation of action executions in frontal cortex from action intentions in PPC can thus explain a variety of intriguing phenomenon that arise after disconnective brain injuries such as alien hand syndrome, in which patients report that one arm appears to move and act according to its own free will, apparently with intentions of its own that are not consciously accessible to the patient. An important point here is that the dorsal stream is usually considered "unconscious", however, this work highlights the tight link between neural activity in PPC and conscious understanding of one's own actions.

Flexible Sensory Control of Motor Actions

The work described above provides evidence that interconnected neurons in parietal and frontal cortex contribute to the production of specific motor acts, which may be performed both with and without visual guidance. Many of these neurons have both visual and somatosensory receptive fields, indicating that a single "action-specific" neuron can process more than one type of sensory input. This suggests that if one sensory modality is unavailable (i.e., vision is removed) the movement could still be performed based on the remaining sensory inputs (i.e., haptics).

This view is supported by a number of lines of evidence. First, it has been shown that motor plans are coded in multiple spatial reference frames (i.e., gaze-centered, hand-centered, body-centered coordinates, etc.) all of which contribute to motor control, but with different and flexible weightings (McGuire and Sabes, 2009). The reference frame that is most reliable in any given situation receives the heaviest weighting. So, in the absence of vision, non-visual or postural coordinates would make the most significant contribution to action control. Second, cortical areas traditionally considered unisensory, are capable of processing similar object characteristics (i.e., form) derived from other modalities (Fiehler et al., 2009; Sathian and Lacey, 2007; Stilla and Sathian, 2008). This suggests that the neural representations of haptic and visual object features are similar enough that "unisensory" cortical areas are capable of encoding either representation. Third, haptic and visual representations of object shape appear to converge to produce a multimodal representation of the object (Lacey and Sathian, 2011). Although this multimodal representation has largely been studied in the ventral stream where it is thought to subserve cross-modal perception, a similar process is proposed to occur in the intraparietal sulcus to create a multimodal representation of object shape that can be used to guide action.

These findings support the transition to a new theory of brain organization that define cortical areas based on their functional output, regardless of their sensory inputs (Pascual-Leone and Hamilton, 2001). A number of interesting questions, specifically related to sensorimotor control, arise from this new model that may be addressed by future research. (1) How are different parietofrontal action pathways initially established during evolution or development? (2) Are these action pathways initially established under a single form of sensory control with secondary access by other modalities or are they established under multimodal control from the outset? (3) Do all the action pathways use the same weighting metric or is one modality the preferred input for one action but not another? (4) If action pathways are flexible in terms of the sensory inputs that they process, can we create new sensory devices that can "tap in" to the already existing action pathways? (5) How are new motor behaviours or action pathways created… can one action pathway split to produce multiple variations of a single behavior? Can multiple action pathways be combined to produce a single, more complex, behavior?

Rationale for Thesis

The act of reaching out to grasp an object in order to retrieve it and place it in the mouth provides a suitable behavioural model for investigating differences in sensory control for reaching, grasping, and hand-to-mouth actions, each of which is proposed to be mediated by a different parietofrontal module. While reaching and grasping have largely been investigated from the perspective of their role in visually guided prehension, less is known about how these movements are executed in the absence of vision. The purpose of the present thesis was to describe motoric changes in Reach, Grasp, and Hand-to-Mouth movements under conditions where visual inputs are removed or degraded in order to determine the contribution of non-visual modalities, specifically somatosensation, to each of these behaviours.

Theory

The Dual Visuomotor Channel (DVC) theory posits that prehension consists of two movements, a Reach and a Grasp, which are mediated by separate but interacting visuomotor pathways projecting from occipital to parietofrontal cortex (Figure 1.3, Jeannerod et al., 1981, 1995). The Reach serves to transport and orient the hand in relation to the location and orientation (extrinsic properties) of the target, while the Grasp serves to open, shape, and close the hand to the size and shape (intrinsic properties) of the target. When vision is available, the extrinsic and intrinsic properties of the target can be determined concurrently. This allows for simultaneous activation of both the Reach and the Grasp pathways, resulting in behavioral integration of the Reach and the Grasp into a seemless prehensile act whereby the hand opens, shapes, and largely closes by the time it contacts the target (also referred to as hand "preshaping").

While the DVC theory has received significant support from electrophysiological (Kaas et al., 2013), lesion (Cavina-Pratesi et al., 2010a), and neuroimaging (Cavina-Pratesi et al., 2010b) studies, support has not been derived from behavioural work. According to the DVC theory, isolated changes in target location should produce isolated changes in the Reach without affecting the Grasp and vice versa. Unfortunately, behavioural investigations thus far have found that modifications to one spatial property, either target location or target size, introduces compensatory changes in both the Reach and the Grasp (Jakobson and Goodale, 1991; Paulignan et al., Paulignan et al., 1990a,b).

An alternate approach, rather than manipulating the relative intrinsic and extrinsic properties of the target, is to remove vision altogether. If online visual input is the critical factor required to integrate the Reach and the Grasp together, then by removing vision it should be possible to fully dissociate the Reach and the Grasp.

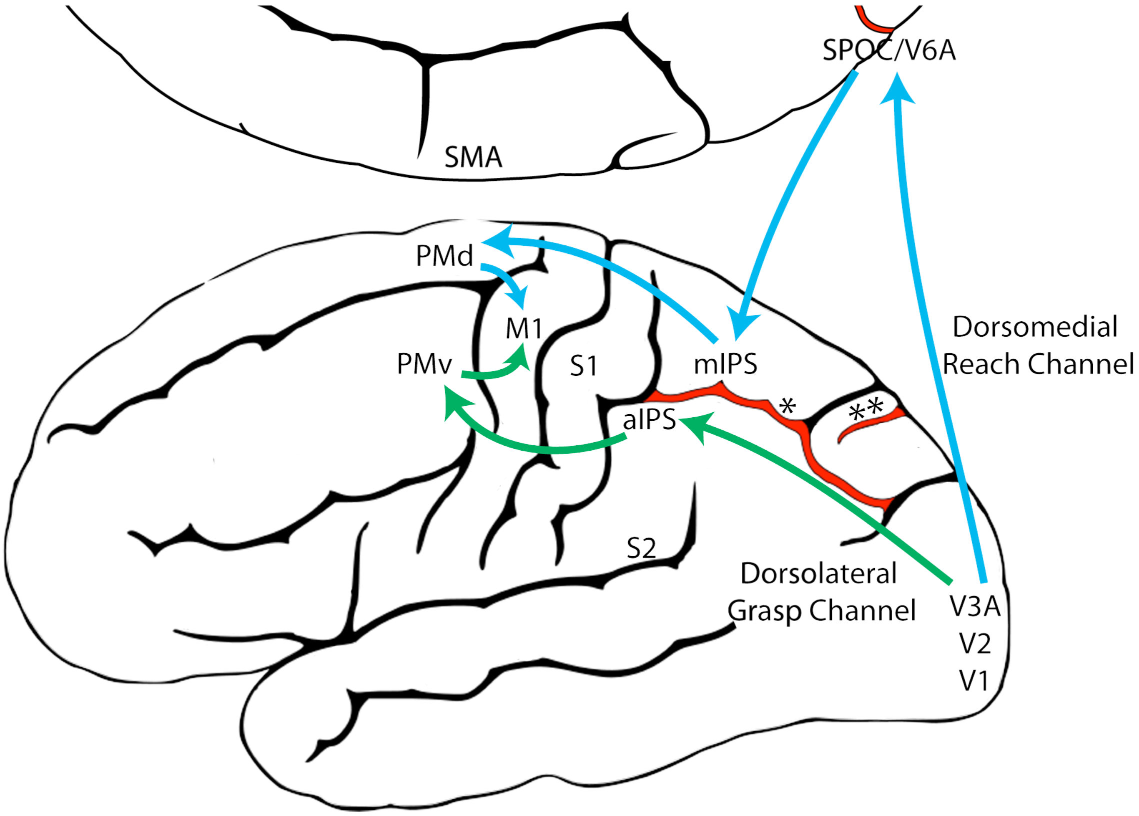


Figure 1.3 The dorsomedial Reach pathway (Blue) and the dorsolateral Grasp pathway (Green), adapted from Grafton, 2010 (aIPS – Anterior Intraparietal Sulcus, M1 – Primary Motor Cortex, mIPS – Medial Intraparietal Sulcus, PMd – Dorsal Premotor Cortex, PMv – Ventral Premotor Cortex, S1 – Primary Somatosensory Cortex, S2 – Secondary Somatosensory Cortex, SMA – Supplementary Motor Area, SPOC – Superior Parieto-Occiptal Cortex, V1 – Primary Visual Cortex, V2 – Secondary Visual Cortex, V3A – Visual Area 3A, V6A – Visual Area 6A, * - Intraparietal Sulcus, ** - Parieto-Occipital Sulcus).

Hypotheses

Hypothesis 1: According to the DVC theory, foveal vision is required to integrate the Reach and the Grasp into a single prehensile act. Thus, I hypothesize that when vision is unavailable the two movements will become dependent on non-visual somatosensory feedback associated with target contact resulting in temporal dissociation of the Reach and the Grasp. Thus, when people reach-to-grasp an unseen and uncertain target item they will not integrate the Reach and the Grasp together, but will Reach to the target in order to locate it by touch and then use somatosensory feedback associated with that touch in order to shape and close the hand to Grasp (Experiment 1).

Hypothesis 2: If the Reach and the Grasp are separate movements, as proposed by the DVC theory, then the two movements may be mediated by different sensory control systems, i.e., the Reach and the Grasp may be differentially dependent on vision. Thus, I hypothesize that previous haptic experience will have differential effects on the Reach versus the Grasp. Thus, people that reach-to-grasp an unseen and uncertain target repeatedly will show differential improvements in Reach trajectory versus Grasp formation (Experiment 2).

Hypothesis 3: The DVC theory proposes that foveal vision simultaneously extracts both the extrinsic (i.e., location and orientation) and intrinsic (i.e., size and shape) properties of the target, resulting in simultaneous execution of the Reach and the Grasp as a seemless prehensile act. Thus, I hypothesize that if vision is not available, but the extrinsic and intrinsic properties of the target can be extracted from a different sensory system (i.e., somatosensation), this will result in re-integration of the Reach and the Grasp such that the hand opens, shapes, and closes by the time it touches the target. Thus, unsighted adults reaching to grasp a target held in their own mouth will integrate the Reach and the Grasp together such that the hand opens, shapes, and closes before contact with the target (Experiment 3).

Hypothesis 4: If the Reach and Grasp are separate movements, as proposed by the DVC theory, then it should be possible to identify different developmental profiles for the Reach and the Grasp. Thus, I hypothesize that separate Reach and Grasp movements are initially established under somatosensory control before they are integrated together under foveal vision. Thus, young infants will produce separate Reach and Grasp movements under somatosensory control before they can integrate the two movements together such that the hand opens, shapes, and closes, before making contact with the target (Experiment 4).

Experiments

Experiment 1. *Handshaping using hapsis resembles visually guided hand shaping.* This experiment was designed to examine how the Reach-to-Grasp movement is performed when the target is both unseen and unknown prior to haptic contact. Participants reached without vision for three different sized food targets, which were presented in a random sequence. The results suggest that (1) unsighted adults temporally dissociate the Reach and the Grasp so that haptic feedback associated with target contact can be used to first locate the target and then shape the hand to grasp it; (2) after initial contact, various strategies may be used to prepare the hand for grasping. In some instances the digits release all contact with the target before shaping to grasp, at other times some digits maintain contact and manipulate the target while the remain digits shape to grasp; and, (3) Grasp aperture scales accurately to target size, regardless of whether it is guided by vision of hapsis.

Experiment 2. *Nonvisual learning of intrinsic object properties in a reaching task dissociates Grasp from Reach.* This experiment was designed to determine whether repeated nonvisual reaching for a consistent target object could calibrate and integrate Reach and Grasp movements in a way similar to those guided by vision. Unsighted participants reached for the same target object at the same target location for 50 consecutive trials. The results suggest that (1) Reach and Grasp movements respond differently to previous nonvisual experience; (2) hand movements related to extrinsic object properties (the Reach) may be more efficient when produced by online visual control, and (3) hand movements related to intrinsic object properties (the Grasp) may be more flexible in terms of their sensory control.

Experiment 3. *Oral hapsis guides accurate hand preshaping for grasping food targets in the mouth.* This experiment was designed to determine the extent to which haptic feedback from the mouth could be used to integrate the Reach and the Grasp such that the hand opens, shapes, and largely closes before target contact when reaching to grasp and retrieve a food item from the mouth. Participants reached and grasped three different size food items, which were located either in their own mouth or on a pedestal in front of them. The results suggest that (1) unlike hand preshaping to distal targets, hand preshaping to oral targets was unaffected by visual occlusion suggesting that the act is exclusively under haptic control; (2) when reaching to an appropriately sized target, haptic feedback from the mouth is as effective as vision for calibrating peak Grasp aperture prior to target contact; and (3) hand preshaping, as a function of the frontal and parietal cortices could have originated under somatosensory control.

Experiment 4. *Haptic grasping configurations in early infancy reveal different developmental profiles for visual guidance of the Reach vs. the Grasp.* This experiment was designed to examine the Reach and Grasp configurations of infants aged 4 to 24 months, compared to adults who reached with and without vision. The results suggest that (1) young infants reconfigure the Reach and the Grasp, similar to unsighted adults, in order to capitalize on haptic feedback associated with target contact, (2) the developmental transition from haptic to visual control is asymmetrical with visual guidance of the Reach preceding that of the Grasp, and (3) integration of separate Reach and Grasp movements into a single prehensile act occurs over a prolonged developmental time period lasting into early childhood.

Chapter 2

Hand shaping using hapsis resembles visually guided hand shaping

Abstract

The reach-to-grasp movement is composed of a number of movement elements including hand transport, hand shaping and grasping. These movement elements are featured in grasping when it is guided by vision, when it is guided by haptic input from the non-reaching hand or other body parts, and when it is guided by offline perceptual (remembered) knowledge. An unanswered question is, how is the reach-to-grasp movement achieved when all information about the target must be acquired by the grasping hand? The answer to this question was obtained by asking participants to reach for three randomly presented food items that varied in size: an orange slice, a small round donut ball, or a blueberry. In order to constrain the grasping pattern, participants were asked to pick up an item with the intention of placing it in the mouth. Thus, in the unsighted condition, participants did not know which item they were reaching for until they made haptic contact with it. Hand transport, shaping, and grasping were examined using frame-by-frame video analysis and linear kinematics. These measures showed that in unsighted reaching, hand transport first served to establish haptic contact between either the second or third digit and the target. After haptic identification of the target, the hand and/or grasping digits adjusted their trajectory, reshaped and reoriented for grasping. A comparison of haptically-guided grasping and visually-guided grasping indicated that the two were very similar. This similarity is discussed in relation to contemporary ideas concerning the neural mechanisms that guide hand use.

Introduction

The reach-to-grasp movement is proposed to be composed of a number of limb movement elements. These include hand transport, digit shaping, and a digit grasp (Arbib 1981; Desmurget et al. 1996; Desmurget and Prablanc 1997; Elliott and Connolly, 1984; Iberall et al. 1986; Jacobsen and Sperling 1986; Jeannerod 1981, 1984, 1986, 1998; Kapandji 1982; MacKenzie and Iberall, 1994a; Mamassian 1997; Napier 1956; Paulignan et al. 1991; Stelmach et al. 1994). In hand transport, the arm and hand are advanced towards the target, in digit shaping the index finger and thumb shape to the size and orientation of the target and in grasping, the digits close to grip the target with respect to its intended use. Vision plays an important role in guiding these movements (Goodale et al. 1993, 1994, 2004; Goodale and Milner 1992; Hu et al. 1999; Jakobson and Goodale 1991; Jeannerod 1981,1986; Wing et al. 1986). Yet, there are many situations in which vision is not available to directly guide reaching, grasping, or manipulatory actions of the hand. For instance, when reaching into one's pocket to grasp a pen or a coin or when searching for the light switch in a dark room. In these situations hapsis likely plays a central role. Previous studies have shown that the hand is appropriately shaped when a participant reaches to an unseen body part (Edwards et al., 2005) or to an unseen object held by the non-reaching hand (Pettypiece et al. 2009; Pettypiece et al. 2010). The hand also shapes appropriately to an unseen but remembered object (Castiello et al. 1993; Fiehler et al. 2011; Hu et al. 1999; Jakobson and Goodale 1991; Wing et al., 1986). Nevertheless, in all of these studies the participant knew the location, properties, and identity of the target before the reach was initiated, thus allowing the participant to preshape the hand during transport for grasping.

It is not known how the reach-to-grasp movement is performed when the target is both unseen and unknown prior to haptic contact. One way of investigating this question is to modify the traditional reach-to-grasp task such that participants reach for uncertain targets in the absence of vision. An uncertain target could be one of a number of familiar targets but which is unknown on any given trial. This procedure differs from that in previous studies as both identification and grasping of the target must be performed solely by the reaching hand, and only after initial haptic contact with the target is established. According to previous studies of nonvisual reaching, one might hypothesize that the participant may simply use a larger peak aperture during transport to ensure purchase of the target (Jakobson and Goodale 1991). Alternately, a participant may simply close the hand at contact with the target without shaping (Goodale et al. 1993; Jakobson et al. 1991; Jeannerod 1986; Jeannerod et al. 1994). A third strategy might be that a participant parses the movement into an initial component that identifies the target and a follow-up component that uses movement elements of hand shaping appropriate for object purchase. The dependent measures in the present study evaluated which of these three strategies is used.

Participants reached first with vision, then without vision, for ethologically-relevant food targets of varying size; orange slices (large), round donut balls (medium) hereafter referred to as “donuts”, and blueberries (small), which were placed one at a time, on a pedestal centered in front of the subject. When vision was occluded, randomization of the food items ensured that while participants were familiar with the targets, they did not know, at the onset of each trial, which food item they were reaching for. In order to constrain the grip pattern used to grasp the targets (Iberall et al. 1986; Napier 1956; Sartori et al. 2011; Valyear et al. 2011; Wong and Whishaw 2004), participants were asked to place the targets in their mouth after grasping. Offline, frame-by-frame video analysis, and motion capture kinematics, were used to evaluate hand transport, shaping, and grasping in both conditions.

Materials and Methods

Participants

Participants were 12 young adults (6 females, 6 males: M ± SD age = 20.14 ± 1.91 years) recruited from the University of Lethbridge. All participants provided informed consent and were self-reported to be right-handed and of good health with no history of neurological or motor disorders. All participants had normal or corrected-to-normal vision. The University of Lethbridge Human Subject Research Committee approved the study. Due to a technical error, kinematic data from a single male participant was excluded from analysis.

Reaching Task

Participants were seated in a comfortable upright position. A self-standing, height-adjustable pedestal was placed directly in front of the participant at a horizontal reach distance normalized to the participant's arm length (100% of length from shoulder to tip of index finger with elbow at 180° flexion) and a vertical height normalized to the participant's trunk height (100% of height from floor to outstretched arm while seated and with shoulder at 90° flexion) (de Bruin et al. 2008; Whishaw et al. 2002). When necessary, visual occlusion was achieved using PLATO vision occluding goggles (Translucent Technologies, Toronto, ON) worn on the participant's face. Because opening of the goggles permits central vision but still occludes peripheral vision, participants did not wear the goggles when reaching to visual targets.

Procedures

Kinematic and behavioural data were acquired from the right hand while participants reached to a distal pedestal for three different sized food items; orange slices, donuts, and blueberries. Participants first completed the Vision condition and then the No Vision condition (Figure 2.1).

Figure 2.1A illustrates the Vision condition. The participant did not wear occlusion goggles. At the beginning of each trial, the participant placed the right hand in the "start position", with the right index finger and thumb pressed together and resting on the anterior aspect of the right knee (Jakobson and Goodale 1991; Pettypiece et al. 2010). A single food item was placed on the pedestal. The participant was instructed to reach for the item as if she were going to pick it up and eat it. After a verbal "one, two, three, GO" command, the participant reached for the food item with the right hand, grasped it, and brought it to the mouth (as if to eat it) before handing it to the experimenter.

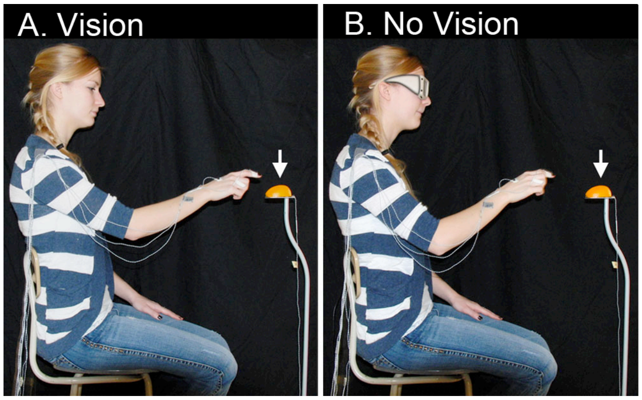


Figure 2.1 The reach-to-grasp task (A) with and (B) without vision. White arrows indicate the location of the food item at the beginning of each trial. Note: In the No Vision condition participants wore occlusion goggles.

At the completion of each trial the participant returned the right hand to the “start” position in preparation for the next trial. The three possible food items were presented in random order with six repetitions of each for a total of 18 trials.

Figure 2.1B illustrates the No Vision condition. The task was the same as in the Vision condition, except that the participant wore occlusion goggles to occlude vision prior to, and throughout, the task to ensure that they did not know which of the three possible target items they were reaching for on any given trial.

Kinematic Data Collection

Hand kinematics were recorded using an Optotrak Certus Motion Capture System and NDI Dataview and NDI First Principles software (Northern Digital Inc.; Jakobson and Goodale 1991). Infrared emitting diodes (IREDs) were positioned on the thumb, index finger, dorsum of the hand, and the top of the pedestal. For each trial, IRED positions were sampled at 200Hz for 4 seconds following the verbal cue to initiate reaching.

Kinematic Data Analysis

Figure 2.2 illustrates the kinematic measures used to define hand preshaping. Aperture (mm) was calculated as the difference between the IRED positions on the thumb and the index finger. The change in Aperture (y axis) was plotted against Time (x axis), and is represented by the curved line. (1) *Peak Aperture* is defined as the maximum

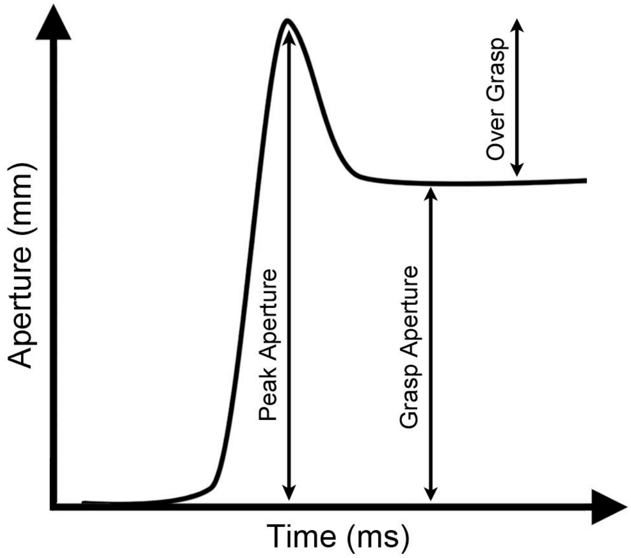


Figure 2.2 Three measures of hand aperture (mm) over time (ms). The curved line indicates the changing distance between the index finger and the thumb as the hand approaches the food item. Peak Aperture: the maximum index-thumb aperture that occurs prior to contact with the food item. Grasp Aperture: the constant index-thumb aperture that occurs when the participant grasps, and holds, the food item. Over Grasp: the difference between the Peak Aperture and the Grasp Aperture.

aperture obtained between movement onset and first contact with the target, or between first contact with the target and grasping of the target. (2) *Grasp Aperture* is defined as the final aperture obtained during actual grasping (and holding) of the target object. (3) *Over Grasp* is defined as the difference between peak aperture and grasp aperture and is used as a measure of hand preshaping accuracy, such that a smaller over grasp indicates more accurate preshaping of the hand. To control for variability in IRED positioning, the index-thumb aperture during the initial “start position,” was subtracted from all subsequent aperture measures for each participant.

For relative comparisons of aperture change throughout the reach-to-grasp task, reaching trials were trimmed from a fixed start (movement onset) to a fixed finish (final grasp) using visual inspection of the aperture displacement signal, and confirmed with video analysis. Trimmed aperture signals were downsampled to 101 frames using the ‘rubberband’ function in Matlab (Mathworks Inc.). Average change in aperture (y axis) was then plotted against normalized time (x axis).

Behavioural Data Collection

A digital video camera was positioned sagittal to the participant to record a reach-side view of the participant from lower leg to head at 30 frames/sec and 1/1000 shutter speed. A second digital camera was positioned dorsolateral to the pedestal to record the shape of the hand as it approached the target on the pedestal. Representative still frames were captured from digital video recordings with the video editing software Final Cut Pro (http://www.apple.com). Pictures were cropped and adjusted for color and brightness contrast in Adobe Photoshop (V. 11.0) but were not altered in any other way.

Behavioural Data Analysis

A number of behavioural measures were scored by performing off-line, frame-by-frame analysis of the video record.

(1) *Movement Times* were determined by counting the number of frames from movement onset to first contact and to final grasp.

(2) *Digit Shaping*, as indicated by changes in index-thumb aperture in the kinematic profiles, was verified by reviewing hand shaping transitions on the video record both before and after first contact with the target.

(3) *Digit Orienting* was determined by adapting previously defined methods (Goodale et al. 1994; Iberall et al. 1986; Stelmach et al. 1994) to frame-by-frame video analysis. The video record was reviewed for a subset of participants (n = 9) and the location of first contact and final grasp contacts were marked on the target object. The average final grasp contact location in the Vision condition was considered the “ideal” grasp contact location. To quantify the extent to which a first contact or final grasp contact deviated from the ideal, the distance between the actual contact point and the ideal contact point were measured in Photoshop (V.11.0). Humans are known to adopt a preferred digit-thumb opposition orientation when reaching to grasp a distal object (Gentilucci et al. 1996; Goodale et al. 1994; Iberall et al. 1986; Stelmach et al. 1994). Thus, localization of digit-to-target contacts along a single axis of the target, and close to

the "ideal" contact location, indicates the presence of a preferred digit-thumb opposition orientation. Variation in the location of digit-to-target contacts indicates the absence of a preferred digit-thumb opposition orientation.

(4) *Grasping Strategy* refers to the use of different digit-to-target manipulations in order to facilitate successful grasping of the target after first contact. Different grasping strategies were identified by reviewing digit shaping transitions (of both the grasping and non-grasping digits) after first contact on the video record. Five different grasping strategies were identified. A single "visual grasping strategy" was used in the Vision condition. A basic "haptic grasping strategy" was used in the No vision condition, but three variations of the haptic strategy (variation 1, variation 2, and variation 3) could also be used. See Results section for a more detailed description of each grasping strategy.

(5) *Grip* was determined by reviewing the video record and documenting whether the target was grasped with a pincer grip or precision grip. The pincer grip is characterized by gripping of the target between the thumb and one digit of the same hand. The precision grip features gripping of the target between the thumb and two or more digits of the same hand.

Statistical Analysis

Results were subject to analysis of variance (ANOVA) using the computer program SPSS (v. 19.0.0). Sex (MALE vs. FEMALE) served as a between-subjects factor. Feedback (VISION vs. NO VISION), Target (ORANGE, DONUT, and BLUEBERRY), Trial (1, 2, 3, 4, 5, and 6), Time (TO FIRST CONTACT, TO GRASP)

First Contact Strategy (DIGIT, THUMB, and DIGIT + THUMB), Grasp Strategy (VISUAL, HAPTIC, VARIATION 1, VARIATION 2, VARIATION 3), and Grip (PINCER vs. PRECISION) served as within-subjects factors. A *p*-value of less than 0.05 was considered significant. Follow-up post hoc comparisons were subject to bonferroni correction.

Results

Sex was found to have no significant effect on Peak Aperture [F(1,9) = 0.130, p > 0.05)], Over Grasp [F(1,9) = 1.442, p > 0.05)], or Grasp Aperture [F(1,9) = 1.90, p > 0.05]. For this reason, data from male and female participants is combined in the following descriptions.

Temporal Organization of the Reach-to-Grasp Movement

Figure 2.3 summarizes the temporal organization of the reach-to-grasp movement when reaching with and without vision. The results represent the mean across all trials, objects, and participants.

In the Vision condition, peak index-thumb aperture occured during transport of the hand to the target, after which the target was first contacted and then grasped. The entire reaching action, from movement onset to grasp, took less than 1 second. In the No Vision condition, participants took about the same amount of time to reach peak aperture, however, after peak aperture they took significantly longer to make first contact and to

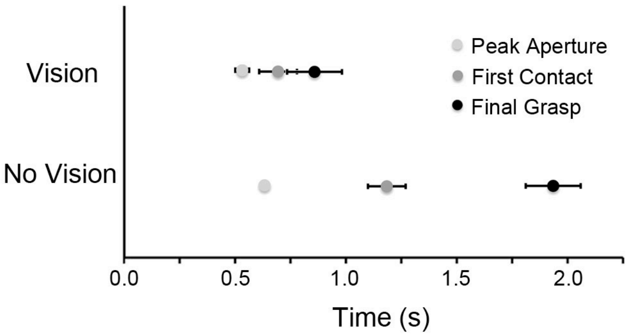


Figure 2.3 Time occurrence of peak aperture (light grey), first contact (dark grey), and grasp (black) of the reach-to-grasp movement when reaching to a distal object with and without vision (mean and standard error). Note: Peak aperture (light grey) occurred at a similar time in the Vision and No Vision conditions; however, in the No Vision condition both first contact (dark grey, $p < 0.001$) and grasp (black, $p < 0.001$) occurred later, when compared to the Vision condition.

grasp the target. The entire reaching action took almost 2 seconds. These main findings were confirmed by ANOVAs that gave significant effects of Feedback X Time to Grasp [F(1,10) = 37.060, $p < 0.001$] and Feedback X Time to First Contact [F(1,20) = 78.713, $p< 0.001$].

Because there were differences in the temporal organization of the reach-to-grasp movement in the Vision and No Vision conditions, the following reaching descriptions will be partitioned such that Transport (movement onset to first contact) will be featured first, then Grasping (first contact to final grasp), and finally visually- and haptically-guided hand shaping will be compared.

Transport

A comparison of the Vision and the No Vision conditions indicated that accurate hand preshaping and orienting occurred during transport when reaching to a seen target but not when reaching to an unseen target. A default hand shape and orientation, neither of which scaled to the size, shape, or orientation of the target, was used during hand transport in the No Vision condition. In brief, hand transport in the Vision condition was directed toward grasping the object, whereas hand transport in the No Vision condition was directed toward identifying the target. This general conclusion is supported by the following detailed descriptions.

Hand preshaping with vision. Figure 2.4 summarizes the results of hand preshaping when reaching with vision for three different sized food items located on a distal pedestal. When reaching with vision, participants preshaped the hand according to

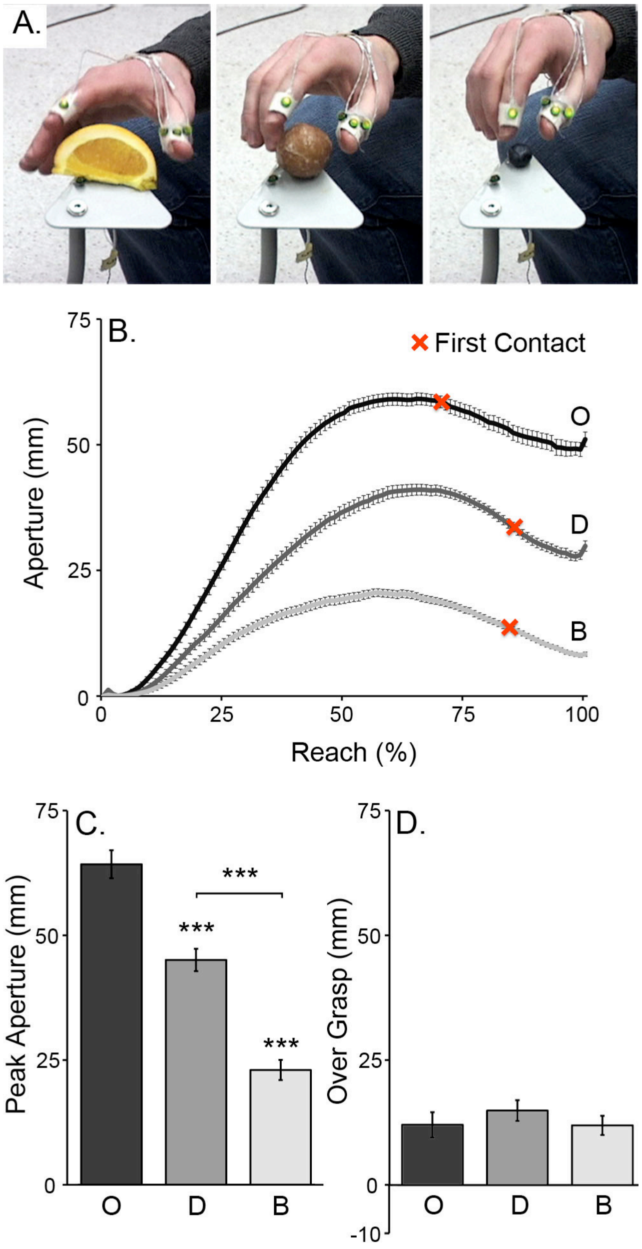


Figure 2.4 Hand shaping and peak aperture prior to first contact in the Vision condition. (A) Representative photos of the hand shape and orientation used to grasp an orange slice, donut, and blueberry. (B) Kinematic profiles (mean ± standard error) of the index-thumb aperture when reaching for an orange slice, donut, and blueberry. (C) Peak Aperture (mean ± standard error) and (D) Over Grasp (mean ± standard error) when reaching for different sized food items. Note: Hand shape and Peak Aperture scaled to food item size, but Over Grasp did not, (O - Orange slice, D – Donut, B – Blueberry, ***$p < 0.001$).

target size during transport (Figure 2.4A). When reaching for an orange slice (left), the index-thumb aperture was large, digits 2 through 5 were almost fully extended, and the thumb was fully extended. When reaching for a donut (middle), the index-thumb aperture was an intermediate size and all digits were partly flexed. When reaching for a blueberry (right), the index-thumb aperture was small and the digits were semi-flexed in a pre-pincer grasp position. For all targets, the pads of the index finger and thumb aligned in opposition, and were oriented towards opposing sides of the target.

Kinematic analysis of index-thumb aperture confirmed the video description. Figure 2.4B shows index-thumb aperture profiles (mean ± standard error of all participants and all trials) when reaching to targets of varying size with vision. When reaching with vision, peak aperture scaled to object size such that it was largest when reaching for an orange, intermediate when reaching for a donut, and smallest when reaching for a blueberry (Figure 4C). Over grasp did not vary according to object size (Figure 2.4D).

3.2.2 Hand preshaping without vision. Figure 2.5 shows the results of hand preshaping when reaching without vision for different sized food items. When reaching without vision, participants did not systematically preshape the hand according to food item size during transport (Figure 2.5A). Instead, a common, “exploratory”, hand shape was used to reach for orange slices (left), donuts (middle), and blueberries (right). To make this hand shape, all digits were extended in an open and neutral posture. This hand shape did not reflect the use of a planned “grasping” hand shape, scaled to the size of the largest target (the orange slice), because the pads of the index finger and thumb did not align in opposition and did not orient towards opposing sides of the target.

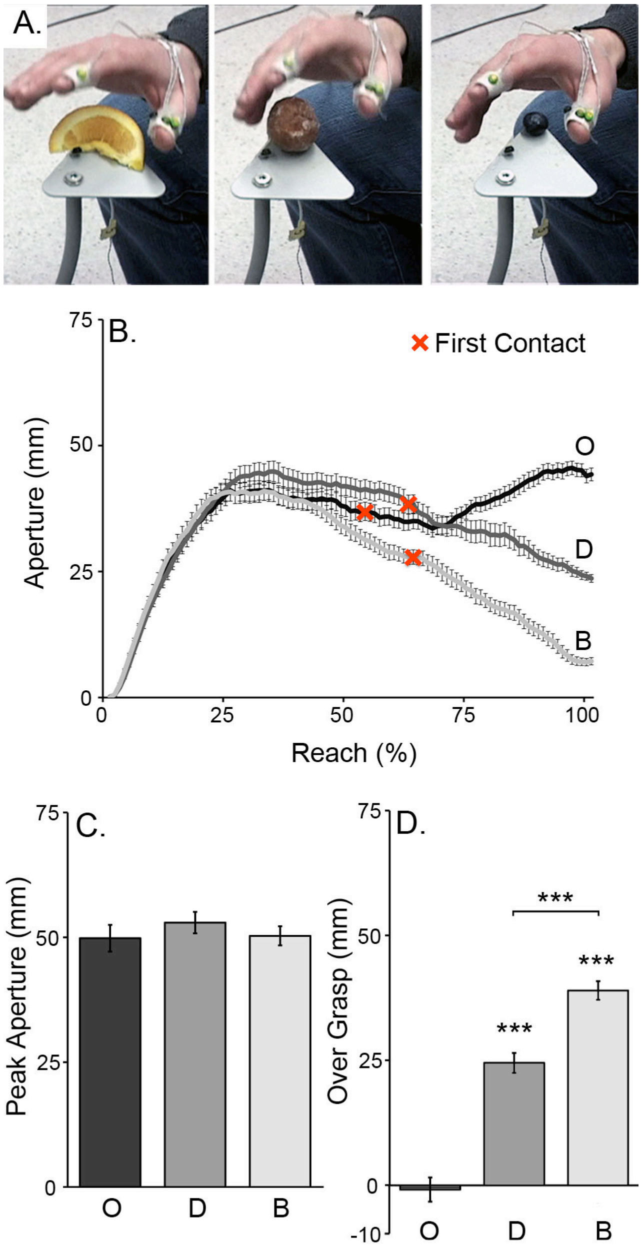


Figure 2.5 Hand shaping and peak aperture prior to first contact in the No Vision condition. (A) Representative photos of the hand shape and orientation used to grasp an orange slice, donut, and blueberry. (B) Kinematic profiles (mean ± standard error) of the index-thumb aperture when reaching for an orange slice, donut, and blueberry. (C) Peak Aperture (mean ± standard error) and (D) Over Grasp (mean ± standard error) when reaching for different sized food items. Note: Hand shaping and peak aperture did not scale to food item size. A "default" hand shape and peak aperture were adopted, causing the Over Grasp to be inversely scaled to food item size, (O - Orange slice, D – Donut, B – Blueberry, $***p < 0.001$).

Kinematic analysis of index-thumb aperture confirmed the video description. Figure 2.5B shows index-thumb aperture profiles (mean ± standard error of all participants and trials) when reaching to targets of varying size without vision. During transport, the hand adopted a “default” peak aperture regardless of the size of the target food item (Figure 2.5C). Because a “default” peak aperture was consistently used, the size of the over grasp was inversely related to food item size, such that the over grasp was smallest when reaching for an orange slice, intermediate when reaching for a donut, and largest when reaching for a blueberry (Figure 2.5D). Importantly, the default peak aperture used in the No Vision condition was significantly smaller than the peak aperture used when reaching to a visible orange slice ($p < 0.05$, compare Figure 2.4C and 2.5C), indicating that when reaching to an unseen and unpredictable target, the largest possible peak aperture was not employed during hand transport. These main findings were confirmed by the statistical and follow-up post-hoc analyses. For peak aperture, there was no significant effect of Feedback [$F(1,10) = 2.032$, $p > 0.05$], but a significant effect of Object [$F(2,20) = 101.088$, $p < 0.001$] and Feedback X Object [$F(2, 20) = 267.399$, $p < 0.001$]. For over grasp, there was no significant effect of Feedback [$F(1,10) = 3.579$, $p > 0.05$], but a significant effect of Object [$F(2,20) = 110.926$, $p < 0.001$], and Feedback X Object [$F(2,20) = 227.276$, $p < 0.001$].

Hand shaping at first contact with and without vision. Hand shaping and orienting were also examined at the point of first contact with the target object. Figure 2.6A shows representative still frames of a participant at the point of first contact when reaching to a donut with vision (left) and without vision (right).

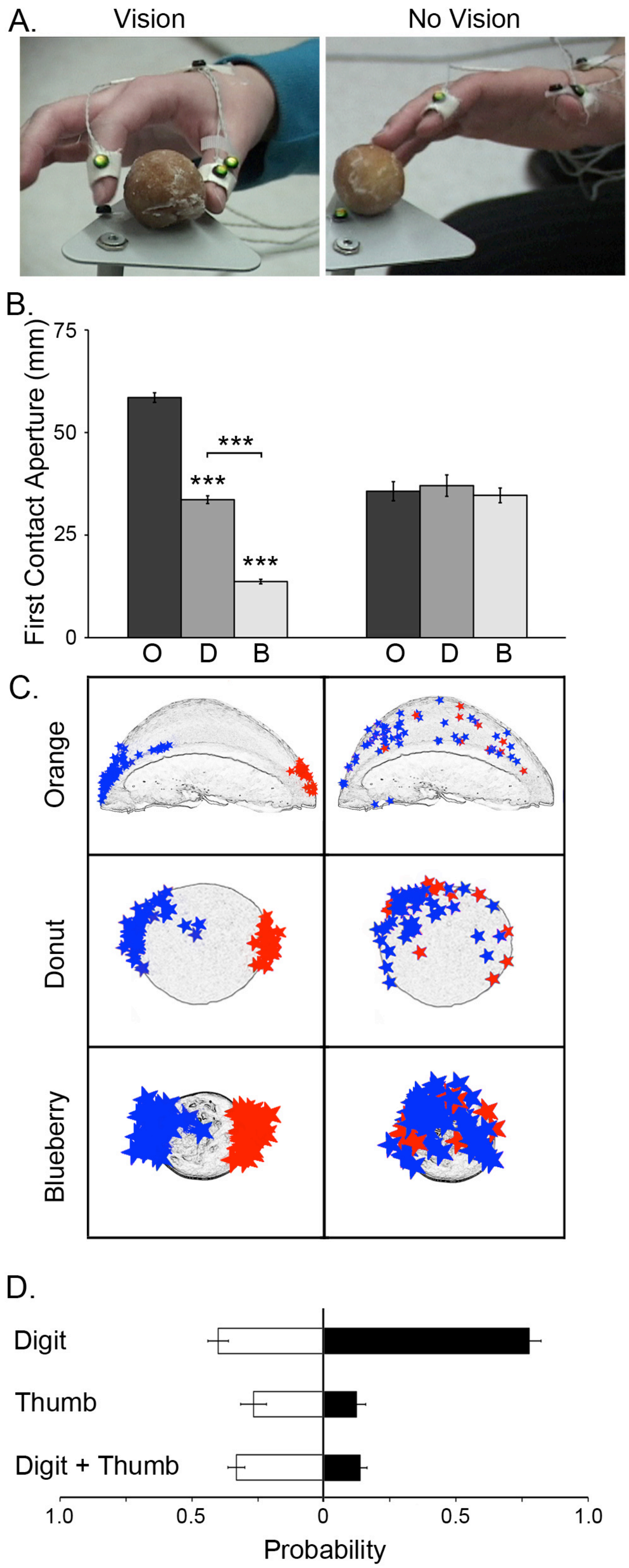


Figure 2.6 First contact. Hand shape, aperture, and orientation in the Vision condition (left) and No Vision condition (right). (A) Representative photos of the hand shape used to make first contact with a donut. (B) The index-thumb aperture (mean ± standard error) at first contact with an orange slice, donut, and blueberry. (C) The location of first contact on an orange slice, donut, and blueberry. In relation to the participant, the left portion of each target is located distally while the right portion of each target is located proximally (as in Figure 6A). Contacts made with a digit are shown in blue (dark grey) and contacts made with the thumb are shown in red (light grey; summed across all participants and trials). (D) The probability (mean ± standard error) that a digit, the thumb, or the thumb plus another digit made first contact with the target. Note: In the Vision condition the hand shape, index-thumb aperture, and digit-thumb opposition orientation, matched the size, shape, and orientation of the target object. In the No Vision condition, participants predominatly used a single digit to make first contact, without a scaled aperture, or appropriate opposition-orientation (O - Orange slice, D – Donut, B – Blueberry, ***$p < 0.001$).

Hand shape and orientation differed at first contact when reaching with vision as compared to without vision.

Kinematic analysis confirmed the behavioural observation that accurate hand shaping was present at the point of first contact in the Vision condition, but not in the No Vision condition (Figure 2.6B). Hand aperture scaled to object size, such that it was largest when reaching for an orange slice, intermediate when reaching for a donut, and smallest when reaching for a blueberry in the Vision condition. In the No Vision condition, a default hand aperture was observed at first contact, regardless of target size. These findings were confirmed by an ANOVA that gave no significant effect of Feedback [$F(1,10) = 0.048$, $p > 0.05$], a significant effect of Object [$F(2,20) = 143.473$, $p < 0.001$], and a significant effect of Feedback X Object [$F(2,20 = 114.779$, $p < 0.001$].

Frame-by-frame video analysis confirmed that the hand was already oriented to the target at first contact in the Vision condition, but not in the No Vision condition. Figure 2.6C shows the three target objects and the locations at which first contact occurred with (left) and without (right) vision (summed across all participants and trials, not to scale). Blue stars represent contact points made with a digit (usually the index or middle finger) and red stars represent contact points made with the thumb. The location of first contact deviated significantly further from the ideal grasp contact locations in the No Vision ($M \pm SE = 9.96 \pm 0.67$ mm) compared to the Vision condition ($M \pm SE = 2.92 \pm 0.33$ mm). In the Vision condition, the location of first contacts is indicative of a digit-thumb opposition orientation along the rostral-caudal axis of the target object. In the No Vision condition, the location of first contacts was randomized across the dorsal surface of the target object in a haphazard way, indicating the absence of a preferred digit-thumb opposition orientation. These findings were confirmed by an ANOVA that gave a significant effect of Feedback [F(1,8) = 71.069, $p < 0.001$].

Frame-by-frame video analysis was also used to determine which digit made first contact with the target object. Figure 2.6D shows the probability that participants made first contact with a single finger, the thumb, or both at the same time when reaching with and without vision. In the Vision condition, all three scenarios occurred with equal probability. This differed significantly from the No Vision condition, in which first contact was almost always made with a single finger. This difference is likely due to the fact that in the Vision condition, the hand was shaped and oriented to the target prior to first contact, thus increasing the likelihood that first contact could occur with the finger, thumb, or both. In the No Vision condition the digits were almost always extended at first contact, thus increasing the likelihood that first contact would be made with a digit other than the thumb. These main findings were confirmed by an ANOVA that gave significant effects for Feedback [F(1,11) = 13.200, $p < 0.01$], First Contact Strategy [F(2,22) = 44.098, $p < 0.001$], and Feedback X First Contact Strategy [F(2,22) = 22.639, $p < 0.001$].

Grasping

Compared to the Vision condition, participants took significantly longer to grasp the target after first contact was made in the No Vision condition. This difference was explained by the different grasping strategies used in the two conditions. In the Vision condition grasping of the target immediately followed first contact with the target. In the No Vision condition, the hand did not immediately grasp the target after first contact.

Rather, the hand withdrew from the target after contact, the digits first collected (flexed and closed toward the starting position), then shaped to target size, shape, and orientation, after which the object was grasped. This general conclusion is supported by the following detailed descriptions.

Different grasping strategies with and without vision. Figure 2.7 illustrates the basic grasping strategies used from first contact to final grasp when reaching with (Figure 2.7A) and without vision (Figure 2.7B). When reaching with vision a visual grasping strategy was used. The hand was shaped and oriented to the target prior to contact. This facilitated immediate grasping of the target, such that only a slight flexion of the digits or thumb was required to achieve the final grasp posture. When reaching without vision a haptic grasping strategy was used. The hand was not shaped or oriented at first contact. Thus, a second hand transport was initiated after haptic contact with the target. This haptic grasping strategy was characterized by a retraction of the hand and/or digits from the target, followed by hand shaping and digit orienting to the size and shape of the target, as well as adjustments in digit-to-target contact location. Despite irregular hand shaping and orienting prior to first contact with the target in the absence of visual feedback, the use of this haptic strategy after first contact facilitated successful grasping of the target.

Variations of the haptic grasping strategy. Depending on hand shape, aperture, and location of first contact with the target, variations of the haptic grasping strategy could be opportunistically applied. Nevertheless, each variation still passed through a critical phase in which the hand shaped and oriented to the target prior to grasping it.

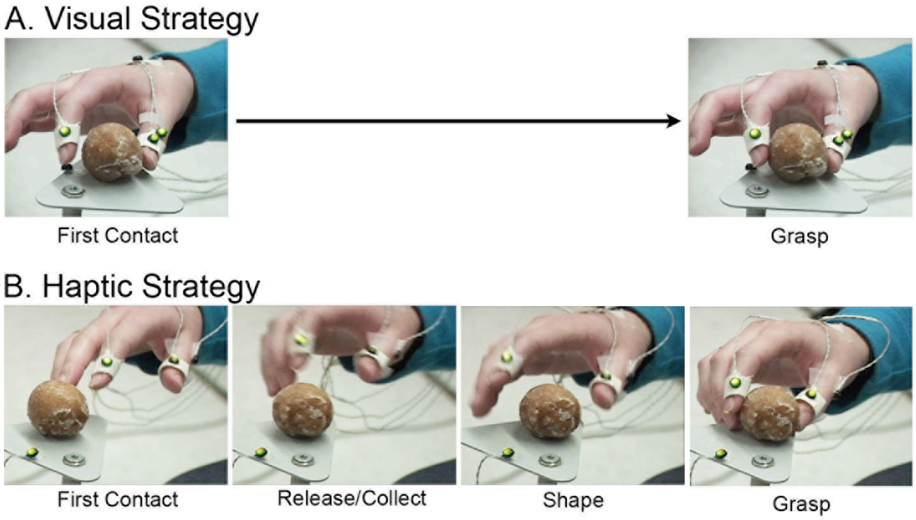


Figure 2.7 Representative still frames illustrating the (A) the visual strategy and (B) haptic strategy used between first contact and final grasp. Note: For the haptic strategy, unlike the visual strategy, hand shape, aperture, and orientation scaled to the target after the hand released the target.

Figure 2.8 illustrates variations of the haptic grasping strategy used in the No Vision condition.

Figure 2.8A illustrates Variation 1 of the haptic grasping strategy. At first contact the hand was already semi-shaped in anticipation of contacting a target object. First contact was made with either the thumb or a digit, but occurred at an inappropriate location on the target object. Thus, both the location of contact and hand shape was adjusted prior to establishing the final grasp posture.

Figure 2.8B illustrates Variation 2 of the haptic grasping strategy. At first contact the hand was not shaped in any manner that would support immediate grasping of the target object. First contact was made most often with a digit (rather than the thumb), but always at a location on the target object that was conducive to initiating movement towards the appropriate final grasp orientation. Because the location of first contact and hand orientation were opportune, a simple flexion of the thumb allowed for successful "capture" of the target between the digit and thumb in an efficient final grasp posture; however, because the hand was not appropriately shaped at first contact, final closure of the hand took longer, and the flexion of the thumb was greater, than when compared to the visual grasping strategy (Figure 2.7A).

Figure 2.8C illustrates Variation 3 of the haptic grasping strategy. At first contact the hand was not appropriately shaped for grasping the target. Contact was made with a digit (rather than the thumb) and occurred at an inappropriate location, usually the dorsal surface of the target. To facilitate grasping, the digit that made first contact maintained contact, while an adjacent digit established a second contact with the target. Meanwhile, the digit that made first contact may or may not have "rolled" the target object towards

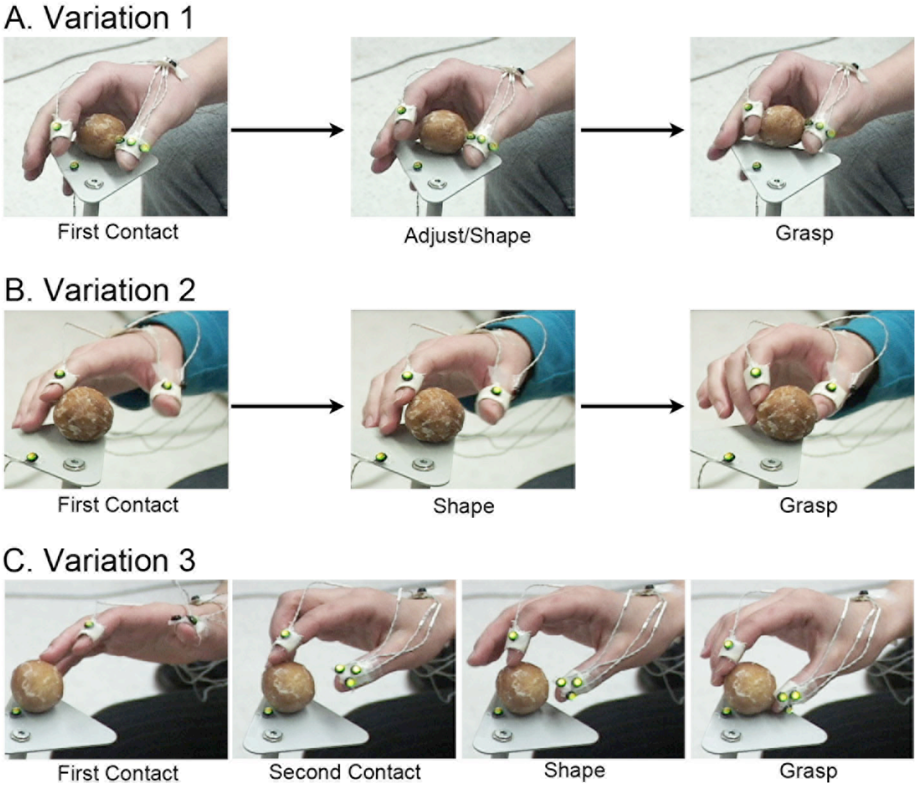


Figure 2.8 Representative still frames illustrate the 3 variations of the haptic strategy (A, B, and C). Note: For all variations, hand shape and/or orientation at first contact did not conform to the size, shape and orientation of the target object. Nevertheless, all strategies pass through a stage of hand shaping and orienting to produce a successful final grasp.

the participant to facilitate the second contact. After second contact, the digit that made first contact released the target and shaped, along with the thumb, in order to achieve the final grasp posture.

Frequencey of different hand shaping strategies with and without vision. Figure 2.9 shows the probability that participants used a specific grasping strategy when reaching either with or without vision. In the Vision condition, the basic visual strategy was used with a probability nearly equal to 1. In the No Vision condition, the probability of using the visual strategy dropped to 0; whereas, the probability of using the basic haptic strategy increased significantly, as did the probability of using variations of it. The use of variation 1 was favored when reaching for an orange slice as compared to a donut or blueberry. These main findings were confirmed by an ANOVA that found a significant effect of Feedback X Grasping Strategy [$F(4,44) = 96.232$, $p < 0.001$], Target X Grasping Strategy [$F(8,88) = 5.342$, $p < 0.001$], and Feedback X Target X Grasping Strategy [$F(8,88) = 6.179$, $p < 0.001$].

Kinematic profiles of grasping variations with and without vision. Each grasping strategy and variation was associated with a unique kinematic index-thumb aperture profile. Figure 2.10 shows representative aperture profiles starting at first contact and ending at final grasp, for the visual strategy, the haptic strategy, and each variation of the haptic strategy.

Figure 2.10A shows a kinematic profile for the visual strategy. At first contact the index-thumb aperture was already nearly equivalent to the final grasp aperture; only a slight decrease in aperture was needed to complete the grasp. Figure 2.10B shows a kinematic profile for the basic haptic strategy. A steady index-thumb aperture was

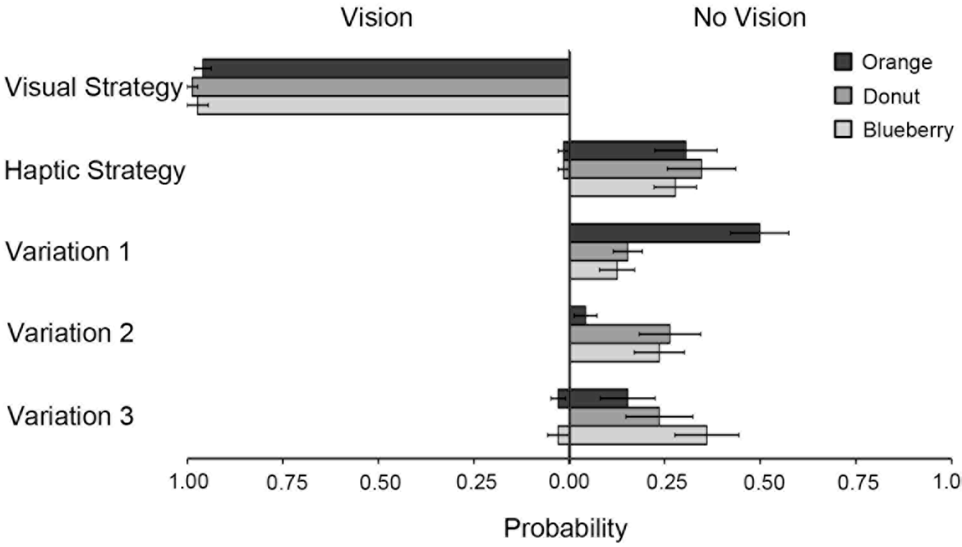


Figure 2.9 The probability that each grasping strategy was used when reaching for an orange slice, donut, or blueberry in the Vision and No Vision conditions (mean ± standard error) is shown. Note: The visual strategy was highly favoured in the Vision condition but not in the No Vision condition ($p < 0.001$). The haptic strategy, and the three variations of it, almost never occurred in the Vision condition, but occurred with equally frequency in the No Vision condition (haptic strategy, $p < 0.001$; variation 1, $p < 0.001$; variation 2, $p < 0.001$; variation 3, $p < 0.05$). Of the haptic strategies, variation 1 was highly favoured when reaching for an orange slice, but not when reaching for a donut or blueberry ($p < 0.001$).

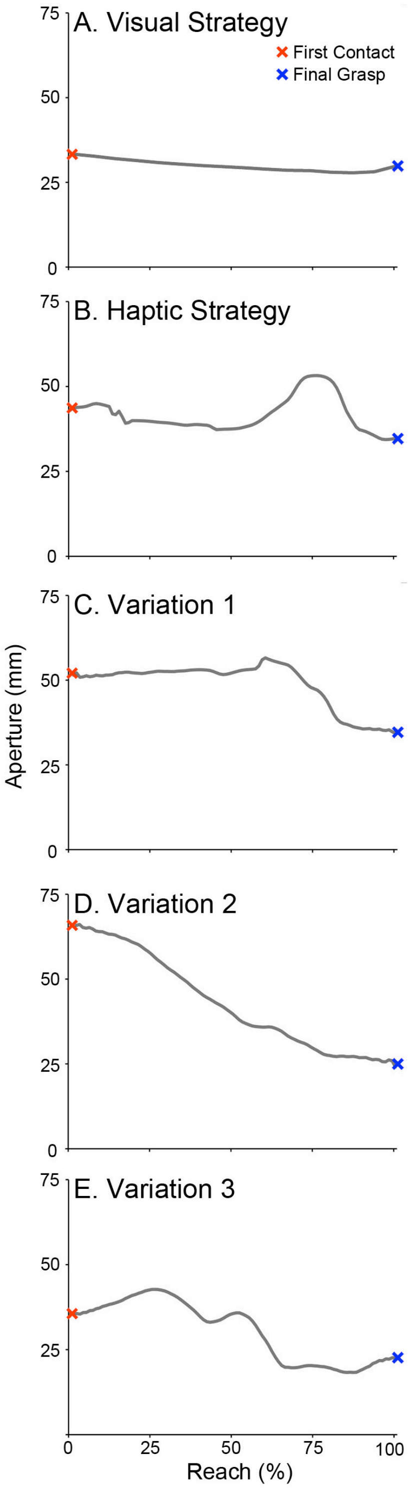


Figure 2.10 Representative kinematic profiles, from first contact to grasp, of the index-thumb aperture (mm) for each of the grasping strategies; (A) visual strategy, (B) haptic strategy, (C) variation 1, (D) variation 2, and (E) variation 3. Note: a peak aperture is observed between first Contact and grasp) for the basic haptic strategy, as well as variation 1, and variation 3.

maintained after first contact until an obvious peak aperture occurred prior to grasping of the target. Figure 2.10C shows a kinematic profile for variation 1 of the haptic strategy. After first contact, a steady index-thumb aperture was maintained until a small peak aperture occurred prior to grasping of the target object. Figure 2.10D shows a kinematic profile for variation 2. After first contact, a steady decrease in the index-thumb aperture occurred until final grasp aperture was reached. A second peak aperture was not observed, but may have been concealed by the fact that the hand aperture was so large at first contact, resulting in a linear decrease in aperture that could obscure the formation of an index-thumb aperture, scaled to the size of the target object. Figure 2.10E shows a kinematic profile for variation 3. After first contact, two additional peaks in index-thumb aperture occurred prior to grasping of the target.

Comparison of visual vs. haptic strategies for hand shaping, orienting, and grasping

Hand shaping, orienting, and grasping appeared very similar in the visual strategy and haptic strategy. A more detailed comparison as summarized below, confirmed this conclusion.

To determine whether hand shaping scaled to target size in haptically-guided grasping, as it does in visually-guided grasping, index-thumb peak aperture was compared in both. A peak aperture could be identified after first contact in over half of the No Vision kinematic profiles (Table 2.1). The 112 No Vision trials were paired with 112 corresponding Vision trials (ie., trials with the same target object) and a follow-up ANOVA was run to compare the size of peak aperture before first contact in the Vision

Table 2.1 Grasp strategies used when reaching to a distal object with or without vision and the occurrence of a 2nd Peak Aperture during the Grasping Phase of the reach for each strategy

Feedback	Grasping Strategy	Frequency of 2nd Peak Aperture	Frequency of 2nd Peak Aperture (%)
Vision	Vision	0/210	0%
	Haptic	0/0	0%
	Variation 1	4/6	67%
	Variation 2	0/0	0%
	Variation 3	0/0	0%
	Total	**4/216**	**1.9%**
No Vision	Vision	0/0	0%
	Haptic	45/67	67%
	Variation 1	35/59	59%
	Variation 2	0/36	0%
	Variation 3	32/54	59%
	Total	**112/216**	**52%**

condition and after first contact in the No Vision condition. Figure 2.11 shows peak aperture size before first contact in the Vision condition (white bars) and after first contact in the No Vision condition (black bars). In both conditions, peak aperture scaled to target size. Overall, peak aperture size did not significantly differ in the Vision and No Vision conditions. Nevertheless, when reaching for an orange slice, peak aperture was smaller in the No Vision condition compared to the Vision condition. This was likely due to the increased use of haptic grasping strategy variation 1 (Figure 2.9) which was associated with a relatively small peak aperture (Figure 2.10C). These findings were confirmed by an ANOVA that gave no significant effect of Feedback [$F(1,10) = 3.571$, $p > 0.05$], but significant effects of Object [$F(2,20) = 203.831$, $p < 0.001$] and Feedback X Object [$F(2,20) = 9.281$, $p < 0.001$] and follow-up post hoc analyses.

In order to compare the effectiveness of the visual and haptic grasping strategies, hand shape, orientation, and grip posture were examined at final grasp. Figure 2.12A shows representative still frames of final grasp when reaching to a donut with (left) and without vision (right). A similar hand shape and index-thumb aperture were clearly achieved in both conditions. This result was confirmed by the kinematic analysis (Figure 12B), which found that the grasp aperture for the orange slice, donut, and blueberry scaled to object size regardless of differences in sensory feedback. These findings were also confirmed by an ANOVA, that gave no significant effect of Feedback [$F(1,10) = 0.526$, $p > 0.05$], and no significant effect of Feedback X Object [$F(2,20 = 0.814$, $p > 0.05$], but a significant effect of Object [$F(2,20) = 350.605$, $p < 0.001$].

Frame-by-frame video analysis also confirmed that the same opposition orientation was adopted at final grasp in the Vision and No Vision condition.

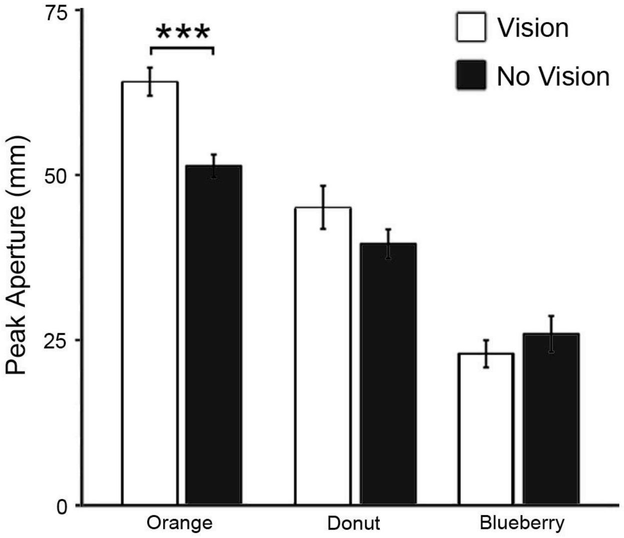


Figure 2.11 Peak Aperture (mm) when reaching in the Vision and No Vision conditions (mean ± standard error). Note: In the vision condition, peak aperture scaled to object size during hand transport. In the No Vision condition, peak aperture also scaled to object size, but only after first contact with the target (O - Orange slice, D – Donut, B – Blueberry, ***$p < 0.001$, **$p < 0.01$).

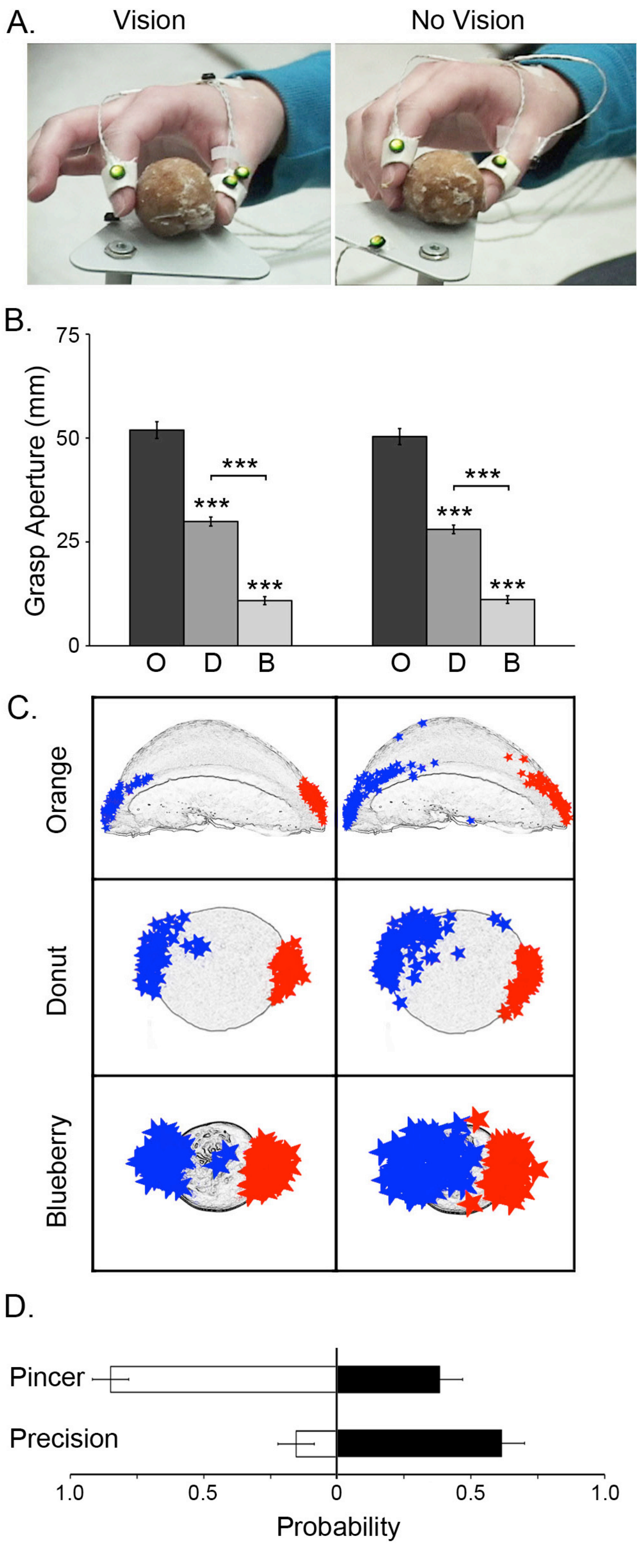


Figure 2.12 Hand shape, aperture, orientation, and grip at final grasp in the Vision (left) and No Vision conditions (right). (A) Representative photos of the hand shape used to grasp a donut. (B) The index-thumb aperture used to grasp an orange slice, donut, and blueberry (mean ± standard error). (C) The location of final grasp contacts on an orange slice, donut, and blueberry. In relation to the participant, the left portion of each target is located distally while the right portion of each target is located proximally (as in Figure 2.12A). Contacts made with a digit are shown in blue (dark grey) and contacts made with the thumb are shown in red (light grey; summed across all participants and trials). (D) The probability that a pincer grip or precision grip was used to grasp the target object (mean ± standard error). Note: In both the Vision and No Vision conditions the hand shape, index-thumb aperture, and final grasp contact locations were scaled and oriented to the size and shape of the target object at final grasp. The only difference was that in the No Vision condition a precision grip occurred more often than a pincer grip, (O - Orange slice, D – Donut, B – Blueberry, ***$p < 0.001$).

Figure 2.12C shows the location on the target object at which final grasp contacts occurred when reaching for an orange, donut, or blueberry with (left) and without (right) vision (summed across all participants and trials). Blue (dark grey) stars represent contact points made with a digit (usually the index or middle finger) and red (light grey) stars represent contact points made with the thumb. The location of final grasp contacts deviated slightly further from the ideal grasp contact locations in the No Vision ($M \pm SE = 3.13 \pm 0.22$ mm) compared to the Vision condition ($M \pm SE = 2.32 \pm 0.14$ mm). Nevertheless, despite differences in index-thumb opposition orientation at first contact (Figure 2.6C), a common index-thumb opposition orientation, aligned with the rostral-caudal axis, was used to grasp the target in both the Vision and No Vision conditions. These findings were confirmed by an ANOVA that gave a significant effect of Feedback [$F(1,8) = 6.733$, $p < 0.05$].

The only major difference at final grasp was related to the type of grip used in the Vision vs. No Vision conditions. Figure 2.12D shows the probability that participants used either a pincer grip or a precision grip when reaching for a distal object with or without vision. In the Vision condition, the probability of grasping the target with a pincer grip was significantly higher compared to the probability of using other precision grips. The reverse was true in the No Vision condition, for which the use of other precision grips occurred with a much higher probability than the pincer grip. These main findings were confirmed by an ANOVA that did not give a significant effect of Grip [$F(1,11) = 3.107$, $p > 0.05$], but a significant effect of Feedback X Grip [$F(1,11) = 32.201$, $p < 0.001$]. In the No Vision condition, the use of a third digit in the precision grip might offer additional motor support for grasping of the target (Gentilucci et al.

2003), or it could play a primarily sensory role, by monitoring the state of interaction between the hand and target, while the remaining digit and thumb perform the primary motor action of grasping (Mackenzie and Iberall 1994b).

Discussion

This study provides the first description of the reach-to-grasp movement to uncertain targets in the absence of vision. Participants reached for orange slices, donuts, and blueberries placed on a distal pedestal. Participants were unaware, prior to haptic contact, which target they were reaching for. Frame-by-frame video analysis and kinematic motion capture were used to examine hand shaping, orienting, and grasping. The results of the present study extend previous work (Bernier and Grafton, 2010; Monaco et al. 2010, Pettypiece et al. 2009; Pettypiece et al. 2010; Castiello et al. 1993; Fiehler et al. 2011; Hu et al. 1999; Jakobson and Goodale 1991; Wing and Turton 1986) in three important ways. First, unlike other forms of visually- and haptically-guided grasping, hand shaping and orienting did not accompany hand transport when reaching to an unseen and uncertain target. Rather, hand transport served simply to establish haptic contact with the target, possibly in order to identify it. Second, after the target was contacted, the hand did not simply close, rather the hand adjusted its trajectory, often collecting the digits at the same time, before reorienting and reshaping for grasping. Third, variations of this basic strategy allowed for concurrent haptic exploration and manipulation of the target with some digits while the remaining digits released and shaped for grasping. Despite differences in the sensory information used to guide grasping, hand shaping in the visual and haptic conditions were similar in that the grasping digits displayed a similar overgrasp and grasp. The common hand shaping elements applied under both visual and haptic control suggests that these different forms of grasping perhaps stem from a common neural origin.

The design of the present experiment featured three manipulations that required haptic localization and identification of the target prior to grasping of it. First, ethologically-relevant food items of varying size were used to ensure that participants were familiar with the reaching targets. Second, participants were asked to grasp an object as if it were to be eaten. This constraint ensured that all subjects used a similar grasping pattern, a pincer or other precision grip, for all objects (Iberall et al. 1986; Napier 1956; Sartori et al. 2011). Third, visual occlusion ensured that both target identification and grasping were performed only by the grasping hand. As in previous studies, targets ranged in size so that hand shaping and orientating to the intrinsic properties (size and shape) of each target could be easily evaluated using frame-by-frame video analysis and kinematic motion capture (Jakobson and Goodale, 1991; Jeannerod 1981, 1984, 1986).

Some caveats must be made with respect to the procedures used. First, the kinematic method is limited, in that it does not provide a comprehensive measure of all hand shaping/orienting transitions. Although the video records clearly indicated how the hand was shaped and oriented for grasping, parts of the hand were sometimes obscured so that kinematic results were sometimes incompletely captured. Second, only the aperture between the index finger and thumb was measured. Shaping, however, also occured between the middle finger and thumb (Figure 8D, Frame 3), confirming the adaptability of the digits in perfoming a variety of precision grasps (Wong and Whishaw 2004). Thus, peak aperture could not be measured on all of the haptic trials. Nevertheless, 52% of the haptic trials provided data that could be subjected to kinematic analysis. In future experiments, by the use of multiple camera views, measurement of the aperture between the thumb and other digits would likely increase the number of trials that could be subjected to kinematic analysis. Third, the reaching targets were restricted to a small number of categorically-related food items placed in a constant location. It is possible that novel variations of the haptic strategy might be introduced for grasping a wider range of targets at varied locations. For instance, tools such as a hammer can be grasped in many different ways. Yet only a specific grasping pattern supports proper use of the tool. In future experiments, it would be interesting to determine whether the use of tools as reaching targets would enhance the parsing of the reach-to-grasp movement and/or increase the number of concurrent exploratory/manipulatory hand shapes used prior to preshaping for grasping. Nevertheless, people use a similar hand shape to grasp targets with a common function (ie. to be brought to the mouth for eating). Thus, the chosen targets and location were ideal for standardizing final grip pattern across participants and trials.

When reaching without vision to an uncertain target, the transport phase did not serve to prepare the hand for grasping. Instead, the hand served an exploratory function with the simple aim of establishing haptic contact with the target, presumably to identify it. This conclusion is supported by three observations. First, unlike visually-guided reaching, when the hand approached the target, its shape and aperture did not scale to the size of the target. Rather, a standard hand shape and aperture were used. Second, the aperture of this standard hand shape was intermediate in size (smaller than an orange slice but larger than a blueberry). This differs from other forms of nonvisual reaching, ie., reaching to a remembered target, for which a larger-than-normal peak aperture is used as a means to facilitate grasping of the target despite errors in hand transport (Jakobson and Goodale, 1991). Third, the standard hand shape used during transport in the haptic condition did not simply reflect an averaging of the index-thumb aperture in relation to the three possible target sizes (Chapman et al. 2010). This is because the hand shape used to make first contact in the haptic condition was not a "grasping" hand shape at all. Rather, an "exploratory" hand shape was used, in which the digits were open and extended, and so, contact was made with a digit tip at a random location on the target. This contrasts with the "grasping" hand shape used in the visual condition, in which the digits were shaped, oriented, and directed to specific contact points on the target. In sum, the hand shape and orientation used during transport in the haptic condition are suggestive of an exploratory hand posture that serves to maximize the sensory range of each digit in order to contact and identify the target.

When reaching without vision to an uncertain target, hand shaping for grasping did occur as a sequence of discrete movement elements, but only after haptic contact was made with the target. This conclusion is supported by a number of experimental measures. First, after making contact, the hand and/or grasping digits sometimes closed and flexed into a collected hand posture. This collected hand posture is a common movement primitive known to precede natural hand shaping (Sacrey et al. 2009; Sacrey and Whishaw 2010; Saling et al. 1996; Timman et al. 1996; Whishaw et al. 2010a; Whishaw et al. 2010b). Second, the adoption of this posture allowed the hand to transition from an open and extended exploratory hand shape, which increased the likelihood that one of the digits would contact the target, into a grasping hand shape, using whichever digits were best positioned to form a grip with the thumb. Third, this grasping hand shape both scaled and oriented to the target, after which, successful grasping of the target occurred. Taken together, these results argue that movement elements of hand collection, shaping, and orienting, which are characteristic of visually-guided grasping, are also applied using haptic information from a touched target.

When subjects reached without vision to an uncertain target, they did display variations in the haptic grasping strategy and the variations reveal that the hand could concurrently perform a number of acts. Sometimes, the first digit to contact the food stabilized it, meanwhile, shaping and grasping were performed by the remaining digits and thumb. At other times the target was “rolled” by a digit or between digits in order to manipulate it into a more convenient position for grasping, which was again performed by the remaining digits and thumb. These variations resembled both the manipulatory hand shapes described by Elliott and Connolly (1984), as well as the exploratory hand shapes described by Lederman and Klatzky (1998). Nevertheless, in each variation the hand still passed through a phase in which it was shaped and oriented to the target prior to grasping. Thus, in addition to exploring, manipulating, and stabilizing the target, the hand concurrently executed a common hand shaping sequence for grasping.

Hand shaping in the visual condition and haptic condition were very similar in a number of ways. In both conditions, hand aperture scaled to the size of the target such that a large peak aperture was used to grasp an orange slice and a small peak aperture was used to grasp a blueberry; in both conditions, the index finger and thumb oriented to similar opposing sides of the target, and; in both conditions, successful grasping of the target was achieved such that it could be brought to the mouth for eating. Taken together, these results indicate that the same hand shaping strategy that is implemented during transport in the visual condition is used after contact in the haptic condition. Despite differences in sensory control, this strategy always involved shaping of the hand, scaling of the index-thumb aperture, and orienting of the index finger and thumb to opposing side of the target, prior to grasping.

The use of a seemingly similar movement in both visually- and haptically-guided grasping, is suggestive of a common neural origin for hand shaping for grasping despite differences in sensory conditions. A common neural representation for grasping could be coded within a human homologue of the macaque grasping circuit (Castiello et al. 2000). The areas in this circuit, especially AIP, appear to play a critical role in grasping (Murata et al. 1997; Rizzolatti et al. 1998), are activated by multiple forms of sensory input related to grasping (Binkofski et al. 1999), and are active during the grasping actions of numerous distal effectors (Castiello et al. 2000; Jacobs et al. 2010). It is also possible, however, that there are separate representations for visually and haptically guided grasping. It is suggested, for example, that visually guided and nonvisually guided hand shaping are mediated by parietal vs temporal lobe pathways in humans (Bernier and Grafton 2010; De Santis et al. 2007; Goodale et al. 2004; Goodale and Milner 1992; Reed et al. 2005; Sathian et al. 2011). Thus, the haptically executed grasping described here, although similar to visually-guided grasping, may nonetheless be mediated by the same offline temporal lobe pathway that mediates memory-guided grasping (Goodale et al. 2004). Nevertheless, because haptic contact was sometimes maintained during hand shaping for grasping, it is possible that haptically-guided grasping could also be mediated by the same online parietal pathway that mediates visually-guided grasping (Goodale and Milner 1992).

In conclusion, the present results support the postulate of the DVC theory that the Reach and the Grasp are separate movements, likely mediated by different neural pathways. They also confirm the first hypothesis of this thesis that foveal vision is required to integrate the Reach and the Grasp into a seemless prehensile act by showing that when vision is not available to determine the extrinsic and intrinsic properties of the target the two movements dissociate so that haptic feedback associated with target contact may first guide the Reach in locating the target and then the Grasp in shaping the hand for target purchase.

Chapter 3

Nonvisual learning of intrinsic object properties in a reaching task dissociates Grasp from Reach

Abstract

The Dual Visuomotor Channel theory proposes that skilled reaching is composed of a Reach that directs the hand in relation to the extrinsic properties of an object (e.g., location) and a Grasp that opens and closes the hand in relation to the intrinsic properties of an object (e.g., size). While Reach and Grasp movements are often guided by vision they can also be performed without vision when reaching for a body part or an object on one's own body. Memory of a recently touched but unseen object can also be used to guide Reach and Grasp movements although the touch-response memory durations described are extremely brief (Karl et al., 2012a). The purpose of the present study was to determine whether repeated non-visual reaching for a consistent object could calibrate Reach and Grasp movements in a way similar to those guided by vision. The non-vision group wore vision occluding goggles and reached for fifty consecutive trials for a round donut ball placed on a pedestal. The control group performed the same task with vision. Frame-by-frame video analysis and linear kinematics revealed that non-vision participants consistently used an elevated Reach trajectory, in which the hand, rather than being directed towards the target in the horizontal plane, was first elevated above the target before being lowered to touch and locate it. First contact was established with the dorsal surface of the target and thus adjustments in contact locations were often required for purchase. Although non-vision participants initially used an open and extended hand during transport, with practice they began to scale digit aperture to object size with an accuracy and temporal relation similar to vision participants. The different ways in which the Reach and Grasp movements respond to non-visual learning is discussed in relation to

support for the dual channel theory of reaching and to the idea that the Reach and Grasp channels may be differentially dependent on online visual guidance.

Introduction

The reach-to-grasp action, in which a participant advances a hand to acquire an object, is used for many daily functions including eating. The Dual Visuomotor Channel theory (Jeannerod 1981) proposes that the act is composed of two movements. The Reach is guided by extrinsic object properties (e.g., location) whereas the Grasp is guided by intrinsic object properties (e.g., size). The Reach transports the hand to the target and the Grasp opens and closes the digits for object purchase (Arbib 1981; Jeannerod 1981, 1999; Jeannerod et al. 1998). The anatomical substrates of the two channels are proposed to be occipitoparietal pathways in the dorsal stream (Goodale and Milner 1992; Rizzolatti and Matelli 2003); a dorsomedial stream for the Reach and a dorsolateral stream for the Grasp (Binkofski et al. 1998, 1999; Cavina-Pratesi et al. 2010a,b; Jeannerod et al. 1994,1995; Murata et al. 2000; Rizzolatti et al. 1998; Tanne-Gariepy et al. 2002). Reach and Grasp movements can also be made without vision in order to grasp body parts (Edwards et al., 2005), objects on the body (Edwards et al. 2005; Pettypiece et al. 2009, 2010), or objects held in the mouth (Karl et al. 2012b). These findings, along with findings from anatomical and imaging studies (Anema et al. 2009; Bernier and Grafton 2010; Binkofski et al. 1999; Dijkerman and de Haan 2007; James et al. 2002), show that nonvisual systems can access the Reach and Grasp channels.

The question of whether Reach and Grasp movements can also be produced from memory has been addressed in a number of studies (Goodale et al. 1994a; Hu and Goodale 1999; Karl et al. 2012a). Karl et al. (2012a) report that visually occluded participants use an exploratory movement to seek out and identify an object and after contact, withdraw the hand and/or digits, scale digit-thumb aperture to object size, and redirect the digits to appropriate locations on the object with movements and accuracy similar to that performed under online visual control. Although memory demands in this study were minor and the distance of hand transport was short, the results raise the question of whether repeated non-visual experience with a consistent object might calibrate Reach and Grasp movements so that they are similar to those guided by vision. An experimental design in which the reinforcement contingencies enable error correction on successive trials was postulated to be especially conducive for calibrating movements toward the intrinsic and extrinsic properties of the unseen target object (Bingham et al. 2007). Accordingly, the present study was designed to determine if accurate Reach and Grasp movements can be learned without vision by having participants reach for the same unseen object repeatedly. If accurate Reach and Grasp movements can be calibrated from non-visual experience, the result would support the finding that reaching movements can be produced from memory (Bingham et al. 2007; Karl et al. 2012a). If non-visual experience did not result in accurate Reach and Grasp movements, the result would support the suggestion that offline reaching is different from online reaching (Goodale et al., 1994a; Hu and Goodale 1999).

In the present study, one group of ten healthy adult participants wore vision occluding goggles and reached to a small round donut ball placed on a pedestal in front of them. A second group of ten participants performed the same task with full vision. At the end of fifty consecutive trials, group assignments were reversed. In the initial condition, the visually occluded participants did not know what the target was going to be, and thus had to learn both its intrinsic and extrinsic properties without visual feedback. In order to constrain the grip pattern used to grasp the target (Karl et al. 2012a,b; Napier 1956, 1980; Sartori et al. 2011; Valyear et al. 2011), participants were asked to bring the target to the mouth "as if they were going to eat it," after grasping it. Off-line, frame-by-frame video analysis and linear kinematics were used to describe the Reach and Grasp movements and their temporal organization.

Materials and Methods

Participants

The minimum number of participants required was determined by an a priori power analysis (G*Power: Faul et al., 2007). Results from a pilot study found that the effect size for peak grip aperture between sighted and unsighted participants was large, t(18) = 3.706, p = .002, Cohen's d = 1.66, indicating that a total sample of 14 people would be needed to detect (at 80% chance) an effect of this size as significant with alpha at 0.05. Thus, similar to previous studies (Goodale et al. 1994), 20 young adults (11 women and 9 men: M ± SD age = 22.35 ± 3.13 years) were recruited from the University of Lethbridge to participate in the present study. All participants provided informed consent and were self-reported to be right-handed and of good health with no history of neurological or motor disorders. All participants had normal or corrected-to-normal vision. The University of Lethbridge, Human Subject Research Committee approved the study.

Procedures

A between-subjects design was employed to simplify the demands on each participant and to reduce interference effects with respect to the objectives of the study.

Participants were seated in a comfortable upright position. A self-standing, height-adjustable pedestal was placed directly in front of the participant at a horizontal reach distance normalized to the participant's arm length (100% of length from shoulder to tip of index finger with elbow at 180° flexion) and a vertical height normalized to the participant's trunk height (100% of height from floor to outstretched arm while seated and with shoulder at 90° flexion; de Bruin et al. 2008; Karl et al. 2012a,b; Whishaw et al. 2002). All participants were shown the general location at which the reaching target would be placed and told that the reaching target would be small enough to grasp with one hand. When necessary, visual occlusion was achieved using PLATO vision occluding goggles (Translucent Technologies, Toronto, ON) worn on the participant's face. Kinematic and behavioural data were acquired from the right hand as participants reached and grasped the donut.

Figure 3.1a illustrates the VISION condition (n = 10). At the beginning of each trial, the participant placed the right hand in the "start" position with the right index finger and thumb pressed together and resting on the anterior aspect on the right knee (Jakobson and Goodale 1991; Pettypiece et al. 2010). The target object, a round donut ball approximately 28.82 ± 1.67 mm in diameter was placed on the pedestal. The participant was instructed to reach for the item as if she was going to pick it up and eat it. After a verbal "one, two, three, GO" command, the participant reached for the donut with the right hand, grasped it, and brought it to the mouth (as if to eat it) before handing it to the experimenter. The participant then returned the right hand to the "start" position in

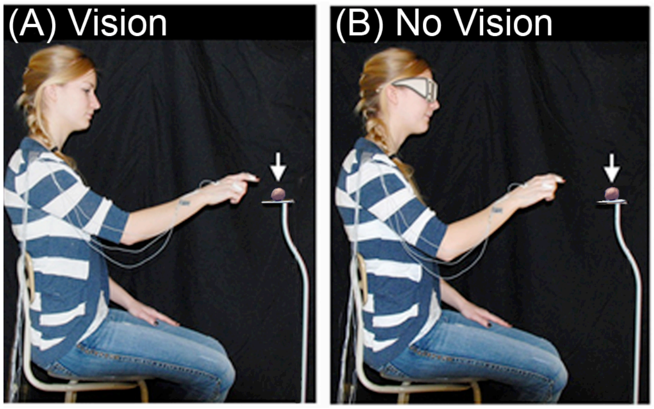


Figure 3.1 The reach-to-grasp task (A) with and (B) without vision. *White arrows* indicate the location of the donut ball at the beginning of each trial. Note: in the NO VISION condition participants wore occlusion goggles.

preparation for the next trial. A total of fifty consecutive trials were performed by each VISION participant. Figure 3.1b illustrates the NO VISION condition (n = 10). The task was the same as in the VISION condition, except that the participant wore vision occluding goggles prior to, and throughout, the testing session to ensure that they could not visually identify the reaching target. The kinematic data from one participant in the NO VISION group was degraded and excluded from analysis.

Kinematic data collection and analysis

Hand kinematics were recorded using an Optotrak Certus Motion Capture System and NDI Dataview and NDI First Principles software (Northern Digital Inc. Waterloo, ON; Jakobson and Goodale 1991). Infrared-emitting diodes (IREDs) were positioned on the thumb, index finger, middle finger, and wrist. For each trial, IRED positions were sampled at 200 Hz for 4 s following the verbal cue to initiate reaching.

Figure 3.2 illustrates the kinematic measures used in the present study. Aperture (mm) was calculated as the distance between the IRED positions on the thumb and the index finger. The change in Aperture (y-axis) was plotted against Time (x-axis) and is represented by the curved line. (1) *Peak Aperture* is defined as the maximum aperture obtained between movement onset and first contact with the object and is used as an indicator of anticipatory digit scaling. (2) *First Contact Aperture* is defined as the aperture obtained at first contact with the object. (3) *Final Grasp Aperture* is defined as the final aperture obtained during actual grasping (and holding) of the object. To control for variability of IRED positioning, the index-thumb aperture during the initial

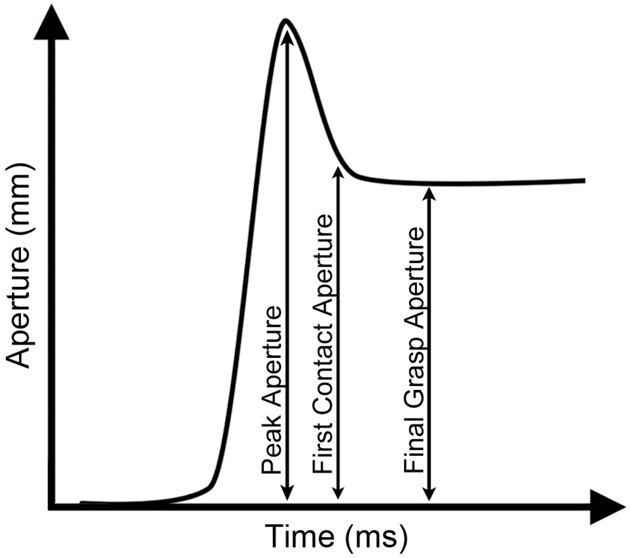


Figure 3.2 Measures of Peak Aperture, First Contact Aperture, and Final Grasp Aperture (mm) plotted against time (ms). The *curved line* indicates the changing distance between the index finger and thumb as the hand transitions from the "start" position to holding of the object.

"start position," was subtracted from all subsequent aperture measures for each trial for each participant (Karl et al. 2012a,b).

Behavioural data collection and analysis

A digital video camera was positioned sagittal to the participant to record a reach-side view of the participant from the lower leg to head at 30 frames/sec and 1/1,000 shutter speed. Another high speed video camera was also positioned to record a reach-side view of the participant at 300 frames/sec. The high speed video camera was time-synced with the Optotrak using NDI First Principles software. Representative still frames were captured from digital video recordings with the video editing software Final Cut Pro (http://www.apple.com). Pictures were cropped and adjusted for color and brightness contrast in Adobe Photoshop (V. 11.0) but not altered in any other way.

A number of behavioural measures were scored by performing off-line, frame-by-frame analysis of the video record and comparing it to the time synchronized kinematic data.

1. *Maximum Trajectory Height* refers to the maximum vertical distance between the index knuckle of the right hand and the dorsal surface of the pedestal during hand transport towards the reaching target. Frame-by-frame video analysis and the image analyzing software ImageJ 1.45S (http://imagej.nih.gov/ij) were used to plot the trajectory of the right index knuckle and the tip of the right index finger during hand transport towards the reaching target. The maximum vertical distance between the right index knuckle and the center of the pedestal was measured and calculated using

basic trigonometry. The actual length of a single side of the pedestal surface was used to scale all calculated measures.

2. *Digit Contact Locations* were determined by adapting previously defined methods (Goodale et al. 1994; Iberall et al. 1986; Stelmach et al. 1994) to frame-by-frame video analysis. The video record was reviewed for all participants for each condition, and the location of first contact and final grasp contacts was marked on the target object. The average final grasp contact location in the VISION condition was considered the "ideal" grasp target location. To quantify the extent to which a first contact or final grasp contact deviated from the ideal, the distance between the actual contact point and the ideal contact point was measured in Photoshop (V.11.0).
3. *Digit to Make First Contact* was determined by reviewing the video record and documenting which digit (palm, thumb, index, middle, ring, or pinkie) made first contact with the object.
4. *Final Grip Posture* was determined by reviewing the video record and documenting whether the target was grasped with a precision grip or a power grip. The precision grip features gripping of the target between the thumb and two or more digits of the same hand. The power grip features gripping of the target between the palm of the hand and one or more digits of the same hand.
5. *Movement Times* were obtained by examining the video record to determine the time of occurrence of key movement components and was confirmed using the time-synced kinematic data. *Time of movement onset* is defined as the moment of observable movement of the hand towards the donut ball. *Time of peak aperture* is defined as the time from movement onset to peak aperture prior to contact with the donut ball. *Time*

of first contact is defined as the time from movement onset to first contact with the donut ball. *Time of final grasp* is defined as the time from movement onset to final grasp of the donut ball.

Statistical analysis

Results were subject to a mixed analysis of variance (mixed ANOVA) using the computer program SPSS (v. 19.0.0). Sex (MALE vs. FEMALE) and Condition (VISION vs. NO VISION) served as between-subjects factors. Trial (1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 or FIRST 5 vs. LAST 5), Aperture (PEAK, FIRST CONTACT, FINAL GRASP), Time (TO PEAK APERTURE, TO FIRST CONTACT, and TO FINAL GRASP), Digit to Make First Contact (PALM, THUMB, INDEX, MIDDLE, RING, PINKIE), and Final Grip Posture (PRECISION vs. POWER) served as within-subjects factors. A *p* value of less than 0.05 was considered significant. Follow-up pairwise comparisons and post hoc analyses were subjected to bonferroni correction and power analyses were performed using G*Power 3.1 (Faul et al. 2007; http://www.psycho.uni-duesseldorf.de/abteilungen/aap/gpower3/). Results are reported as the mean ± within-subjects standard error of the mean.

Results

Reach Trajectory

Figure 3.3a shows the maximum vertical trajectory height, measured from the right index knuckle, when reaching to the donut ball on trial 1 and trial 50 in the VISION

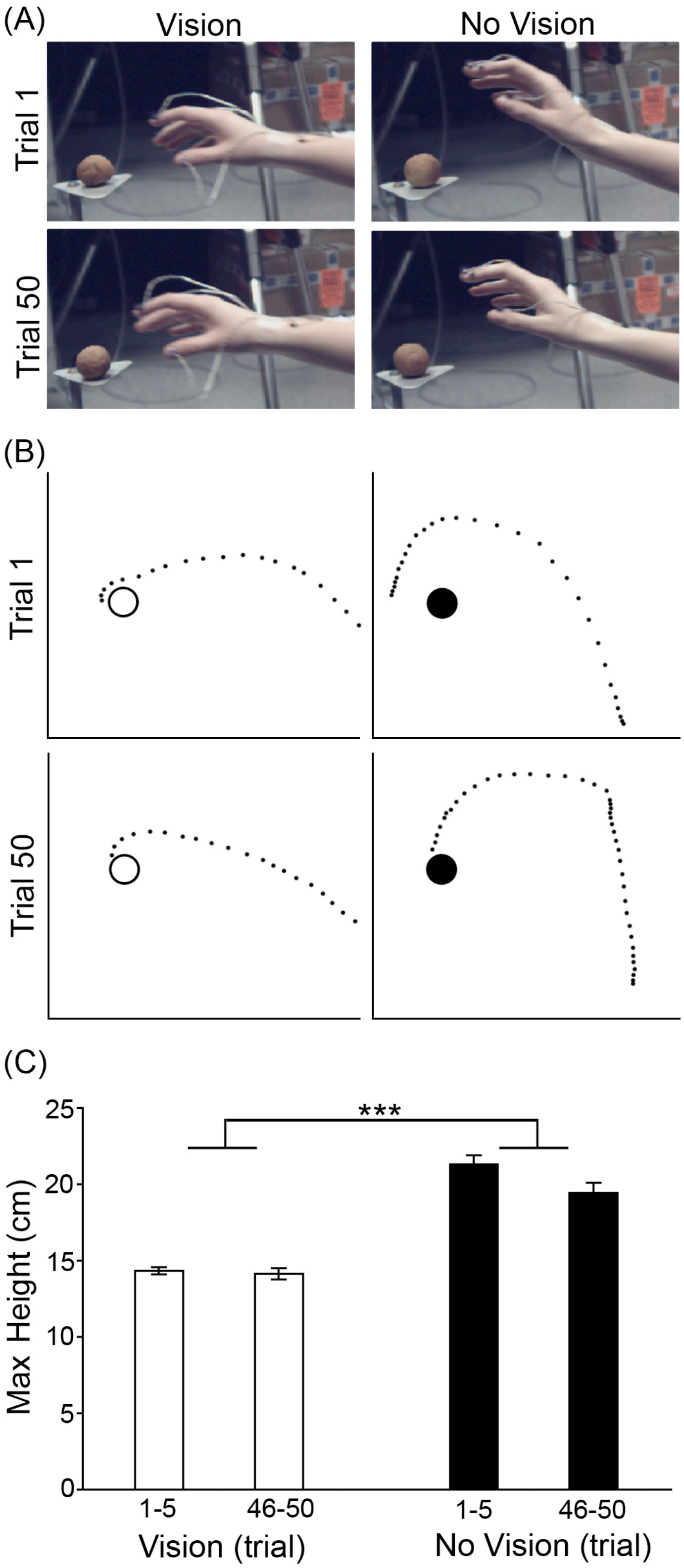


Figure 3.3 Representative still frames of the wrist, forearm, and hand at the maximum height of the Reach trajectory on trial 1 (top) and trial 50 (bottom) in the VISION and NO VISION conditions (A). Example Reach trajectories, determined by tracking the tip of the index finger, on trial 1 (top) and trial 50 (bottom) in the VISION and NO VISION conditions (B). The maximum Reach trajectory height (cm) for the first and last five trials (mean ± SE) when reaching in the VISION (white bars) and NO VISION (black bars) conditions (C). The maximum height of the Reach trajectory was consistently greater in the NO VISION condition compared to the VISION condition, (***$p < 0.001$).

and NO VISION conditions. The elevation of the trajectory was clearly greater in the NO VISION compared to VISION condition, even after repeated reaching trials.

Figure 3.3b shows the trajectory of the tip of the index finger on approach to the donut on trial 1 and trial 50 in the VISION and NO VISION conditions. When reaching to a visible object, reach trajectory was direct and approached the object in the horizontal plane. When reaching to an unseen object the reach trajectory was elevated above the expected location of the object and then lowered onto its dorsal surface. Despite repeated reaching trials, participants in the NO VISION condition maintained an elevated Reach trajectory.

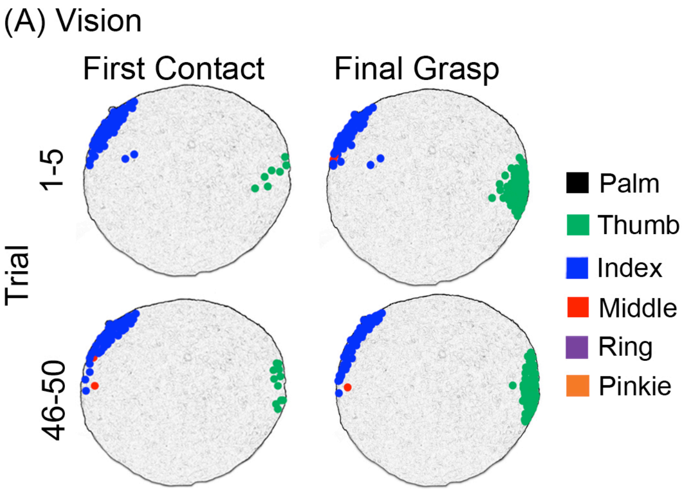
Kinematic analysis of maximum trajectory height confirmed the video description. Figure 3.3b shows the maximum trajectory height (mean ± SE of all participants) on the first five and last five reaching trials in the VISION (white bars) and NO VISION (black bars) conditions. Maximum trajectory height was significantly elevated in the NO VISION compared to VISION condition irrespective of trial number. In the NO VISION condition, maximum trajectory height appeared to decrease slightly with repeated reaching experience, but the effect was not significant.

These main findings were confirmed by a repeated measures mixed ANOVA that gave a significant effect of Condition [$F(1,17) = 35.673$, $p < 0.001$], but no significant effect of Trial [$F(9, 153) = 1.173$, $p > 0.05$] or Trial X Condition [$F(9,153) = 0.835$, $p > 0.05$].

Digit Placement: First Contact and Final Grasp Contact Locations

Figure 3.4 shows the location of digit-to-object contact locations at first contact (left) and at final grasp (right) for the first five and last five trials in the VISION (Fig. 3.4a) and NO VISION (Fig. 3.4b) conditions. This shows the extent to which the digits could be directed towards appropriate locations on the object before first contact and after first contact. In the VISION condition participants usually established first contact with the object by using the index finger to contact the distal side of the object or by using the thumb to contact the proximal side of the object. Because first contact was established with the grasping digits, and at appropriate locations on the object, no significant adjustments in digit-to-object contact locations were required after first contact in order to successfully grasp the object. This was true for both the early and late VISION trials. In the early NO VISION trials participants usually established first contact between the palm and the dorsal surface of the object. However, by later trials first contact was generally established with the index or middle finger, but still with the dorsal surface of the object. The location of first contacts differed significantly compared to the location of final grasp contacts and this was true for both the early and the late NO VISION trials. Thus, in the NO VISION condition, adjustments in digit-to-object contact locations were made after first contact in order to re-direct the digits to appropriate locations on the object in order to successfully grasp it (Karl et al., 2012a). These adjustments were still required after repeated reaching experience with the object.

These results were confirmed by the statistical analysis. For location of first contact there were significant effects of Condition [$F(1,17) = 57.667$, $p < 0.001$], Trial [$F(9,153) = 15.569$, $p < 0.001$], and Trial X Condition [$F(1,17) = 13.303$, $p < 0.001$]. The significant effect of Trial found in this analysis is due to large variation between trials in



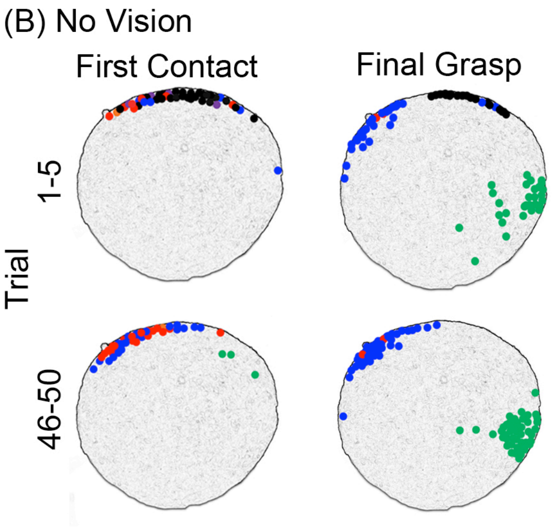


Figure 3.4 Digit-to-object contact locations at first contact (left) and final grasp (right) on the first five (top) and last five (bottom) trials in the VISION (A) and NO VISION (B) conditions. In relation to the participant, the *left portion* of each target is located distally and the *right portion* of each target is located proximally. Contacts were made with the palm (black), thumb (green), index (blue), middle (red), ring (purple), or pinkie (orange) finger. Note: digit-to-object contact locations did not change between first contact and final grasp in the VISION condition, but did change in the NO VISION condition.

the NO VISION condition and is not due to a learning effect. This is demonstrated by the fact that in the NO VISION condition, the location of first contact deviated further from the ideal contact location on trial 50 (M ± SE = 10.28 ± 0.86 mm) compared to trial 1 (M ± SE = 6.97 ± 0.85 mm). For location of final grasp contacts there were significant effects of Condition [F(1,17) = 1.108.812, $p < 0.001$], Trial [F(9,153) = 2.563, $p < 0.01$], and Trial X Condition [F(9,153) = 2.905, $p < 0.01$].

Digit to Make First Contact

Figure 3.5 shows the probability that participants made first contact with the object using the palm, or one of the digits on the first five and last five trials in the VISION and NO VISION conditions. Figure 3.5a shows that in the VISION condition participants tended to make first contact with either the thumb or index finger. This was consistent across both early and late reaching trials. Figure 3.5b shows that in the early NO VISION trials, first contact was randomized across the palm, index, middle, or ring finger. With repeated reaching experience, however, first contact came to be primarily established with either the index or middle finger, indicating reduced variability in which digit was used to make first contact with the object, but still differed from the VISION condition in which first contact was consistently made with the thumb or index finger. This indicates that with repeated reaching experience visually occluded participants are better able to direct a more appropriate part of the hand (i.e. the index or middle finger) to the location of the target. Nevertheless, they never achieve the level of accuracy observed in the VISION condition, in which the primary grasping digits are always used to establish first contact with the object.

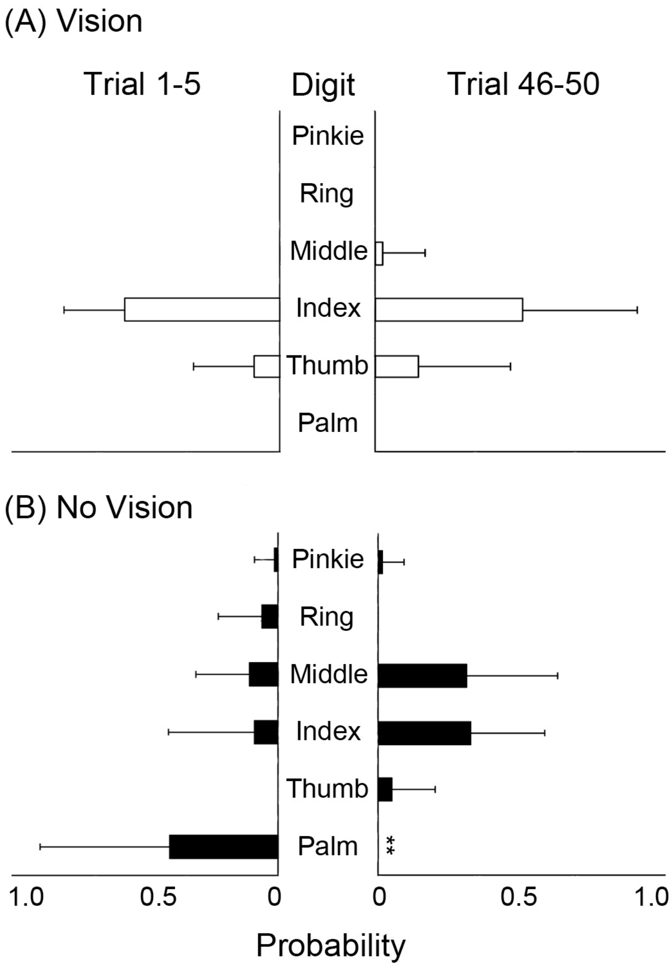


Figure 3.5 The probability (mean ± SE) that the palm or one of the fingers made first contact with the object on the first five and last five trials in the VISION (A) and NO VISION (B) conditions, (**p < 0.01).

These main findings were confirmed by a repeated measures ANOVA that gave significant effects of Digit [F(5,85) = 50.019, $p < 0.001$], Digit X Condition [F(5,85) = 22.936, $p < 0.001$], Trial X Digit [F(45, 765) = 2.140, $p < 0.001$], and Trial X Digit X Condition [F(45,765) = 2.071, $p < 0.001$], but no significant effect of Trial [F(9,153) = 0.895, $p > 0.05$]. Follow-up pairwise comparisons revealed that in the NO VISION condition the proportion of trials on which first contact was establish with the palm significantly decreased between the first five trials and last five trials [t(8) = 2.801, $p < 0.01$].

Digit Scaling: Peak Aperture

Figure 3.6a shows the shaping of the hand at the point of peak digit-thumb aperture during transport to the object on trial 1 and trial 50 in the VISION and NO VISION conditions. In the VISION condition a "grasping" hand shape was present at peak aperture such that the digits and thumb were directed towards opposite sides of the object and the index-thumb aperture appeared slightly larger than the object. This same hand shape was consistently employed from trial 1 through to trial 50. In the NO VISION condition the hand shape used at peak aperture differed from trial 1 through to trial 50. On trial 1 an open and extended hand shape was present at peak aperture. The digits did not align to opposite sides of the target and the digit-thumb aperture did not appear to scale to the size of the target before contact. However, with repeated reaching experience, participants began to oppose the index finger and thumb at peak aperture, which also appeared to scale to the size of the object.

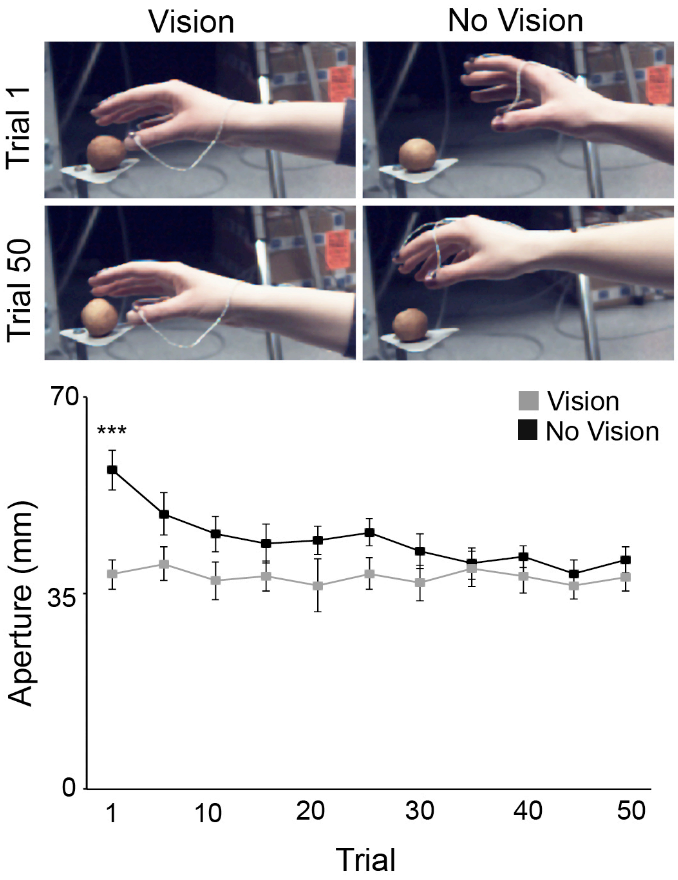


Figure 3.6 Representative still frames of the hand and digits at peak aperture on trial 1 (top) and trial 50 (bottom) in the VISION and NO VISION conditions (A). Size of peak aperture (mean ± SE, mm) on trials 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 in the VISION (grey squares) and NO VISION (black squares) conditions (B). Note: on early trials peak aperture was significantly greater in the NO VISION compared to VISION condition , (***$p < 0.001$). By trial 5 peak aperture did not significantly differ between the two conditions.

Kinematic analysis confirmed the video description. Figure 3.6b shows the size of the peak digit-thumb aperture on every 5th trial in the VISION (grey) and NO VISION (black) conditions. In the earliest trials, peak aperture was significantly larger in the NO VISION compared to the VISION condition. However, with repeated reaching experience and by trial 5, peak aperture in the NO VISION condition decreased and eventually achieved a level of accuracy comparable to that seen in the VISION condition. This accuracy was maintained until the end of the testing session.

These main findings were confirmed by the statistical analysis. For peak aperture there was a significant effect of Condition [$F(1,17) = 3.447$, $p < 0.001$], Trial [$F(10,170) = 4.767$, $p < 0.001$], and Trial X Condition [$F(10,170) = 3.454$, $p < 0.001$]. A retrospective power analysis revealed an effect size of $(f) = 0.451$ and a power > 0.80 for this interaction. Follow-up pairwise comparisons revealed that peak aperture differed significantly between the VISION and NO VISION groups on Trial 1 [$t(17) = 4.247$, $p < 0.001$]. Peak aperture did not significantly differ between the two groups on trials 5 to 50, [$F(1, 17) = 2.122$, $p > 0.05$, effect size $(f) = 0.293$]. Power analysis revealed that in order for an effect of this size to be detected (80% chance) as significant at an alpha of 0.05, a sample of 74 participants would be required. In order for a significant difference to be detected on trial 50 [$t(17) = 0.868$, $p = 0.397$, Cohen’s $d = 0.421$], a sample of 180 participants would be required.

Anticipatory Digit Closure: Aperture at First Contact

Figure 3.7a shows the shaping of the hand at the point of first contact with the object on trial 1 and trial 50 in the VISION and NO VISION conditions. This provides a

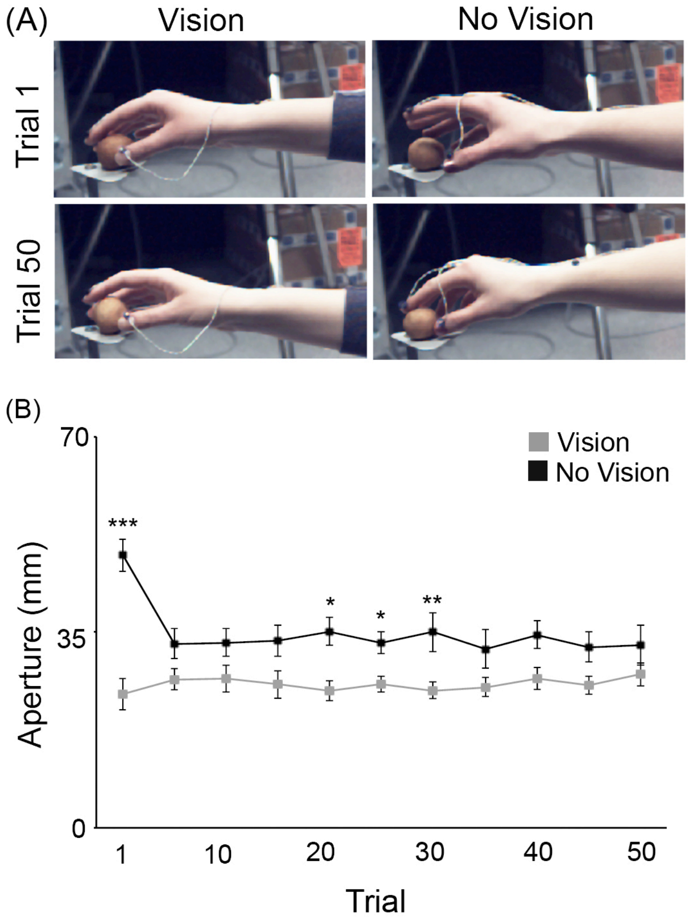


Figure 3.7 Representative still frames of the hand and digits at first contact with the object on trial 1 (top) and trial 50 (bottom) in the VISION and NO VISION conditions (A). Size of digit-thumb aperture (mean ± SE, mm) at first contact with the object on trials 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 in the VISION (grey squares) and NO VISION (black squares) conditions (B), (***$p < 0.001$, **$p < 0.01$, *$p < 0.05$).

measure of the extent of anticipatory closure of the hand on approach to the object. In the VISION condition the hand had almost fully closed by the time of first contact with the object. This was consistent for trial 1 through to trial 50. In the NO VISION condition the extent of anticipatory hand closure differed between trials. On the first trial the hand did not appear to close on approach to the object at all. Thus an open and "exploratory" hand shape was used to establish first contact with the object. By trial 5, however, the hand began to show significant closure upon approach to the target. Nevertheless, the extent of anticipatory hand closure was varied and did not always reach the same level as that observed in the VISION condition.

Kinematic analysis confirmed the video description. Figure 3.7b shows the size of the digit-thumb aperture at first contact on every 5th trial in the VISION (grey) and NO VISION (black) conditions. On the first trial, digit-thumb aperture at first contact was significantly larger in the NO VISION compared to the VISION condition. However, with repeated reaching experience and by trial 5, the aperture of the hand at first contact in the NO VISION condition significantly decreased, although it did not always reach the same level as seen in the VISION condition.

These main findings were confirmed by the statistical analysis. For aperture at first contact there was a significant effect of Condition [$F(1,17) = 11.022$, $p < 0.01$], Trial [$F(10,170) = 3.826$, $p < 0.001$], and Trial X Condition [$F(10,170) = 6.484$, $p < 0.001$]. Follow-up pairwise comparisons revealed that peak aperture differed between the VISION and NO VISION groups on Trial 1 [$t(17) = 6.190$, $p < 0.001$], Trial 20 [$t(17) = 3.498$, $p < 0.05$], Trial 25 [$t(17) = 3.076$, $p < 0.05$], and Trial 30 [$t(17) = 2.876$, $p < 0.001$].

Aperture at Final Grasp

Figure 3.8a shows the shaping of the hand at the point of final grasp with the object on trial 1 and trial 50 in the VISION and NO VISION conditions. In the VISION condition the digits and thumb appeared to grasp the target by applying grasping forces to opposite sides of the target. This was consistent from trial 1 through to trial 50. In the earliest NO VISION trials the digits did not always align to opposing sides of the target, but they did always align in opposition with each other. With repeated reaching experience, participants in the NO VISION condition became more adept at aligning the digits to opposite sides of the target at final grasp.

Kinematic analysis confirmed the video description. Figure 3.8b shows the size of the digit-thumb aperture at final grasp on every 5th trial in the VISION (grey) and NO VISION (black) conditions. Although the alignment of the digits with the target sometimes varied, final grasp aperture did not differ between the VISION and NO VISION conditions on any of the trials. These results confirm that the significant effects found for peak aperture and aperture at first contact were not related to a difference in the digit-thumb aperture used at final grasp.

These main findings were confirmed by the statistical analysis. For aperture at final grasp there was no significant effect of Condition [$F(1,17) = 0.261$, $p > 0.05$], Trial [$F(10,170) = 1.392$, $p > 0.05$], or Trial X Condition [$F(10,170) = 1.411$, $p > 0.05$].

Final Grip Posture

Figure 3.9 shows the probability that participants used a precision grip or power grip to grasp the object in the VISION and NO VISION conditions. Figure 3.9a

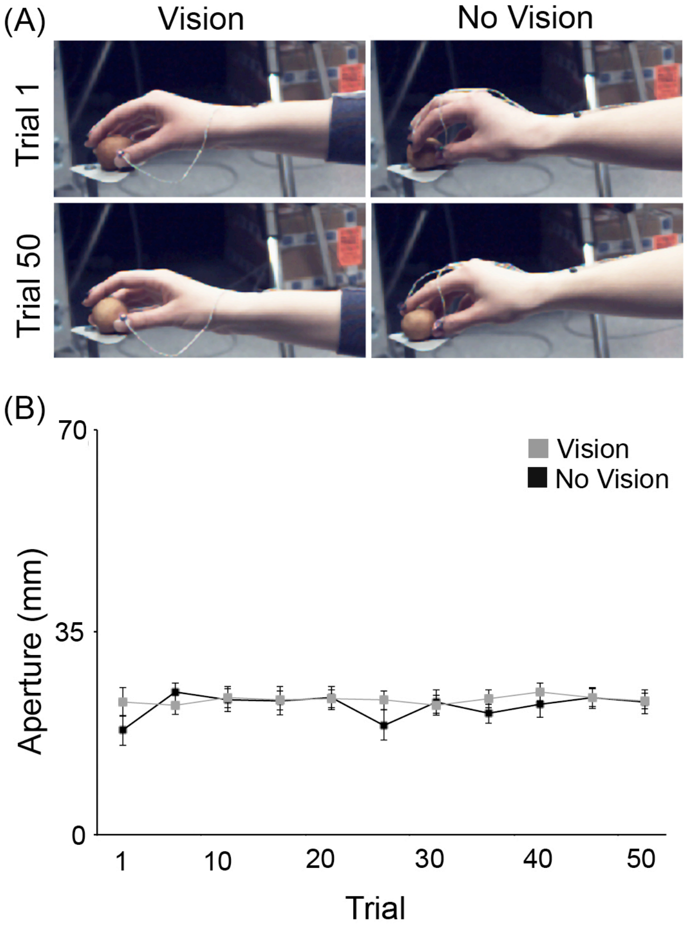


Figure 3.8 Representative still frames of the hand and digits at final grasp of the object on trial 1 (top) and trial 50 (bottom) in the VISION and NO VISION conditions (A). Size of digit-thumb aperture (mean ± SE, mm) at final grasp on trials 1, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 in the VISION (grey squares) and NO VISION (black squares) conditions (B). Note: digit-thumb aperture at final grasp did not significantly differ between the VISION and NO VISION conditions.

shows that in the VISION condition, participants consistently favoured a precision grip for both early and late trials. Figure 3.9b shows that in the NO VISION condition participants utilized a precision grip and a power grip with equal probability on trial 1; however, by trial 50 participants used only a precision grip, much like in the VISION condition.

These main findings were confirmed by the statistical analysis that found significant effects of Grip [$F(1,17) = 75.605$, $p < 0.001$], Condition X Grip [$F(1,17) = 11.184$, $p < 0.001$], Trial X Grip [$F(1,17) = 11.184$, $p < 0.001$], and Condition X Grip X Trial [$F(1,17) = 11.184$, $p < 0.001$]. Follow-up pairwise comparisons revealed that grip used in the NO VISION condition differed significantly from the first five to last five trials; the use of power grip was significantly decreased [$t(8) = 3.162$, $p < 0.05$], whereas the use of a precision grip significantly increased [$t(8) = 3.162$, $p < 0.05$].

Actual Movement Timing

Figure 3.10a shows the temporal organization of peak aperture, first contact, and final grasp as a function of time. In the VISION condition, total movement time (from movement onset to final grasp) was less than 1 second and did not differ between the first five ($M \pm SE = 0.98 \pm 0.04$ s) and last five ($M \pm SE = 0.88 \pm 0.03$ s) trials. In the NO VISION condition, total movement time was significantly longer compared to the VISION trials; however, there was a significant decrease in total movement time between the first five ($M \pm SE = 2.19 \pm 0.20$ s) and the last five ($M \pm SE = 1.38 \pm 0.16$ s) NO VISION trials. This was due to a reduction in the amount of time devoted to transitioning from first contact to final grasp, likely because anticipatory digit scaling was largely

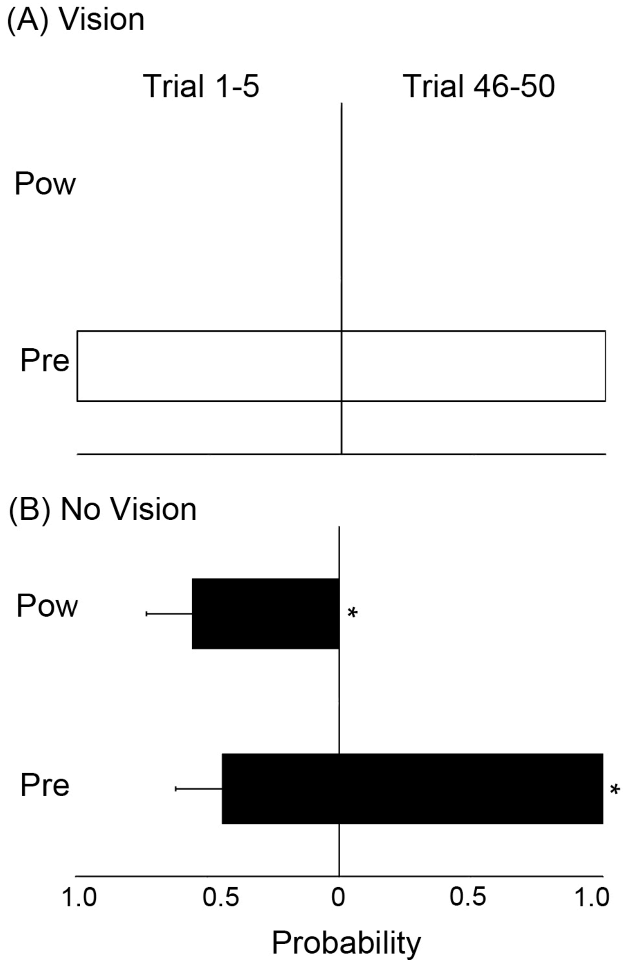


Figure 3.9 The probability that participants used either a power or precision grip (mean ± SE) to grasp the target in the VISION (A) and NO VISION (B) conditions, (*Pow* Power Grip, *Pre* Precision Grip, $*p < 0.05$).

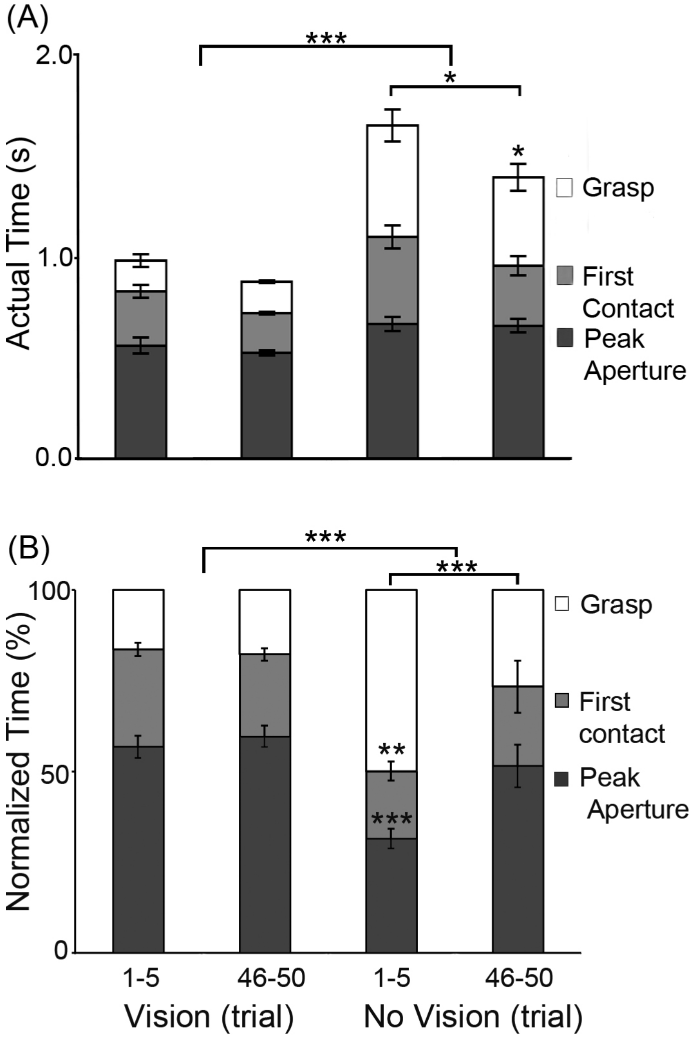


Figure 3.10 The timing of peak aperture (dark grey, mean ± SE), first contact (light grey, mean ± SE), and final grasp (white, mean ± SE) as a function of actual time (s; A) and normalized time (%; B) on the first five and last five trials in the VISION and NO VISION conditions, (*$p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

achieved before contact, rather than after contact, in the later NO VISION trials.

These main findings were confirmed by the statistical analysis. For Peak Aperture there was no significant effect of Condition [$F(1,17) = 3.420, p > 0.05$], Trial [$F(1,17) = 0.710, p > 0.05$], or Trial X Condition [$F(1,17) = 0.248, p > 0.05$]. For First Contact there was a significant effect of Condition [$F(1,17) = 5.781, p < 0.05$] but not Trial [$F(1,17) = 4.364, p > 0.05$] or Trial X Condition [$F(1,17) = 0.077, p > 0.05$]. For Final Grasp there was a significant effect of Condition [$F(1,17) = 35.869, p <0.001$], Trial [$F(1,17) = 42.698, p < 0.001$], and Trial X Condition [$F(1,17) = 8.536, p <0.001$]. Follow-up pairwise comparisons revealed that in the NO VISION condition the time of final grasp [$t(8) = 2.484, p <0.05$] occurred significantly earlier on the last five trials compared to the first five trials.

Normalized Movement Timing

Figure 3.10b shows the temporal organization of peak aperture, first contact, and final grasp as a function of normalized time. In the VISION condition, peak aperture occurred about 57% of the way through the movement and first contact occurred about 84% of the way through the movement. This remained consistent across all fifty reaching trials. In the early NO VISION trials, peak aperture and first contact occurred relatively earlier in the movement, at about 32% and 50% of the way through the movement, respectively. This was because half of all movement time was dedicated to transitioning from first contact to final grasp. With repeated reaching experience the temporal organization of the movement came to reflect that seen in the VISION condition. This was largely due to a reduction in the amount of time required to transition from first contact to final grasp.

These main findings were confirmed by the statistical analysis. For Peak Aperture there was a significant effect of Condition [F(1,17) = 38.528, $p < 0.001$], Trial [F(1,17) = 27.090, $p < 0.001$] and Trial X Condition [F(1,17) = 14.931, $p < 0.001$]. For First Contact there was a significant effect of Condition [F(1,17) = 47.603, $p < 0.001$], Trial [F(1,17) = 20.977, $p < 0.001$], and Trial X Condition [F(1,17) = 26.310, $p < 0.001$]. Follow-up pairwise comparisons revealed that in the NO VISION condition the time of peak aperture [t(8) = 5.227, $p < 0.001$] and the time of first contact [t(8) = 4.712, $p < 0.01$] occurred proportionally earlier on the first five trials compared to the last five trials.

Non-visual Reach and Grasp movements after visual training

To test the robustness of the results presented above, the participants in the VISION group were asked to perform five NO VISION trials after they had completed the VISION task. The Reach trajectory and the peak aperture of the Grasp were examined to determine whether these measures were affected by visual reach training in a manner similar to non-visual training.

Figure 3.11a shows the maximum trajectory height (mean ± SE of all participants). Participants that had visual training but then switched to the non-visual task (VISION-TO-NO VISION) immediately switched to using an elevated Reach trajectory. This was confirmed by the statistical analysis that found a significant effect of Condition [F(2,25) = 12.422, $p < 0.001$], but no significant effect of Trial [F(4,100) = 0.623, $p > 0.05$], or Trial X Condition [F(8, 100) = 0.663, $p > 0.05$]. Follow-up post hoc analyses

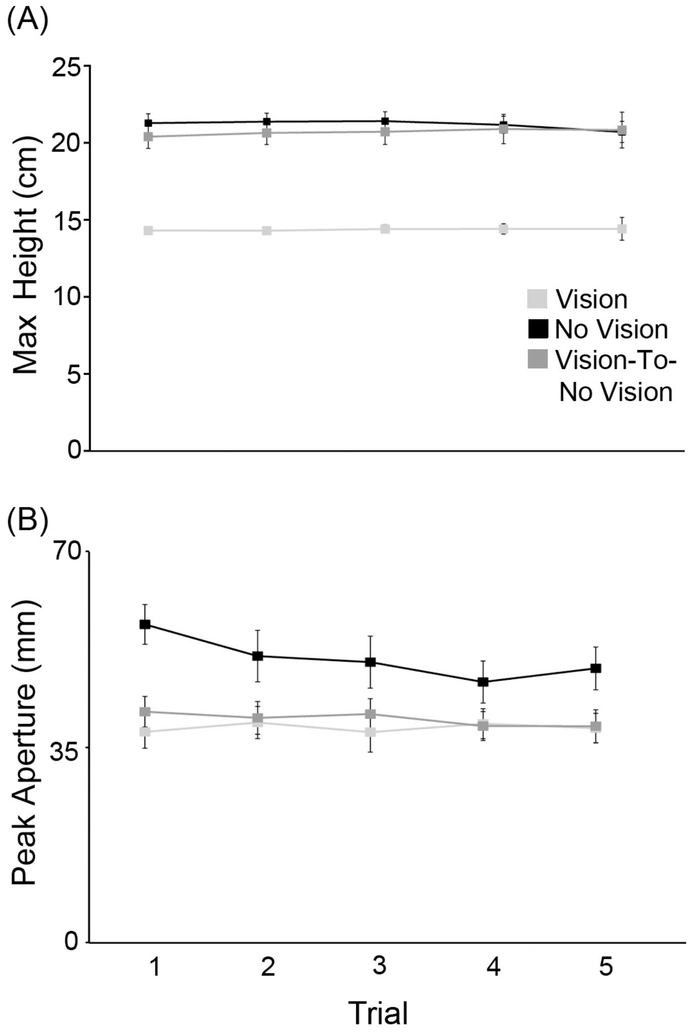


Figure 3.11 The maximum Reach trajectory height (mean ± SE, cm) for the first trials when reaching in the VISION (light grey), NO VISION (black) and VISION-TO-NO VISION conditions (A). Peak aperture (mean ± SE, mm) for the first five trials when reaching in the VISION (light grey), NO VISION (black), and VISION-TO-NO VISION (dark grey) conditions. Note: Reach trajectory was immediately elevated when participants switched from the VISION-TO-NO VISION condition. Peak Aperture, however, did not increase but remained the same when participants switched from the VISION-TO-NO VISION condition.

revealed that maximum trajectory height was significantly lower in the VISION condition compared to the NO VISION condition [$t(17) = 7.144$, $p < 0.001$] and the VISION-TO-NO VISION condition [$t(17) = 3.760$, $p < 0.001$].

Figure 3.11b shows the size of peak aperture (mean ± SE of all participants). Participants that had visual training but then switched to the non-visual task did not switch to using a larger peak aperture, instead they maintained a peak aperture that scaled to the size of the object and did not significantly differ from the VISION condition. This was confirmed by the statistical analysis that found a significant effect of Condition [$F(2,25) = 5.344$, $p < 0.01$] but not Trial [$F(4,100) = 2.016$, $p > 0.05$] or Trial X Condition [$F(8,100) = 1.492$ $p > 0.05$]. Follow-up pairwise comparisons revealed that peak aperture was significantly greater in the NO VISION condition compared to the VISION condition [$t(17) = 2.853$, $p < 0.01$] as well as the VISION-TO-NO VISION condition [$t(17) = 2.499$, $p < 0.05$]. There was no significant difference between the VISION and VISION-TO-NO VISION conditions [$t(17) = 0.433$, $p > 0.05$].

Discussion

The question asked in the present study was: can repeated reaching and grasping of an unseen object result in a memory sufficient for producing accurate Reach and Grasp movements similar to those produced under online vision? Sighted and visually occluded participants repeatedly reached for a round donut ball placed on a pedestal in front of them. The results show that with repeated reaching experience, unsighted participants began to modify the Reach and Grasp movements in different ways. The trajectory of the

Reach was consistently elevated so that the hand established first contact with the dorsal surface of the object. The Grasp, however, was characterized by improved anticipatory scaling of digit opening and closing to object size similar to visually guided Grasps. The results were unexpected in that they show that the Reach and Grasp movements respond differently to previous nonvisual experience. The differential changes in the Reach and Grasp movements shows that nonvisual experience differentially calibrates the Reach and Grasp movements suggesting that they are enabled by at least partially different neural substrates (Jeannerod 1981).

The design of the present experiment featured a number of manipulations that ensured accurate measurement of Reach and Grasp movements. First, the intended use of a target is known to influence Reach and Grasp kinematics (Napier 1956, 1980; Sartori et al. 2011; Valyear et al. 2011). Thus, the target object was an ethologically relevant food item and participants were instructed to pick it up as if they were going to eat it. This ensured that all participants grasped the object with a similar intention and thus used a similar grip. Second, at the onset of the experiment, participants in both conditions were only shown the general location at which the object would be placed and were told only that the object would fit in one hand. Thus, the parameters of the Reach and the Grasp were constrained, but not defined, and would need to be learned through nonvisual reaching experience. Both groups received 50 consecutive trials as previous studies demonstrate that feedback from repeated experience allows reaching calibration (Bingham et al. 2007). Performance was evaluated by measuring behavior from frame-by-frame video analysis of the movement and by linear kinematics.

The Reach movement of visual and nonvisual participants differed in three important ways. First, nonvisual participants used an elevated Reach trajectory in which the hand was raised above the object before being lowered down onto it, similar to pantomime Reach movements to an imaginary object as described by Goodale et al. (1994a). This differed from the visual condition, in which the hand was transported directly towards the object in the horizontal plane. Second, as a result of the hand being lowered onto the object from above, nonvisual participants established contact with the dorsal surface of the object rather than the proximal and distal sides as was done by the visual participants. Third, because first contact was establish with the dorsal surface of the object, nonvisual participants performed a number of adjustments, sometimes by fully releasing contact with the object, in order to redirect the digits to the sides of the object, as has been described in previous work with unsighted participants (Karl et al., 2012a). Despite repeated training, nonvisual Reach movements consistently differed from visual Reach movements on these measures. An aspect of the Reach movement that changed with training was that contact with the dorsal surface of the object became less likely to be made with the palm and more likely to be made with the distal digit pads.

The Grasp movement of visual and nonvisual participants differed considerably during early reaching attempts; however, with practice many aspects of the nonvisual Grasp movement came to resemble that of the visual Grasp movement. First, nonvisual participants did not initially scale the grasping digits to object size during hand transport, but instead used an open and extended hand shape with a large peak digit aperture (Karl et al., 2012a), likely to compensate for potential errors in Reach trajectory (Wing et al., 1986). With repeated reaches, however, nonvisual participants began to scale peak digit aperture to a size appropriate for the target object. Second, on early trials, nonvisual participants did not begin to close the digits for grasping until after establishing first contact with the object; but, in later trials they showed a biphasic grasping pattern before object contact in which the digits first opened to a peak aperture followed by closure of the digits on approach to the object. Third, initially the nonvisual participants often grasped the target using a power grip but with practice they came to use a precision grip exclusively. Fourth, on early nonvisual reaching trials a disproportionate amount of time was dedicated to transitioning from first contact to final grasp but with practice the transition became more rapid. In all of these respects, the Grasp of the nonvisual participants came to resemble the Grasp of the visual participants.

In relation to the question asked in the present study, the results show that offline Reach and Grasp movements can benefit from nonvisual practice/learning but only digit scaling becomes calibrated to resemble online Grasp movements. Furthermore, when the group conditions were reversed, the visual group switched to the nonvisual condition displayed a similar dissociation of the Reach and Grasp from the first trial, indicating that previous visual experience also benefited subsequent unsighted Grasp movements. These results are in accord with previous work that shows that digit scaling and peak digit aperture can be calibrated with nonvisual feedback to resemble online visually guided Grasp movements (Bingham et al. 2007; Gentilucci et al. 1995; Opitz et al. 1996; Safstrom and Edin 2004, 2008). It is interesting that the nonvisual Reaches in the present study resemble the pantomime Reaches made to an imaginary object as described by Goodale et al. (1994a). The nonvisual Grasps, however, more closely resemble online Grasps than pantomime Grasps (Goodale et al., 1994a). Thus, the task constraint of actually acquiring a physical object is likely necessary to elicit the dissociation between the Reach and Grasp movements observed in the present study. Considered together, the results of the present study show that previous nonvisual experience can result in offline Grasp, but not Reach movements, that resemble those of online visually guided reaching.

The conclusions derived from this finding should be tempered in relation to a number of caveats, however. The target was not fixed and was at risk for being knocked from the pedestal, there were slight variations in the size and placement of the object from trial to trial, and the participants were not given specific instructions about how they should grip the object. Were modifications made with respect to these procedural aspects of the study, such as fixing the object on a larger platform, stabilizing the participant's sitting position, and placing the hand on a more stable initial support and not on the lap, it is possible that both nonvisual Reach and Grasp movements might come to resemble visual Reach and Grasp movements (see Cavina-Pratesi et al., 2010a). Nevertheless, the present task provided more immediate feedback relevant for reach calibration than have studies in which actual reaching and virtual reaching were alternated (Bingham et al. 2007; Gentilucci et al. 1995; Opitz et al. 1996; Safstrom and Edin 2004, 2008). Therefore, the unexpected finding that the Reach and Grasp movements of visually occluded participants were modified in different ways in relation to the movements of sighted participants appears robust and is relevant to the question of dual channel control of the reaching movement.

The theory that Reach and Grasp movements are enabled by separate neural channels is supported by studies of brain injury (Binkofski et al. 1998; Cavina-Pratesi et al. 2010a; Jeannerod et al., 1994; Shallice et al., 2005), brain imaging (Cavina-Pratesi et al. 2010b), anatomy (Gharbawie et al., 2011; Rizzolatti and Matelli 2003; Tanne-Gariepy et al. 2002), and electrophysiology (Fattori et al. 2005; Kaas et al. 2011; Sakata et al. 1995; Snyder et al. 1997). Definitive support has not come from behavioral analysis, however, as Jakobson and Goodale (1991) as well as others (see Schmidt and Lee 2011 for a review), have reported that when the extrinsic and intrinsic properties of a target are manipulated independently, e.g., by changing only the location of the object or only the size of the object, both the Reach and Grasp change. Thus, the present finding that unsighted participants can scale digit opening and closing to object size, despite a dorsal approach to the object and an inability to direct the digits to appropriate contact locations on the object, provides serendipitous behavioural support for the dual channel theory.

That Reach and Grasp movements can be dissociated by nonvisual experience raises the interesting question of whether the Reach is more dependent on online control than the Grasp. There are differing opinions concerning whether the appropriate placement of the digits in relation to the object should be considered a function of the Reach or the Grasp or indeed whether this is the single salient aspect of reaching (Smeets and Brenner 1999). The present results favour the view that digit placement is the terminal function of the Reach and, as is shown by the present results, can be uncoupled from digit scaling. That the Reach is constrained by task configuration in a way not similarly imposed upon the Grasp could be further examined in future studies. For example, variations in target size, in a between groups design, would be expected to be associated with similar Reach movements as measured by approach direction and contact location, but by changing Grasp movements as measured by digit scaling.

In conclusion, the DVC theory of reaching (Jeannerod, 1981) was intended to explain the visual control of reaching, but modifications of the theory can also explain nonvisually guided reaching. The present results suggest that both Reach and Grasp movements can be performed offline but the differential extent to which they resemble online movements provides behavioural support for the DVC theory and the second hypothesis of this thesis. This conclusion favours the view that hand movements related to extrinsic object properties may be more efficient when produced by online control whereas hand movements related to intrinsic object properties may be more flexible. Indeed, anatomical evidence from non-human primates suggests that the dorsomedial Reach channel may be preferentially connected to visual cortex (Gharbawie et al. 2011a), whereas the dorsolateral Grasp channel receives significant non-visual inputs from somatosensory cortex (Gharbawie et al., 2011a) and inferotemporal cortex (Borra et al. 2008). Perhaps these differences stem from the evolutionary history of the movements, in which the Reach may have evolved from forelimb stepping movements (Georgopoulos and Grillner 1989) whereas the Grasp may have evolved from hand use for food handling, in which non-visual information is used to grasp an object in the mouth (Karl et al. 2012b; Whishaw 2003).

Chapter 4

Oral hapsis guides accurate hand preshaping for grasping food targets in the mouth

Abstract

Preshaping the digits and orienting the hand when reaching to grasp a distal target is proposed to be optimal when guided by vision. A reach-to-grasp movement to an object in one's own mouth is a natural and commonly used movement but there has been no previous description of how it is performed. The movement requires accuracy, but likely depends upon haptic rather than visual guidance, leading to the question of whether the kinematics of this movement are similar to those with vision or whether the movement depends upon an alternate strategy. The present study used frame-by-frame video analysis and linear kinematics to analyze hand movements as participants reached for ethologically relevant food targets placed either at a distal location or in the mouth. When reaching for small and medium sized food items (blueberries and donut balls) that had maximal lip-to-target contact, hand preshaping was equivalent to that used for visually-guided reaching. When reaching for a large food item (orange slice) that extended beyond the edges of the mouth hand preshaping was suboptimal compared to vision. Nevertheless, hapsis from the reaching hand was used to reshape and reorient the hand after first contact with the large target. The equally precise guidance of hand preshaping under oral hapsis is discussed in relation to the idea that hand preshaping, and its requisite neural circuitry, may have originated under somatosensory control, with secondary access by vision.

Introduction

The hand preshaping component of the reach-to-grasp movement is proposed to have evolved under visual control in the primate lineage by animals climbing and reaching for food in an arboreal habitat (Cartmill, 1974; Napier, 1980). In visually-guided hand preshaping, the grasping digits form a peak aperture prior to contact with the target, the digits orient and scale to the intrinsic features of the target, and a successful grasp is almost always achieved on the first attempt (Goodale et al. 1994, 2004; Goodale and Milner 1992; Hu et al. 1999; Jakobson and Goodale 1991; Jeannerod 1981,1986; Jeannerod et al., 1998; Mamassian, 1997; Wing et al., 1986). Thus, other forms of grasping, including haptically-guided grasping which occurs after the hand makes first contact with an unseen target (Edwards et al., 2005; Karl et al., 2012; Pettypiece et al. 2009; Pettypiece et al. 2010) and grasping guided by memory (Berthier et al. 1996; Castiello et al. 1993; Fiehler et al. 2011; Goodale et al., 2004; Hu et al. 1999; Jakobson and Goodale 1991; Wing et al., 1986), are proposed, in part, to capitalize on visually-dependent neural substrates. Nevertheless, one reason that vision may appear to play a superior role in hand preshaping is that the reach-to-grasp movement has been studied mainly from the perspective of its central role in visually-guided reaching.

A commonly performed reaching act is to grasp and manipulate or remove a food item from one’s own mouth. This is a natural behavior that is displayed by animal species in a number of mammalian orders (Iwaniuk and Whishaw, 2000) and is likely guided by oral hapsis. Nevertheless, it is not known whether this form of reaching is as accurate as visually-guided reaching with respect to hand preshaping. There are three possibilities.

First, Pettypiece et al. (2010) find that hand preshaping to a target held in the opposite hand is less accurate than visually-guided hand preshaping, suggesting that haptic guidance is not as useful as visual information. Second, Edwards et al. (2009) find that hand preshaping to objects held against the face is as accurate as that of vision, suggesting that the head centered location of the haptic target improves accuracy. Third, Edwards et al. (2005) report that subjects reaching for their own face-parts show hand preshaping that is more accurate than that of visually-guided reaching, suggesting a role for familiarity in guidance. Given that the lips have a higher 2-point discriminative ability than the hand (van Boven et al., 1994), and given that an object in the mouth is head-centered, it could be predicted that hand preshaping to targets in the mouth might also be more accurate than hand preshaping to a visual target. Because targets of different size provide varying degrees of oral feedback, subjects may use multiple haptically-guided grasping strategies, including a touch and release strategy (Karl et al, 2012). Thus, the purpose of the present experiment was to compare hand preshaping for objects held in the mouth compared to the same objects identified by vision.

Participants reached for small and medium-sized food items (blueberries and donut balls), which achieved optimal contact with the lips and thus provided unambiguous oral feedback about the target's size and shape. Participants also reached for large food items (orange slices) that extended beyond the lateral edges of the mouth, and thus provided ambiguous oral feedback about the target's size and shape. Young adult participants reached for the food items, which were placed either in their mouth or on a pedestal placed in front of them, under both vision and no vision conditions. Hand preshaping, as indicated by index-thumb aperture, was measured using infrared emitting diodes (IREDs) placed on the digits of interest and recorded using a motion capture system. Offline, frame-by-frame video analysis and linear kinematics were then used to measure and compare hand preshaping in all conditions.

Materials and Methods

Participants

Participants were 36 young adults (18 females, 18 males: M ± SD age = 20.14 ± 1.91 years) recruited from the University of Lethbridge. All participants provided informed consent and were self-reported to be right-handed and of good health with no history of neurological or motor disorders. All participants had normal or corrected-to-normal vision. The University of Lethbridge Human Subject Research Committee approved the study.

Experimental Design

Frame-by-frame video analysis and linear kinematics were used to measure hand preshaping as participants reached for and grasped ethologically relevant food targets located either on a distal pedestal or in the participant’s own mouth. Food targets varied in size and consisted of orange slices (large), donut balls (medium), and blueberries (small). A between-subjects experimental design was employed for the present study both to simplify the demands placed on each subject as well as to reduce task expectations with respect to the objectives of the study.

Vision Condition. Hand preshaping was examined as participants reached with vision. Participants were divided into two groups. One group (6 male, 6 female) reached for food targets located on a distal pedestal. Another group (6 male, 6 female) reached for food targets located in the mouth.

No Vision Condition. Hand preshaping was examined as participants reached without vision. Participants were again divided into two groups. The same group of participants (6 male, 6 female) that reached with vision to food targets on a distal pedestal also reached without vision to food targets on a distal pedestal. Another group (6 male, 6 female) reached without vision for food targets located in the mouth. Visual occlusion was achieved using PLATO vision occluding goggles (Translucent Technologies, Toronto, ON) worn on the participant's face.

Reaching Task

Participants were seated in a comfortable upright position. A self-standing, height-adjustable pedestal was placed directly in front of the participant at a horizontal reach distance normalized to the participant's arm length (100% of length from shoulder to tip of index finger with elbow at 180° extension) and a vertical height normalized to the participant's trunk height (100% of height from floor to outstretched arm while seated and with shoulder at 90° flexion) (de Bruin et al., 2008; Whishaw et al., 2002).

Procedures

Vision Condition. Figure 4.1A shows a participant reaching to a target on a distal pedestal with vision. It is known that restriction of a person's field of view can influence the kinematics of the reach-to-grasp movement when directed towards a distal target (Gonzalez-Alvarez et al., 2007; Sivak and MacKenzie, 1990; Watt et al., 2000). Because the occlusion goggles limited the participant's field of view, even when open, the participant did not wear occlusion goggles in the vision condition. At the beginning of each trial, the participant placed the right hand in the "start position", with the right index finger and thumb pressed together and resting on the anterior aspect of the right knee (Jakobson and Goodale, 1991; Pettypiece et al., 2010). A single food item was placed on the pedestal. The participant initiated reaching after a verbal "one, two, three, GO" command. The participant reached for the food item with the right hand, grasped it, and brought it to the mouth (as if to eat it) before handing it to the experimenter (Castiello, 1997; de Bruin et al., 2008; Ferri et al., 2010; Gentilucci 2001; Whishaw et al., 1992b). Although this movement was two-part (transport of the hand to the target followed by withdrawal of the hand and target to the mouth), only the transport phase of the movement (from movement onset to final grasp) was subjected to behavioural and kinematic analyses. At the completion of each trial, the participant returned the right hand to the "start" position in preparation for the next trial. The three possible food items were presented in random order with six repetitions of each for a total of 18 trials. Kinematic data from one male participant were unusable and excluded from this analysis.

Figure 4.1B shows a participant reaching to a target in the mouth with vision. The participant did not wear occlusion goggles. At the beginning of each trial, the participant placed the right hand in the "start position". A single food item was placed in the participant's mouth. The participant initiated reaching after a verbal "one, two, three, GO" command. The participant reached for the food item with the right hand, grasped it,

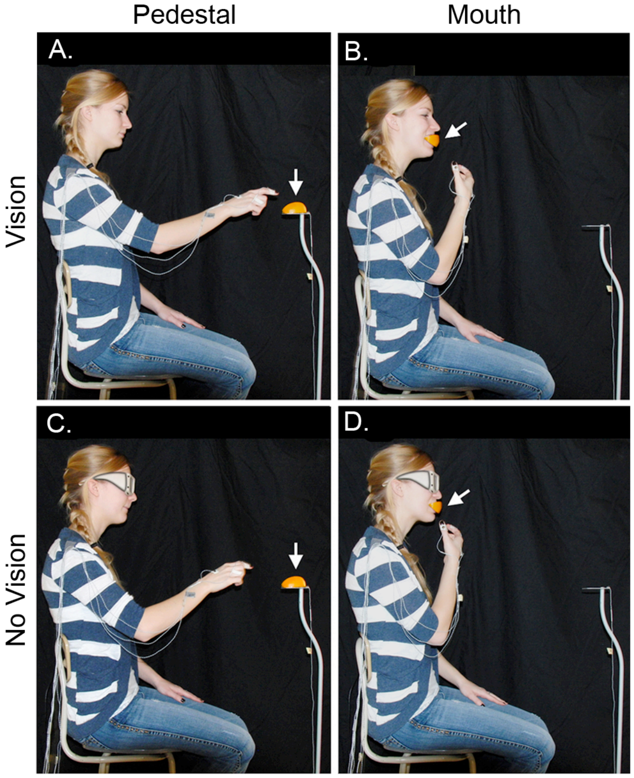


Figure 4.1 The reach-to-grasp task. In the Vision condition (top) participants reached to a target located either on a distal pedestal (A) or in the mouth (B). In the No Vision condition (bottom) participants reached to a target located either on a distal pedestal (C) or in the mouth (D). White arrows indicate the location of the food target at the beginning of each trial. Note: In the No Vision condition participants wore visual occlusion goggles.

and removed it from the mouth before handing it to the experimenter. Again, only the transport phase of the movement (from movement onset to final grasp) was subjected to behavioural and kinematic analyses. At the completion of each trial, the participant returned the right hand to the “start position” in preparation for the next trial. The three possible food items were presented in random order with six repetitions of each for a total of 18 trials. Kinematic data from one male participant were unusable and excluded from this analysis.

No Vision Condition. Figure 4.1C shows a participant reaching to a target on a distal pedestal without vision. The task was the same as in the Vision condition, except that the participant wore occlusion goggles prior to, and throughout, the entire task. Due to randomization of the target object, participants did not know which particular food item they were reaching for on any given trial (Karl et al., 2012).

Figure 4.1D shows a participant reaching to a target in the mouth without vision. The task was the same as in the Vision condition, except that the participant wore occlusion goggles prior to, and throughout, the entire task. Kinematic data from two female participants were unusable and excluded from this analysis.

Reaching Targets

Standardization of Target Size. Orange slices, small round donut balls, and blueberries were used as ethologically relevant reaching targets. Because these targets were placed in the participants’ mouths, different orange slices, donuts, and blueberries were used for each participant. To ensure consistency between target size across all participants, a subset of orange slices (n = 12), donuts (n = 12), and blueberries (n = 12) were measured across their longest axis to determine the average size of each target. The average size and standard error for each target was as follows: Orange slice, 60.53 ± 0.83mm; Donut, 28.82 ± 1.67mm; Blueberry, 12.41 ± 0.33mm. Potential targets outside these standard size ranges were not used in the study.

Oral Target Placement. Figure 4.2 summarizes the positioning of an orange slice, a donut ball, and a blueberry in the mouth. Figure 4.2A shows the placement of an orange slice in the mouth. The lateral tips of the orange slice extended slightly beyond the lateral edges of the lips and the peel of the orange protruded beyond the mouth in the anterior direction. This positioning resulted in ambiguous oral haptic feedback concerning the most distal edges of the orange slice.

Figure 4.2B shows the placement of a donut ball in the mouth. No part of the donut ball extended beyond the lateral edges of the lips. The anterior portion of the donut ball did, however, protrude beyond the lips in the anterior direction. Maximum mouth-to-target contact was achieved between the lips and the circumference of the donut ball. This positioning likely maximized oral haptic feedback concerning target size, without exceeding the sensory range of the lips and mouth.

Figure 4.2C shows the placement of a blueberry in the mouth. No part of the blueberry extended beyond the lateral edges of the lips. Due to the relatively small size of the blueberry, however, only a very small portion of the blueberry protruded beyond the lips in the anterior direction. This positioning likely maximized oral haptic feedback concerning target size. The proximity of the blueberry to the lips, however, may have introduced a physical challenge for the digits when trying to grasp the blueberry.

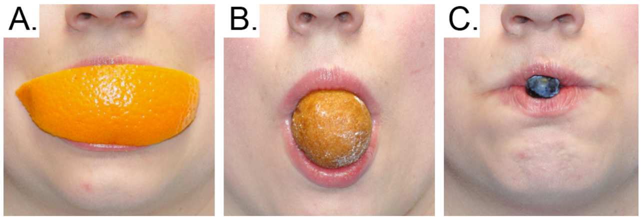


Figure 4.2 Representative photos of the positioning of (A) an orange slice, (B) a donut ball, and (C) a blueberry in the mouth. Note: the lateral tips of the orange slice extend slightly beyond the lateral edges of the lips and the blueberry recedes slightly into the mouth.

Behavioural Data Collection

A digital video camera was positioned sagittal to the participant to record a reach-side view of the participant from lower leg to head at 30 frames/sec and 1/1000 shutter speed. A second digital camera was positioned either dorsolateral to the pedestal, so as to record the shape of the hand as it approached the target on the pedestal, or ventrolateral to the participant's mouth, so as to record the shape of the hand as it approached the food target in the mouth. Representative still frames were captured from digital video recordings with the video editing software Final Cut Pro (http://www.apple.com). Pictures were cropped and adjusted for color and brightness contrast in Adobe Photoshop (V. 11.0) but were not altered in any other way.

Behavioural Data Analysis

A number of behavioural measures were scored by performing off-line, frame-by-frame analysis of the video record. *Total Movement Times* were determined by counting the number of frames from movement onset to final grasp. *Digit Shaping*, as indicated by changes in index-thumb aperture in the kinematic profiles, was verified by reviewing handshaping transitions on the video record during hand transport towards the target. *Grasping Errors* to targets in the mouth were characterized by reviewing hand shaping adjustments both before target contact and after target contact on the video record. An underestimation error was characterized by the use of a smaller than necessary hand aperture at first target contact. An overestimation error was characterized by the use of a larger than necessary hand aperture at first target contact. *Final Grip* was determined by reviewing the video record and documenting whether the target was grasped with a pincer grip or precision grip. The pincer grip features gripping of the target between the thumb and one other digit of the same hand. The precision grip features gripping of the target using the thumb and two or more digits of the same hand.

Kinematic Data Collection

Kinematics from the right hand were recorded using an Optotrak Certus Motion Capture System and NDI Dataview and NDI First Principles software (Northern Digital Inc.; Jakobson & Goodale, 1991). Infrared emitting diodes (IREDs) were positioned on the thumb, index finger, dorsum of the hand, and the top of the pedestal. For each trial, IRED coordinates were sampled at 200Hz for 4 seconds following the verbal cue to initiate reaching.

Kinematic Data Analysis

Figure 4.3 illustrates the kinematic measures used to define hand preshaping. Aperture (mm) was calculated as the three-dimensional resultant between the thumb and index finger IREDs. The change in Aperture (y axis) was plotted against Time (x axis), and is represented by the curved line. *Peak Aperture* is defined as the maximum aperture obtained between movement onset and first contact with the target. *Grasp Aperture* is defined as the final aperture obtained during actual grasping (and holding) of the target object. *Over Grasp* is defined as the difference between peak aperture and grasp aperture and is used as a measure of hand preshaping accuracy, such that a smaller over grasp indicates more accurate preshaping of the hand. To control for variability in IRED positioning, the baseline aperture at the initial “start position,” was subtracted from all

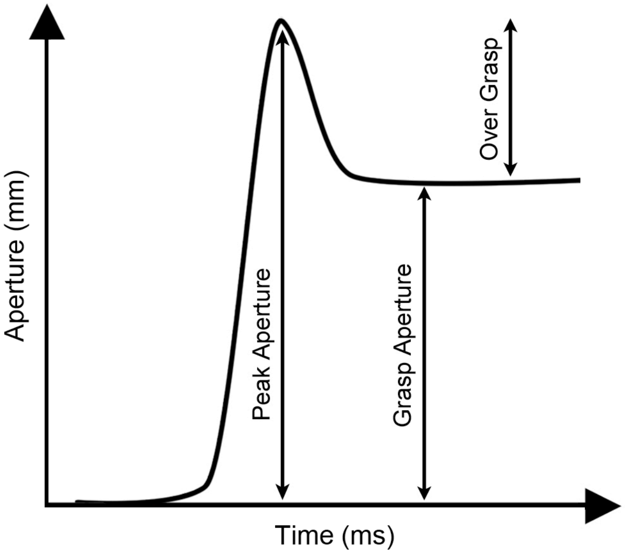


Figure 4.3 Three measures of hand aperture (mm) over time (ms). The curved line indicates the changing distance between the index finger and the thumb as the hand approaches the food target. Peak Aperture: the maximal index-thumb aperture that occurs prior to contact with the food target. Grasp Aperture: the constant index-thumb aperture that occurs when the participant grasps, and holds, the food target. Over Grasp: the difference between the Peak Aperture and the Grasp Aperture.

subsequent aperture measures for each participant.

For relative comparisons of aperture change throughout the reach-to-grasp task, reaching trials were trimmed from a fixed start (movement onset) to a fixed finish (final grasp) using visual inspection of the aperture displacement signal and confirmed with video analysis. Trimmed aperture signals were downsampled to 101 frames using the ‘rubberband’ function in Matlab (Mathworks Inc.). Average change in aperture (y axis) was then plotted against normalized time (x axis).

Statistical Analysis

Results were subject to analysis of variance (ANOVA) using the computer program SPSS (v. 19.0.0). Sex (MALE vs. FEMALE), Feedback (VISION vs. NO VISION), and Location (PEDESTAL vs. MOUTH) served as between-subjects factors. Target (ORANGE, DONUT, and BLUEBERRY), Trial (1, 2, 3, 4, 5, and 6), Grasping Error (UNDERESTIMATION, OVERESTIMATION), and Grip (PINCER vs. PRECISION) served as within-subjects factors. A p-value of less than 0.05 was considered significant. Follow-up post hoc comparisons were subject to bonferroni correction.

Results

Vision Condition

When reaching with vision, hand preshaping scaled to target size regardless of whether the target was located on a distal pedestal or in the participant’s own mouth.

Although both types of reaching were accurate, hand preshaping appeared to be most accurate when reaching to large and medium-sized food targets in the mouth compared to the same targets on a distal pedestal. This suggests that hand preshaping to targets in one's own mouth is similar to, and at least as accurate as, hand preshaping to distal targets using vision. This general conclusion is supported by the following detailed descriptions. Because sex was found to have no significant effect on Peak Aperture [$F(1,18) = 0.125$, $p > 0.05$)], Grasp Aperture [$F(1,18) = 1.733$, $p > 0.05$], or Over Grasp [$F(1,18) = 0.473$, $p > 0.05$)] data from male and female participants were combined.

Reaching to a target on a distal pedestal with vision. Figure 4.4 summarizes the results of hand preshaping when reaching with vision for three different sized food items located on a distal pedestal. When reaching with vision, participants preshaped the hand according to target size prior to grasping (Figure 4.4A). When reaching for an orange slice (left), the index-thumb aperture was large, digits 2 through 5 were almost fully extended, and the thumb was fully extended. When reaching for a donut ball (middle), the index-thumb aperture was an intermediate size and all digits were partly flexed. When reaching for a blueberry (right), the index-thumb aperture was small and the digits were semi-flexed in a pre-pincer grasp position.

Kinematic analysis of index-thumb aperture confirmed the video description. Figure 4.4B shows index-thumb aperture profiles (mean ± standard error of all participants and all trials) when reaching to targets of varying size with vision.

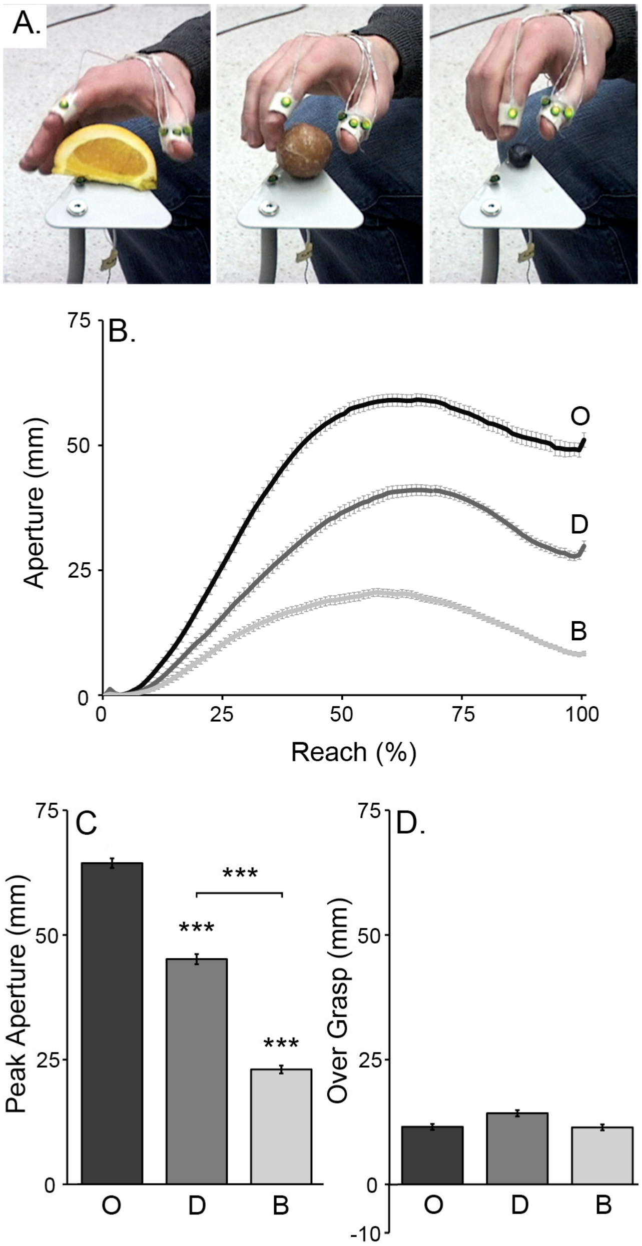


Figure 4.4 Reaching with vision to targets located on a distal pedestal. (A) Representative photos of the hand shape used to grasp an orange slice, donut ball, and blueberry. (B) Kinematic profiles (mean ± standard error) of the index-thumb aperture when reaching for an orange slice, donut ball, and blueberry. (C) Peak Aperture (mean ± standard error) and (D) Over Grasp (mean ± standard error) when reaching for different sized food items. Note: Hand shape and Peak Aperture scaled to food target size, but Over Grasp did not, (O, Orange slice; D, Donut ball; B, Blueberry, ***$p < 0.001$).

When reaching with vision, peak aperture scaled to object size such that it was largest when reaching for an orange, intermediate when reaching for a donut ball, and smallest when reaching for a blueberry (Figure 4.4C). Over grasp did not appear to scale to target size, although it did tend to be slightly larger when reaching for a donut ball (Figure 4.4D).

These main findings were confirmed by statistical analyses. For Peak Aperture, there was a significant effect of Target [$F(2,20) = 508.218$, $P < 0.001$]. For Over Grasp, there was also a significant effect of Target [$F(2,20) = 3.764$, $p < 0.05$]; however, Bonferroni correction of follow-up pairwise comparisons found no significant differences between targets.

Reaching to a target in the mouth with vision. Figure 4.5 summarizes the results of hand preshaping when reaching with vision for three different sized food items located in the mouth. When reaching with vision, participants accurately preshaped the hand according to target size (Figure 4.5A). When reaching for an orange slice (left), the distance between the index finger and thumb was relatively large, digits 2 through 5 were almost fully extended, and the thumb was fully extended. When reaching towards a donut ball (middle), the distance between the index finger and thumb was intermediate and the digits were partly flexed. When reaching for a blueberry (right), the distance between the index finger and thumb was small and the digits were semi-flexed in a pre-pincer grasp position.

Kinematic analysis of index-thumb aperture confirmed the video description. Figure 4.5B shows index-thumb aperture profiles (mean ± standard error of all participants and all trials) when reaching to targets of varying size with vision.

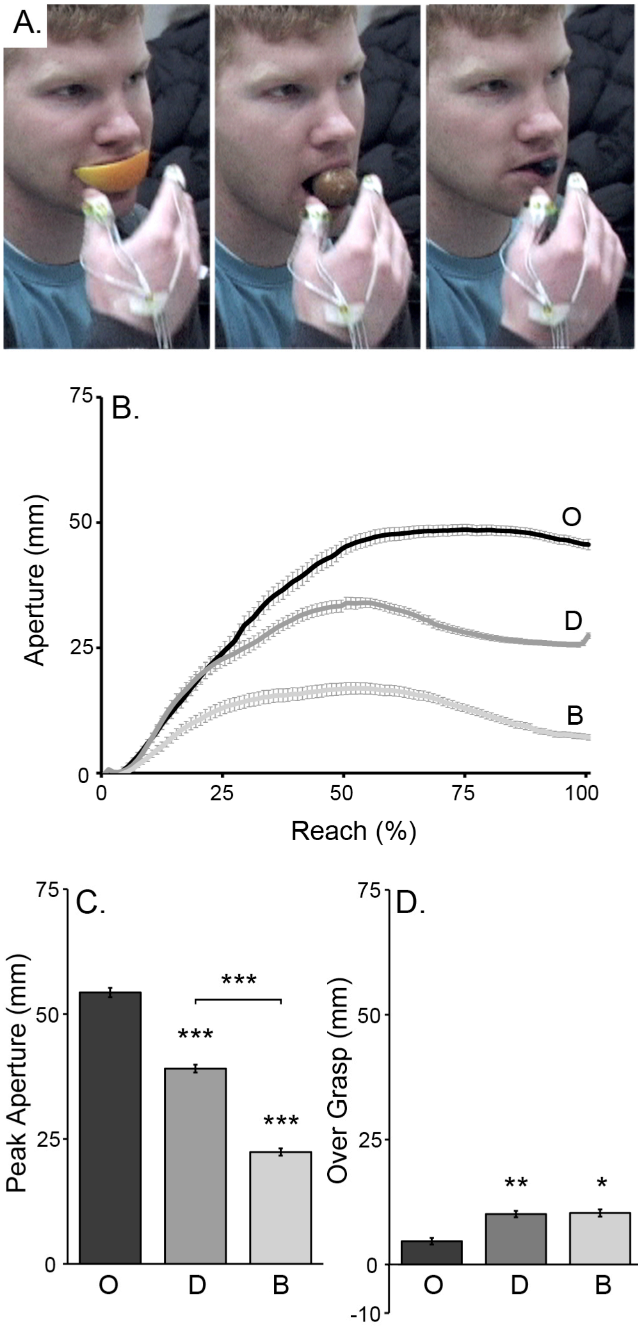


Figure 4.5 Reaching with vision to targets located in the mouth. (A) Representative photos of the hand shape used to grasp an orange slice, donut ball, and blueberry. (B) Kinematic profile of the index-thumb aperture (mean ± standard error) when reaching for an orange slice, donut ball, and blueberry. (C) Peak Aperture (mean ± standard error) and (D) Over Grasp (mean ± standard error) when reaching for different sized food items. Note: Hand shape and Peak Aperture scaled to food target size, but Over Grasp did not, (O, Orange slice; D, Donut ball; B, Blueberry, ***p < 0.001).

When reaching with vision, peak aperture scaled to target size such that it was largest when reaching for an orange slice, intermediate when reaching for a donut ball, and smallest when reaching for a blueberry (Figure 4.5C). Over grasp was smaller when reaching for an orange slice compared to reaching for a donut ball or a blueberry (Figure 4.5D).

These main findings were confirmed by statistical analyses. For Peak Aperture, there was a significant effect of Target [$F(2,20) = 289.494$, $P < 0.001$], and for Over Grasp, there was also a significant effect of Target [$F(2,20) = 16.478$, $p < 0.001$].

Effect of target location on hand preshaping accuracy with vision. Figure 4.6 summarizes the accuracy of hand preshaping, as measured by peak aperture and over grasp, when reaching with vision for food targets located on a distal pedestal or in the mouth. Figure 4.6A shows peak aperture (mean ± stand error of all participants and all trials) when reaching for orange slices, donut balls, and blueberries located either on a distal pedestal (black) or in the mouth (grey). Peak aperture was significantly smaller when reaching for orange slices and donut balls located in the mouth as compared to on a distal pedestal. Figure 4.6B shows over grasp (mean ± stand error of all participants and all trials) when reaching for orange slices, donut balls, or blueberries located either on a distal pedestal (black) or in the mouth (grey). Again, over grasp was significantly smaller when reaching for orange slices and donut balls located in the mouth as compared to on a distal pedestal.

These main findings were confirmed by statistical analyses. For Peak Aperture, there was a significant effect of Location [$F(1,20) = 4.653$, $p < 0.05$] and

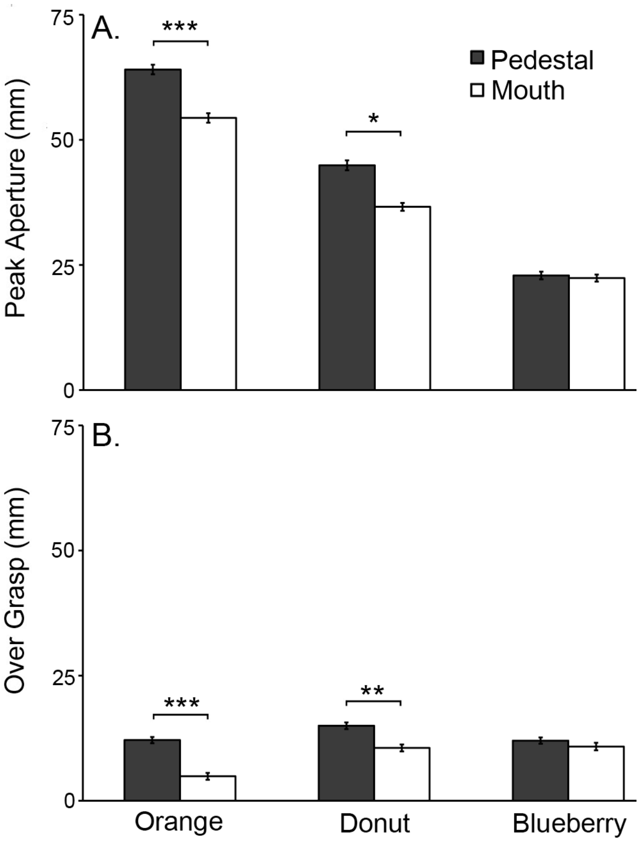


Figure 4.6 Peak Aperture and Over Grasp when reaching with vision to targets located on a distal pedestal or in the mouth. (A) Peak Aperture (mean ± standard error) when reaching for orange slices, donut balls, and blueberries located on a distal pedestal (black) or in the mouth (white). (B) Over Grasp (mean ± standard error) when reaching for orange slices, donut balls, and blueberries located on a distal pedestal (black) or in the mouth (white). Note: Peak Aperture and Over Grasp were significantly smaller when reaching to orange slices and donut balls located in the mouth as compared to the same targets located on a distal pedestal, (***$p < 0.001$, **$p < 0.001$, *$p < 0.05$).

Target X Location [$F(2,40) = 12.305, p < 0.001$]. For Over Grasp, there was a significant effect of Location [$F(1,20) = 6.319, p < 0.05$] and Target X Location [$F(2,40) = 6.365, p < 0.01$].

No Vision Condition

When reaching without vision, hand preshaping scaled to target size if the target was located in the mouth, but not if it was on a distal pedestal. This supports previous findings that online visual information is necessary for accurate hand preshaping to a distal target (Jakobson and Goodale, 1991; Karl et al., 2012). Conversely, hand preshaping remained accurate when reaching to targets in the mouth, despite the loss of vision. This suggests that oral hapsis is sufficient for the guidance of accurate hand preshaping to targets in the mouth. This general conclusion is supported by the following detailed descriptions. Sex was found to have no significant effect on Peak Aperture [$F(1,18) = 0.827, p > 0.05$)], Grasp Aperture [$F(1,18) = 0.387, p > 0.05$], or Over Grasp [$F(1,18) = 1.380, p > 0.05$)]. For this reason, data from male and female participants were combined.

Reaching to a target on a distal pedestal without vision. Figure 4.7 shows the results of hand preshaping when reaching without vision for different sized food items. When reaching without vision, participants did not systematically preshape the hand according to target size during transport (Figure 4.7A). Instead, a similar handshape was used to reach for orange slices (left), donut balls (middle), and blueberries (right). To make this handshape, digits 2 through 5 were almost fully extended and the thumb was fully extended (Karl et al., 2012a).

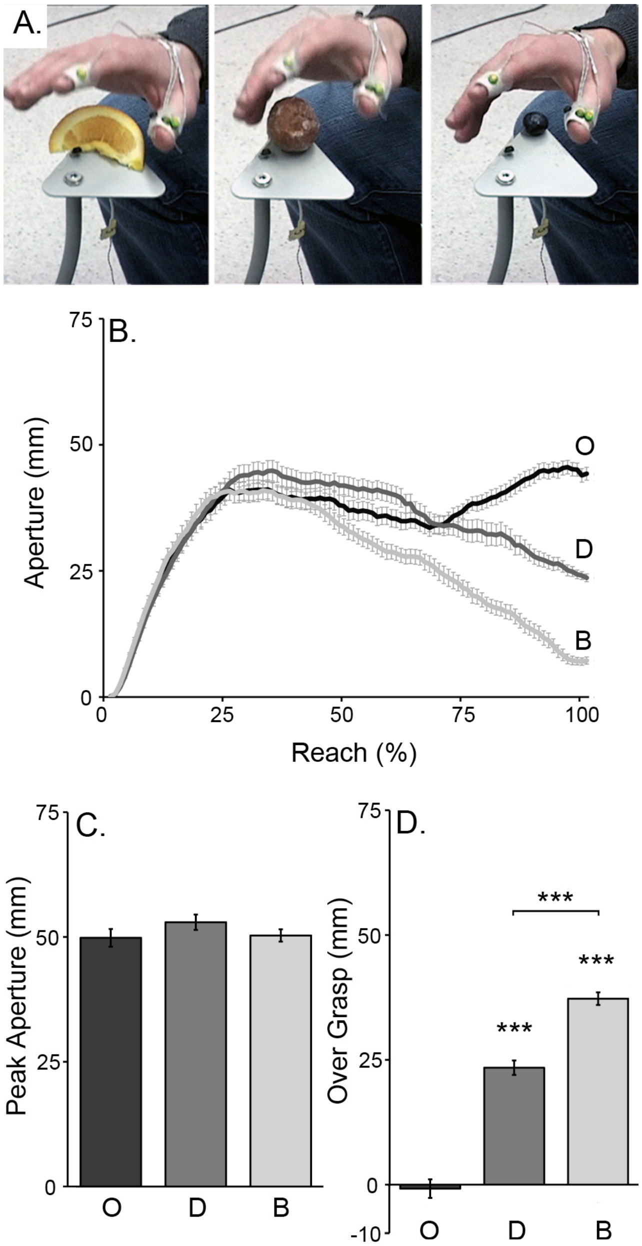


Figure 4.7 Reaching without vision to targets located on a distal pedestal. (A) Representative photos of the hand shape used to grasp an orange slice, donut ball, and blueberry. (B) Kinematic profiles of the index-thumb aperture (mean ± standard error) when reaching for an orange slice, donut ball, and blueberry. (C) Peak Aperture (mean ± standard error) and (D) Over Grasp (mean ± standard error) when reaching for different sized food items. Note: Hand shape and Peak Aperture did not scale to food target size. A “default” hand shape and Peak Aperture were adopted, causing the Over Grasp to be inversely scaled to food item size, (O, Orange slice; D, Donut ball; B, Blueberry, ***$p < 0.001$).

Kinematic analysis of index-thumb aperture confirmed the video description. Figure 4.7B shows index-thumb aperture profiles (mean ± standard error of all participants and trials) when reaching to targets of varying size without vision. During transport, the hand adopted a “default” peak aperture regardless of the size of the target food item (Figure 4.7C). Because a “default” peak aperture was consistently used, the size of the over grasp was inversely related to food item size, such that the over grasp was smallest when reaching for an orange slice, intermediate when reaching for a donut ball, and largest when reaching for a blueberry (Figure 4.7D). These main findings were confirmed by statistical analyses. For Peak Aperture, there was no significant effect of Target [$F(2,22) = 1.425$, $p > 0.05$]. For Over Grasp, there was a significant effect of Target [$F(2,22) = 179.205$, $p < 0.001$].

Reaching to a target in the mouth without vision. Figure 4.8 summarizes the results of hand preshaping when reaching without vision for different sized food items located in the mouth. Although vision was occluded, participants accurately preshaped the hand to target size when it was located in the mouth (Figure 4.8A). When reaching towards an orange slice (left), the distance between the index finger and thumb was relatively large, digits 2 through 5 were almost fully extended, and the thumb was fully extended. When reaching towards a donut ball (middle), the distance between the index finger and thumb was intermediate and the digits were partly flexed. When reaching for a blueberry (right), the distance between the index finger and thumb was small and the digits were semi-flexed in a pre-pincer grasp position.

Kinematic analysis of index-thumb aperture confirmed the video description. Figure 4.8B shows index-thumb aperture profiles (mean ± standard error of all

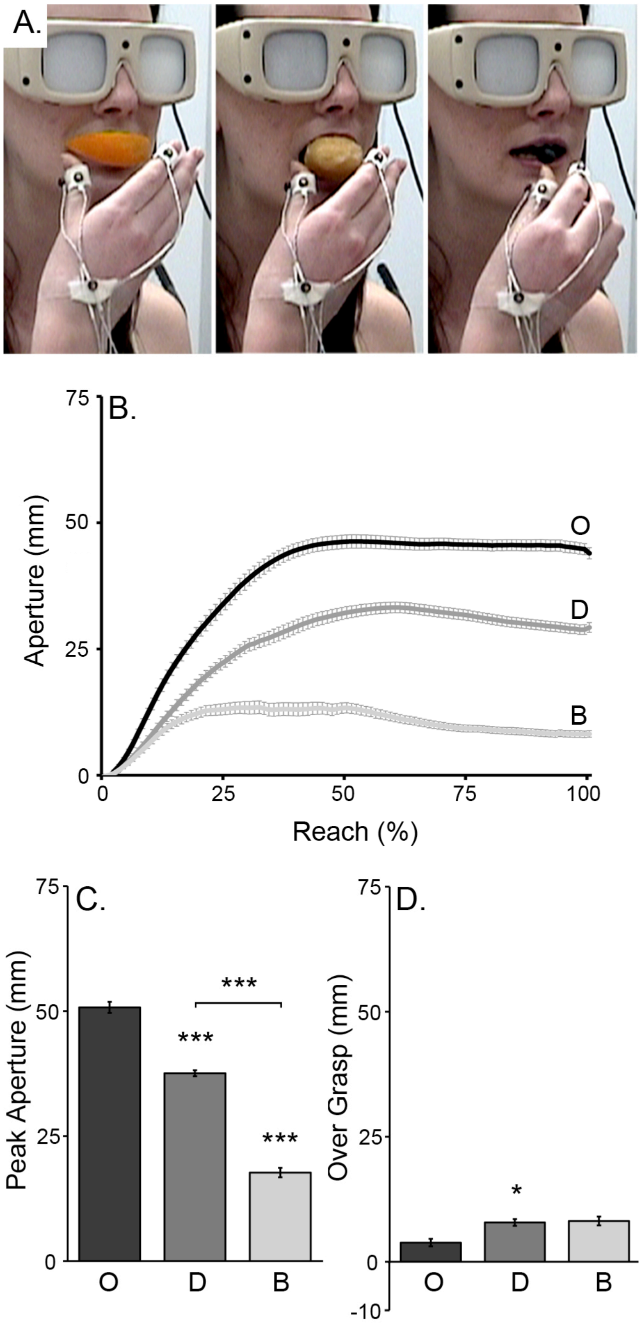


Figure 4.8 Reaching without vision to targets located in the mouth. (A) Representative photos of the hand shape used to grasp an orange slice, donut ball, and blueberry. (B) Kinematic profiles of the index-thumb aperture (mean ± standard error) when reaching for an orange slice, donut ball, and blueberry. (C) Peak Aperture (mean ± standard error) and (D) Over Grasp (mean ± standard error) when reaching for different sized food items. Note: Hand shape and Peak Aperture scaled to target size but Over Grasp did not, (O, Orange slice; D, Donut ball; B, Blueberry, ***$p < 0.001$, *$P < 0.05$).

participants and all trials) when reaching to targets of varying size without vision. When reaching without vision, peak aperture scaled to target size such that it was largest when reaching for an orange slice, intermediate for a donut ball, and smallest for a blueberry (Figure 4.8C). Over Grasp tended to be smaller when reaching for an orange slice compared to a donut ball or blueberry (Figure 4.8D). These main findings were confirmed by the statistical analyses. For Peak Aperture, there was a significant effect of Target [$F(2,18) = 131.560$, $P < 0.001$]. For Over Grasp, there was a significant effect of Target [$F(2,18) = 3.607$, $p < 0.05$].

Effect of target location on hand preshaping accuracy without vision. Figure 4.9 summarizes the accuracy of hand preshaping, as measured by peak aperture and over grasp, when reaching without vision for food targets located on a distal pedestal or in the mouth. Figure 4.9A shows peak aperture (mean ± stand error of all participants and all trials) when reaching for orange slices, donut balls, and blueberries located either on a distal pedestal (black) or in the mouth (grey). Peak aperture was significantly smaller when reaching for donut balls and blueberries located in the mouth as compared to on a distal pedestal. Figure 4.9B shows over grasp (mean ± stand error of all participants and all trials) when reaching for orange slices, donut balls, or blueberries located either on a distal pedestal (black) or in the mouth (grey). Over grasp was significantly smaller when reaching for donut balls and blueberries located in the mouth as compared to on a distal pedestal. These results were due to the fact that when vision was occluded the hand did not preshape at all when reaching to targets on a distal pedestal.

These main findings were confirmed by statistical analyses. For Peak Aperture, there was a significant effect of Location [$F(1,20) = 609.157$, $p < 0.001$] and

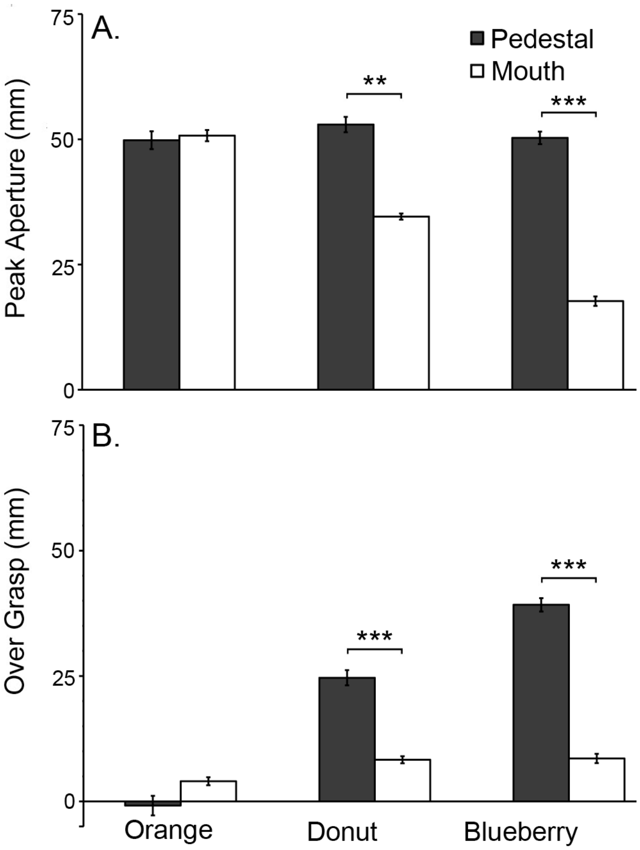


Figure 4.9 Peak Aperture and Over Grasp when reaching without vision to targets located on a distal pedestal or in the mouth. (A) Peak Aperture (mean ± standard error) when reaching for orange slices, donut balls, and blueberries located on a distal pedestal (black) or in the mouth (white). (B) Over Grasp (mean ± standard error) when reaching for orange slices, donut balls, and blueberries located on a distal pedestal (black) or in the mouth (white). Note: Peak Aperture and Over Grasp were significantly smaller when reaching to orange slices and donut balls located in the mouth as compared to the same targets located on a distal pedestal. The large difference is due to the fact that the hand did not scale to target size when reaching to targets on a distal pedestal in the No Vision condition, (***$p < 0.001$, **$p < 0.001$).

Target X Location [$F(2,40) = 67.781$, $p < 0.001$]. For Over Grasp, there was a significant effect of Location [$F(1,20) = 15.242$, $p < 0.001$] and Target X Location [$F(2,40) = 74.954$, $p < 0.001$].

Comparison of the Vision and No Vision conditions

Hand preshaping for reaching and grasping appeared to be very similar for targets located on a distal pedestal compared to targets in the mouth. Nevertheless, reaching to a distal target appeared to be dependent on vision, whereas reaching to a target in the mouth did not. In addition, hand preshaping appeared to be more accurate when reaching to large and medium-sized targets in the mouth compared to the same targets on a distal pedestal, even in the absence of vision. This accuracy suggests that online haptic feedback, rather than vision or offline perceptual knowledge, likely guides grasping to targets in the mouth. A more detailed comparison, as summarized below, confirmed this conclusion.

Time of Peak Aperture Formation. Figure 4.10 summarizes the time of peak aperture formation as a percent of total reach-to-grasp time. In general, time of peak aperture was dependent on vision when reaching to a distal target, but not when reaching to a target in the mouth.

Figure 4.10A shows the time of peak aperture when reaching for an orange slice, donut, and blueberry placed on a distal pedestal in the Vision (left) and No Vision (right) conditions. In the Vision condition, peak aperture generally occurred 52% of the way through the reach; and, was earliest for a blueberry and orange slice, and later for a donut. In the No Vision condition, peak aperture occurred significantly earlier, 34% of the way

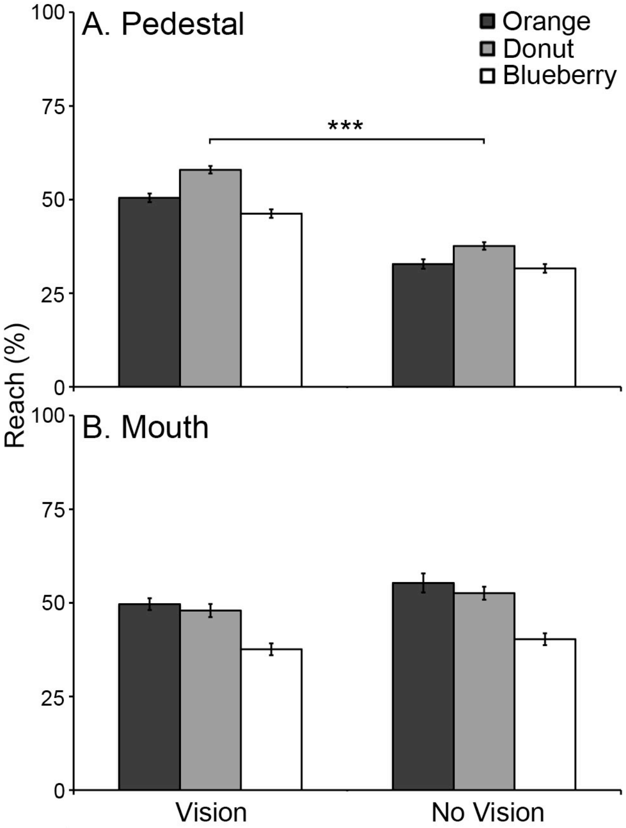


Figure 4.10 Time of Peak Aperture formation as a percent of total movement time when reaching for orange slices, donut balls, and blueberries located (A) on a distal pedestal and (B) in the mouth in the Vision (left) and No Vision (right) conditions. Note: When reaching to a distal pedestal, time of Peak Aperture formation decreased in the No Vision condition compared to the Vision condition. When reaching to the mouth, visual occlusion had no effect on the time of Peak Aperture formation, (***$p < 0.001$).

through the reach, regardless of whether the target was an orange slice, donut or blueberry.

Figure 4.10B shows the time of peak aperture when reaching for an orange slice, donut, and blueberry placed in the mouth in the Vision (left) and No Vision (right) conditions. In the Vision condition, peak aperture generally occurred 45% of the way through the reach. This did not significantly differ from the No Vision condition in which peak aperture generally occurred 49% of the way through the reach. For both conditions, time of peak aperture tended to correspond to target size in that peak aperture occurred earliest when reaching for a blueberry, intermediate when reaching for a donut, and latest when reaching for an orange slice, although the difference between the donut and orange slice was not significant.

These main findings were confirmed by statistical analyses. An overall ANOVA found no significant effect of Location [$F(1,39) = 4.013$, $p > 0.05$], but a significant effect of Feedback [$F(1,39) = 5.435$, $p < 0.05$], and Feedback X Location [$F(1,39) = 17.234$, $p < 0.001$]. For reaches to the pedestal, significant effects were found for Target [$F(2,40) = 13.364$, $p < 0.001$] and Feedback [$F(1,20) = 48.303$, $p < 0.01$], but not for Target X Feedback [$F(2,40) = 1.457$, $p > 0.05$]. For reaches to the mouth, a significant effect was found for Target [$F(2, 38) = 21.543$, $p < 0.001$], but not for Target [$F(2,38) = 21.543$, $p < 0.001$], or Target X Feedback [$F(2,38) = 1.015$, $p > 0.05$].

Total movement time. Figure 4.11A summarizes the total amount of time required to complete the reach-to-grasp movement (mean ± stand error of all participants and all trials) in the Vision (white bars) and No Vision (black bars) conditions when reaching to a target located on a distal pedestal or in the mouth. When reaching to a target

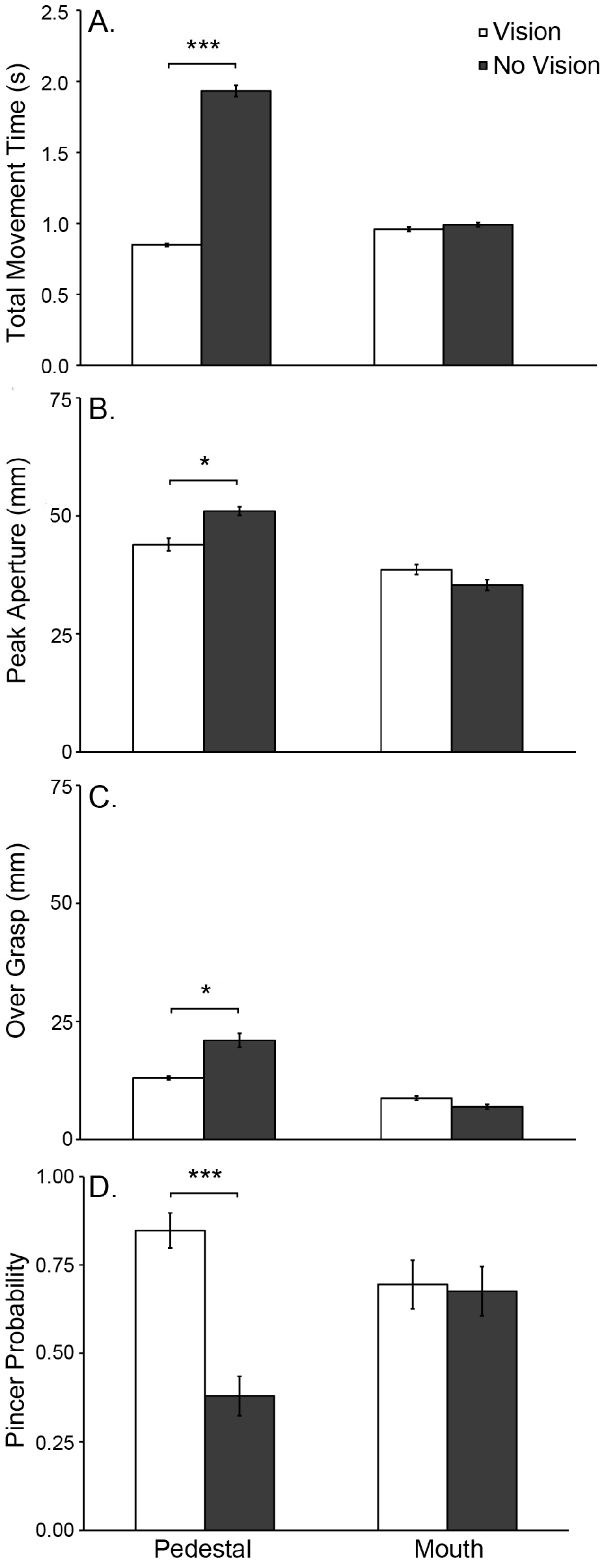


Figure 4.11 Total movement time, Peak Aperture, Over Grasp, and the Probability of using a pincer grip when reaching to targets on a distal pedestal (left) and in the mouth (right) in the Vision (white bars) and No Vision (black bars) conditions. Note: In the No Vision condition, total movement time, Peak Aperture, Over Grasp, and the probability of using a non-pincer grip all increased significantly when reaching to targets on a distal pedestal, but not when reaching to targets in the mouth (***p < 0.001, *p < 0.05).

located on a distal pedestal, total movement time was significantly greater in the No Vision condition compared to the Vision condition. When reaching to a target in the mouth, total movement time did not differ between the two conditions. Thus, total movement time was influenced by visual feedback when reaching to a target located on a distal pedestal, but not when reaching to a target located in one's own mouth.

These main findings were confirmed by statistical analyses, which found a significant effect of Location [$F(1,40) = 35.697$, $p < 0.001$], Feedback [$F(1,40) = 57.811$, $p < 0.001$], and Location X Feedback [$F(1,40) = 51.695$, $p < 0.001$].

Hand preshaping accuracy. Figures 4.11B and 4.11C summarize the effect of visual occlusion on hand preshaping accuracy when reaching to a target located on a distal pedestal (left) or in the mouth (right). Figure 4.11B shows peak aperture (mean ± stand error of all participants and all trials) in the Vision (white bars) and No Vision (black bars) conditions. When reaching to a target located on a distal pedestal, peak aperture increased significantly in the No Vision condition compared to the Vision condition. When reaching to a target in the mouth, peak aperture did not differ between the two conditions. Figure 4.11C shows over grasp (mean ± stand error of all participants and all trials) in the Vision (white bars) and No Vision (black bars) conditions. When reaching to a target located on a distal pedestal, over grasp increased significantly in the No Vision condition compared to the Vision condition. When reaching to a target in the mouth, over grasp did not differ between the two conditions. Thus, visual feedback influenced hand preshaping accuracy when reaching to a target located on a distal pedestal, but not when reaching to a target in one's own mouth.

These main findings were confirmed by statistical analyses. For Peak Aperture, there was a significant effect of Location [$F(1,40) = 24.09$, $p < 0.001$], Location X Feedback [$F(1,40) = 5.84$, $p < 0.05$], and Location X Feedback X Target [$F(2,80) = 77.86$, $p < 0.001$]. For Over Grasp, there was a significant effect of Location [$F(1,40) = 21.25$, $p < 0.001$], Location X Feedback [$F(1,40) = 6.06$, $p < 0.05$], and Location X Feedback X Target [$F(2,80) = 76.55$, $p < 0.001$].

Final grip. Figure 4.11D summarizes the effect of visual occlusion on final grip posture when reaching to a target located on a distal pedestal (left) or in the mouth (right). Figure 4.11D shows the probability (mean ± stand error of all participants and all trials) that a pincer grip was used to grasp the target in the Vision (white bars) and No Vision (black bars) conditions. When reaching to a target located on a distal pedestal, the probability of using a pincer grip decreased significantly in the No Vision condition compared to the Vision condition. When reaching to a target in the mouth, the probability of using a pincer grip did not differ between the two conditions.

These main findings were confirmed by statistical analyses. For Pincer Grip, there was no significant effect of Location [$F(1,44) = 0.667$, $p > 0.05$], but there was a significant effect of Feedback [$F(1,44) = 7.654$, $p < 0.01$] and Location X Feedback [$F(1,44) = 6.531$, $p < 0.05$].

Grasp aperture. Figure 4.12 summarizes the results of actual grasp aperture when participants reached for orange slices, donut balls, and blueberries located either on a distal pedestal or in the mouth. As expected, Grasp Aperture did vary according to target size, such that it was largest for an orange slice, intermediate for a donut ball, and smallest for a blueberry. For each target, actual grasp aperture was the same regardless of

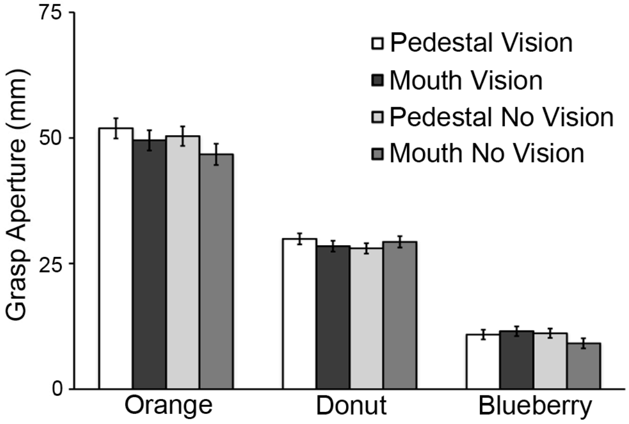


Figure 4.12 Final Grasp Aperture when reaching to orange slices, donut balls, and blueberries located on a distal pedestal and in the mouth. Note: For each food target, actual Grasp Aperture was the same, regardless of where the target was located and whether vision was available or not.

where the target was located or whether visual feedback was available. These results confirm that the smaller over grasp used to reach to a target in the mouth was related to a decrease in peak aperture and not to an increase in actual grasp aperture.

These results were confirmed by statistical analysis, which found a significant effect of Target [F(2,80) = 1174.54, $p < 0.001$]; but no significant effect of Location [F(1,40) = 1.30, $P > 0.05$], Feedback [F(1,40) = 1.32, $p > 0.05$], Location X Feedback [F(1,40) = 0.03, $p > 0.05$], or Location X Feedback X Target [F(2,80) = 1.519, $P > 0.05$].

Effect of object size on hand preshaping to targets in the mouth

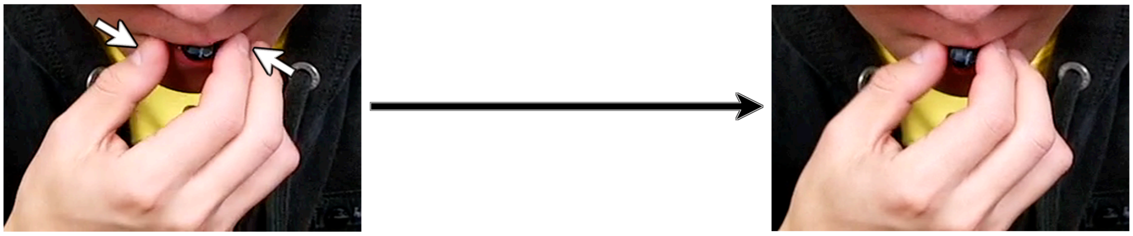
The role of haptic feedback for reaching and grasping targets on a distal pedestal has been addressed in previous work (Karl et al., 2012a). For this reason, only the role of haptic feedback for reaching and grasping oral targets was evaluated in the present study. When reaching to the mouth, hand preshaping accuracy was related to target size in that peak aperture and over grasp were most accurate for an orange slice and least accurate for a blueberry (Fig 4.5). Differences in oral haptic feedback for large vs. small target items likely contributed to these differences. A more detailed comparison, as summarized below, supported this conclusion.

Figure 4.13 summarizes the two types of hand preshaping errors associated with reaching to targets in the mouth. Figure 4.13A illustrates an underestimation error. It appears that because the lateral portions of the orange slice extended slightly beyond the lips, participants tended to underestimate the hand aperture required to grasp it. At first contact, hand aperture was too small to comfortably grasp the orange slice; thus, the thumb or remaining digits (or both) would re-open to form a larger aperture before

A. Underestimation Error

First Contact Adjustment Final Grasp

B. Overestimation Error



First Contact Final Grasp

Figure 4.13 Representative photos illustrating the hand shaping adjustments associated with (A) an underestimation error and (B) on overestimation error. Note: An underestimation error is characterized by the use of a hand aperture that is too small to grasp the target on first contact, followed by a slight opening of the hand (white arrows) in order to achieve the larger final grasp posture. An overestimation error is characterized by the use of a hand aperture that is too large to grasp the target on first contact, thus, at least one of the digits makes initial contact with the lips rather than the target (white arrows), after which hand aperture is adjusted to achieve the smaller final grasp posture.

closing to contact slightly more lateral portions of the orange slice in order to successfully grasp it.

Figure 4.13B illustrates an overestimation error. It appears that because the blueberry tended to recede into the lips and mouth, participants tended to overestimate the hand aperture required to grasp the blueberry. At first contact, hand aperture was too large to grasp the blueberry and the thumb and/or digits often made contact with the surrounding lip tissue. After contact with the lips, the hand would redirect the grasping digits towards the blueberry and slowly close to form a smaller hand aperture in order to successfully grasp it.

The hand shaping transitions used to compensate for underestimation errors and overestimation errors were characterized using frame-by-frame video analysis and linear kinematics. Figures 4.14A and 4.14B provide a topographical description of the digit-to-target contact locations at first contact (red dots) and at final grasp (blue dots) associated with three representative underestimation errors on an orange slice (Fig 4.14A) and three representative overestimation errors on a blueberry (Fig 4.14B). In the event of an underestimation error, digit-to-target contact locations at first contact (red dots) were located medial to the final grasp digit-to-target contact locations (blue dots), indicating that a widening of the digit aperture was required to transition from first contact to final grasp. The opposite was true in the event of an overestimation error, in which case digit-to-target contact locations at first contact (red dots) were located peripherally to the final grasp digit-to-target contact locations (blue dots), indicating that a narrowing of digit aperture was required to transition from first contact to final grasp.

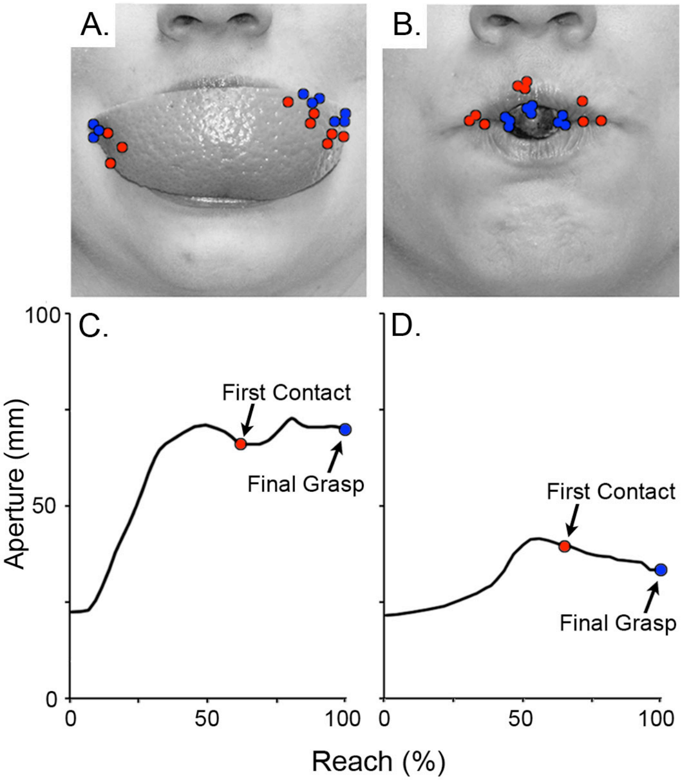


Figure 4.14 Topography of digit-to-target contact locations and aperture profiles associated with 3 representative underestimation errors to an orange slice in the mouth (left) and 3 representative overestimation errors to a blueberry in the mouth (right). (A) Location of first contacts (red dots) and final grasp contacts (blue dots) for underestimation errors to an orange slice in the mouth. (B) Location of first contacts (red dots) and final grasp contacts (blue dots) for overestimation errors to a blueberry in the mouth. (C) A representative index-thumb aperture profile of an underestimation error to an orange slice in the mouth. (D) A representative index-thumb aperture profile of an overestimation error to a blueberry in the mouth. Note: To compensate for an underestimation error the digits must open wider after first contact with the target in order to achieve an appropriate final grasp aperture and contact locations. To compensate for an overestimation error, the digits must close further after first contact with the lips in order to achieve an appropriate final grasp aperture and contact locations on the target.

Linear kinematics confirmed the topographical analyses provided in Figures 4.14A and 4.14B. Figures 4.14C and 4.14D each provide a single, representative digit aperture profile associated with an underestimation error for an orange slice (Fig 4.14C) and an overestimation error for a blueberry (Fig 4.14D). Figure 4.14C shows that in order to compensate for an underestimation error, a second peak aperture (re-opening of the digits) was formed after first contact with the target. After this, the digits closed to a final grasp aperture that was slightly larger than the original digit aperture used at first contact. Figure 4.14D shows that in order to compensate for an overestimation error, after first contact, the digits continued to gradually close for a significant portion of total movement time until achieving final grasp aperture.

Figure 4.15 shows that hand preshaping errors to targets in the mouth were related to target size. Underestimation errors (dark grey bars, Mean ± SE) occurred most frequently when reaching for an orange slice, whereas overestimation errors (light grey bars, Mean ± SE) occurred most frequently when reaching for a blueberry. These results were confirmed by the statistical analysis. For Grasping Errors there was a significant effect of Target [$F(2,38) = 14.664$, $p < 0.001$], but not Feedback [$F(1,19) = 1.268$, $p > 0.05$) or Feedback X Target [$F(2,38) = 0.288$, $p > 0.05$].

Because measures of peak aperture and over grasp were taken only for the first grasping attempt (ie. before first contact), the introduction of underestimation errors and overestimation errors may have led to an artificial increase in hand preshaping accuracy to the orange slice in the mouth and an artificial decrease in hand preshaping accuracy to the blueberry in the mouth. Taken together, these results suggest that there may be an “ideal” target size, for reaching to objects in the mouth. This target size would maximize

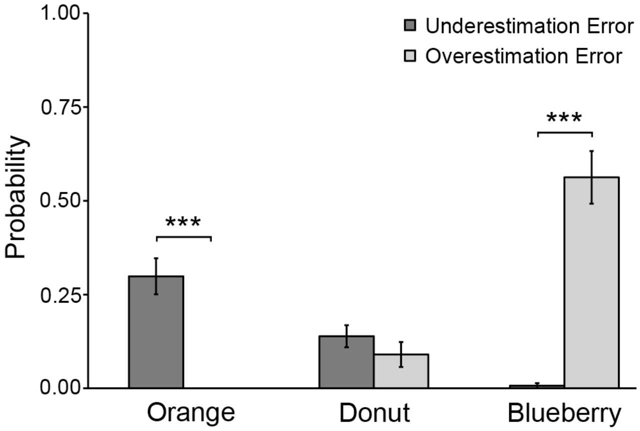


Figure 4.15 The probability (mean ± standard error, across all participants, trials, and feedback conditions) that an underestimation (black bars) or overestimation (white bars) error occurred when reaching for an orange slice, donut ball, and blueberry located in the mouth. Note: Underestimation errors were most common when reaching for the largest target object, an orange slice, while overestimation errors were most common when reaching for the smallest target object, a blueberry, (***, $p < 0.001$).

haptic feedback from the mouth without exceeding the sensory range of the lips and without receding into the mouth.

Discussion

This study provides the first description of hand preshaping to oral targets as compared to visually-guided hand preshaping to the same targets located on a distal pedestal. Frame-by-frame video analysis and linear kinematics revealed that hand preshaping to oral targets was similar to, and at least as accurate as, visually-guided hand preshaping. Unlike hand preshaping to distal targets, hand preshaping to oral targets was unaffected by visual occlusion, suggesting that the act is exclusively under haptic control. This conclusion was supported by the finding that ambiguity in oral haptic feedback, as occurs when the edges of a large target extend beyond the edges of the mouth, results in suboptimal hand preshaping. Nevertheless, haptic feedback from the reaching hand could be used to reshape and reorient the hand after first contact with the ambiguous target. The accurate guidance of hand preshaping by oral hapsis is discussed in relation to the idea that hand preshaping, as a function of the frontal and parietal cortices may have originated under somatosensory control with secondary access by vision.

The design of the present experiment featured three manipulations that ensured accurate measurement of hand preshaping. First, because the intended use of a target dictates how the reach-to-grasp movement is performed (Arbib et al., 1985; Jeannerod, 1981, 1984; Marteniuk et al., 1990), only ethologically relevant food items were used for both oral and distal reaching targets. Second, when reaching to distal targets, participants were instructed to reach for the target as if they were going to pick it up and eat it. Together these manipulations ensured that all subjects grasped the food targets with a similar intention and thus used a similar grasping pattern, a pincer or other precision grip, for all reaches (Iberall et al., 1986; Ingram et al., 2010; Napier 1956; Sartori et al., 2011). Third, as in previous studies, targets ranged in size so that scaling of hand aperture to target size and shape could be easily evaluated using frame-by-frame video analysis and kinematic motion capture (Jakobson and Goodale, 1991; Jeannerod 1981, 1984, 1986).

Some caveats must be made with respect to the procedures used. First the kinematic method is limited in that it does not provide a comprehensive measure of all hand preshaping transitions. Although the video record clearly indicated how the hand was shaped for grasping, parts of the hand were sometimes obscured so that kinematic results were incompletely captured and some data had to be removed. Nevertheless, the large majority of trials provided useful data and could be subjected to kinematic analysis. Second, because gustatory feedback has been shown to influence hand preshaping (Parma et al., 2011a,b), it is possible that gustatory sensations may have contributed to the accuracy of hand preshaping to oral targets in the present study. In future studies, the removal of gustatory feedback, by the use of non-ethologically relevant target items, could address this question. Third, it is possible that asking participants to bring the distal food target to the mouth after grasping it may have elicited different planning and control strategies compared to asking them to simply grasp and retrieve the target, as they were asked to do when reaching to the mouth (Ansuini et al., 2006, 2008; Gentilucci et al., 1997; Sartori et al., 2011). This may limit the extent to which data from the present experiment and data across numerous other studies may be directly compared.

Nevertheless, asking participants to pick up the distal target as if they were going to eat it ensured that a similar, “eating-related affordance or intention” was applied to the reaching movement in both the distal condition and the oral condition of the present study. Fourth, when reaching to unseen distal targets, participants did not know what the target was. This differs from reaching to an unseen oral target, in which case the participants were likely aware of the target’s identity and could use either online haptic feedback or stored perceptual knowledge about the target to guide the reach. Nevertheless, it is known that hand preshaping based on stored perceptual knowledge (memory) is significantly less accurate than hand preshaping based on online sensory feedback (Jakobson and Goodale, 1991). Thus, because hand preshaping accuracy to oral targets was unaffected by visual occlusion, this supports the interpretation that the act is guided primarily by online oral hapsis rather than by stored perceptual knowledge about the target.

Hand preshaping to oral targets is similar to, and at least as accurate as, visually-guided hand preshaping to distal targets. This conclusion is supported by a number of observations. First, in both conditions, hand aperture increased steadily from movement onset until reaching a peak aperture larger than the target, before closing to grasp. Second, regardless of where the target was located, hand shape and aperture scaled accurately to target size such that it was largest for an orange slice, intermediate for a donut ball, and smallest for a blueberry. Third, hand preshaping to both oral and distal targets resulted in successful grasping of the target and an identical final grasp aperture. Interestingly, hand preshaping accuracy (in terms of peak aperture and over grasp) appeared to be greatest when reaching to a donut ball placed in the mouth, as compared to the same target located on a distal pedestal. This suggests that under some circumstances hand preshaping to oral targets may actually be more accurate than visually-guided hand preshaping to the same targets in distal space. In sum, these similarities are suggestive of a common, feed-forward, hand preshaping action pattern that can be implemented when reaching to either visible distal targets or to targets in the mouth.

Time of peak aperture formation differs when reaching to distal targets compared to oral targets. When reaching to a distal target with vision, peak aperture generally occurred 52% of the way through the reach. This is slightly earlier than the 60-75% reported in some previous studies (Jakobson and Goodale, 1991; Jeannerod 1981, 1984; Paulignan et al., 1990). In addition, peak aperture formation occurred earlier than might have been expected when reaching to the largest distal target, an orange slice (Jakobson and Goodale, 1991; Marteniuk et al., 1990; Paulignan et al., 1991), and also when reaching to oral targets. This tendency to form a peak aperture earlier-than-expected is likely due to a number of factors. First, in the present study, total movement time was calculated from movement onset to final grasp. Because the targets in the present study were not completely solid, they were subject to a slight compression upon final grasp. The additional time required to achieve optimal grip friction forces may have caused the time of peak aperture formation to occur proportionally earlier in the total movement time. Second, it is known that peak aperture formation may occur proportionally earlier when “compensatory” or “cautious” grasping strategies must be employed (Jakobson and Goodale, 1991; Karl et al., 2012). In the present study, reaching to an unseen distal target, reaching to a wet and sticky orange slice balanced on a pedestal, and reaching to a target located in one's own mouth, may all represent reaching conditions in which a "cautious" strategy must be employed in order to prevent dropping of the target and/or self-injury. Third, the timing of peak aperture formation may be related to the intended use of the target (Sartori et al., 2011). Because the target was grasped with the intention of either bringing it to the mouth or removing it from the mouth, this may have elicited different planning and grasping strategies compared to a situation in which the intended use of the target is to simply lift it from a table. This may have affected the time of peak aperture formation. In general, the results of these analyses suggest that the physical nature of the reaching target, the intended use of the reaching target, and the "stability" of the reaching target may all influence the timing of peak aperture formation.

Accurate hand preshaping to distal targets requires vision, but hand preshaping to oral targets is guided by hapsis. This conclusion is supported by the following observations. First, without vision, reaching and grasping of distal targets took significantly longer compared to oral targets. Second, although time of peak aperture formation occurred earlier when reaching to unseen distal targets, time of peak aperture was unaffected in the No Vision condition when reaching to oral targets. Third, when reaching without vision to a distal target, peak hand aperture did not scale to target size; instead, a standard peak hand aperture was consistently employed. This differed from reaching to an oral target, in which peak hand aperture scaled to target size, even in the absence of vision. Fourth, the removal of visual feedback resulted in a change in final grip preference when reaching for a distal target. Specifically, a pincer grip was employed more often under normal visual conditions, whereas a precision grip was employed more often under visual occlusion. In contrast, when grasping an oral target, a precision grip was preferred under both visual conditions. The use of a precision grip might reflect a higher reliance on haptic feedback from the reaching hand in order to ensure successful grasping of the target (Karl, 2012; Mackenzie and Iberall, 1994). Taken together, these results show that while visual feedback is required for optimal hand preshaping to distal targets, oral hapsis appears to be sufficient for accurate hand preshaping to targets in the mouth.

Hand preshaping to targets in the mouth is guided primarily by oral hapsis, but haptic feedback from the reaching hand can be used to optimize the movement. This conclusion is supported by the following observations. First, when haptic information from the mouth was ambiguous, as occurred when the lateral tips of the orange slice extend beyond the lips, peak hand aperture was often insufficient to allow for successful grasping of the target. This indicates that hand preshaping to targets in the mouth is guided only by available oral hapsis. Second, in instances where peak hand aperture underestimated actual target size, the reaching hand could re-shape to an appropriate final grasp aperture, but only after first haptic contact with the target. This resembles the parsed strategy of using haptic feedback from the hand to first locate the target, and then to guide re-shaping of the hand after first contact (Karl et al., 2012). Third, when the smallest target receded into the lips, a larger than required peak hand aperture could be used to compensate for anticipated initial contact between the digits and the lips. After initial contact, the digits would then close and produce a successful final grasp. Thus, hand preshaping to targets in the mouth is guided primarily by oral hapsis. Nevertheless, hapsis from the reaching hand can be used to compensate for ambiguous oral haptic feedback in order to successfully grasp an oddly shaped target in the mouth.

The accuracy of hand preshaping to oral haptic targets is likely due to a number of factors. First, the spatial acuity of tactile information on the lips and tongue is high, almost double that of the digits (Van Boven et al., 1994), and can provide precise size and shape information concerning objects held by the mouth. Second, withdrawal of the hand from distal space, in order to place a food item into the mouth, is also guided by somatosensory feedback from the hand, arm, and mouth, rather than by vision (de Bruin et al., 2008, Kaas et al., 2011; Sacrey and Whishaw, 2011). Third, the same neural circuitry that mediates visually-guided hand preshaping to distal targets also mediates haptically-guided hand preshaping. (Binkofski et al. 1998; 1999a,b; De Santis et al., 2007; Reed et al., 2005; Sathian et al., 2011). Thus, the results of the present study suppor the third hypothesis of the present thesis, that online somatosensory inputs concerning the extrinsic and intrinsic properties of the target can result produce temporally integrated Reach and Grasp movements (i.e., hand preshaping) similar to those under vision. The use of a seemingly similar hand preshaping movement, despite differences in sensory control, is suggestive of a common neural origin for hand preshaping to grasp both distal objects and objects in the mouth.

A substantial literature is interpreted as supporting the idea that hand preshaping is a primarily visual act. The classic theories of skilled hand movement evolution, the arboreal theory and the visual predation theory, posit that skilled reaching and grasping originated under visual control in the primate lineage and is a consequence of an arboreal lifestyle (Cartmill, 1974; Napier, 1980). Nevertheless, we suggest that hand preshaping for grasping and its requisite neural circuitry in parietofrontal cortex may have actually originated under haptic control in a common ancestor to rodents and primates in order to grasp a food item in the mouth. Sensory control may have then been modified in more recent mammalian orders to allow primates to redirect the reach-to-grasp movement towards distal targets using vision (Whishaw, 2003).

A number of recent findings support this feeding theory. First, while the reaching and grasping circuitry in primate parietofrontal cortex receives both somatosensory and visual inputs, the somatosensory inputs are direct, whereas the visual inputs are less direct. In fact, it has not been possible to identify any direct connections from visual areas representing central space to the reaching/grasping circuitry in parietofrontal cortex at all (Kaas et al., 2011**,** Stepniewska et al., 2009a,b). Second, all studied branches of primate evolution share the same basic reaching and grasping circuitry in the parietofrontal cortex (Gharbawie et al. 2010, 2011, Kaas et al., 2011, Stepniewska et al. 2005, 2009a,b). Thus, this circuitry likely did not originate in "visually inclined" primates, but was most likely retained from a common ancestor and modified in more recent primate lineages. Third, rats can readily use oral hapsis to guide accurate hand preshaping to food targets located in the mouth (Ivanco et al., 1996; Whishaw et al., 1992a, 1998; Whishaw & Coles, 1996). They cannot, however, use vision to guide hand preshaping to targets in distal space (Hermer-Vazquez, 2007; Metz & Whishaw, 2000; Whishaw, 2003; Whishaw et al., 1992b). This ability does appear to be unique to primates (Hermer-Vazquez et al., 2007; Metz and Whishaw, 2000; Whishaw and Tomie, 1989). Finally, the results of the present study show that not only can humans use oral hapsis to guide accurate hand preshaping to targets in the mouth, but there are instances where this form of hand preshaping is actually more accurate than that guided by vision. Thus, the findings of the present study, combined with previous work, support the feeding theory as a possible explanation for the evolution of skilled hand movements such as hand preshaping.

Chapter 5

Haptic grasping configurations in early infancy reveal different developmental profiles for visual guidance of the Reach vs. the Grasp

Abstract

The Dual Visuomotor Channel theory posits that reaching consists of two movements mediated by separate but interacting visuomotor pathways that project from occipital to parietofrontal cortex. The Reach transports and orients the hand to the target while the Grasp opens and closes the hand for target purchase. Adults rely on foveal vision to synchronize the Reach and the Grasp so that the hand orients, opens, and largely closes by the time it gets to the target. Young infants produce discrete preReach and preGrasp movements, but it is unclear how these movements become synchronized under visual control throughout development. Highspeed 3D video recordings and linear kinematics were used to analyze reaching components, hand orientation, hand aperture, and grasping strategy in infants aged 4 to 24 months compared to adults who reached with and without vision. Infants aged 4 to 8 months resembled adults reaching without vision in that they delayed both Reach orientation and Grasp closure until after target contact, suggesting that they relied primarily on haptic cues to guide reaching. Infants aged 9 to 24 months oriented the Reach prior to target contact, but continued to delay the majority of Grasp closure until after target contact, suggesting that they relied on vision for the Reach vs. haptics for the Grasp. Changes in sensorimotor control were associated with sequential Reach and Grasp configurations in early infancy vs. partially synchronized Reach and Grasp configurations in later infancy. The results argue that 1) haptic inputs likely contribute to the initial development of separate Reach and Grasp pathways in parietofrontal cortex, 2) the Reach and the Grasp are adaptively uncoupled during development, likely to capitalize on different sensory inputs at different developmental

stages, and 3) the developmental transition from haptic to visual control is asymmetrical with visual guidance of the Reach preceding that of the Grasp.

Introduction

The Dual Visuomotor Channel theory proposes that reaching consists of two movements mediated by separate but interacting visuomotor pathways that project from occipital to parietofrontal cortex (Arbib 1981; Cavina-Pratesi et al., 2010a; Culham and Valyear, 2006; Filimon, 2010; Jeannerod 1981; Karl and Whishaw, 2013; Rizzolatti et al. 1998; Tanné-Gariépy et al. 2002). The Reach transports and orients the hand to the target while the Grasp opens and closes the hand for target purchase. Healthy adults visually fixate on a target at movement onset (de Bruin et al., 2008; Sacrey and Whishaw, 2012), which allows them to integrate the Reach and the Grasp into a single prehensile act such that Reach orientation and Grasp closure are largely complete by the time the hand contacts the target (Jeannerod, 1999). If vision is degraded, however, reaching decomposes into its constituent components: an open-handed Reach is first used to locate the target by touching it and then haptic feedback associated with target contact assists shaping and closure of the hand to Grasp (Hall et al., 2014; Karl et al., 2012a; Karl and Whishaw, 2013).

Before infants begin reaching for visual targets they produce discrete preReach and preGrasp movements, suggesting that independent motor control for the Reach vs. the Grasp is established early in postnatal life. PreReach movements such as orienting the eyes and head to a target (Greenman, 1963; Kremenitzer et al., 1977; Hofsten and Rosander, 1997), swiping at a target with a fisted hand (White et al., 1964; Hofsten, 1984), and reaching for an object with the mouth by thrusting the head forward and flexing the abdominals (Foroud and Whishaw, 2012), appear to be at least partially mediated by vision (Hofsten, 1982). In contrast, preGrasp movements such as closing the hand on an object that contacts the palm (Twitchell, 1965), forming spontaneous pincer and precision grips during hand babbling (Rönnqvist and Hofsten, 1994; Wallace and Whishaw, 2003), and configuring the hand to grasp one’s own body or clothing (Wallace and Whishaw, 2003; Thomas et al., in prep) appear to be almost exclusively under somatosensory control (Lockman et al., 1984; Newell et al., 1993). There are at least two possibilities related to how independent preReach and preGrasp movements become integrated under vsion. First, visual control may mature at the same rate for both the Reach and the Grasp, in which case infants would show gradual and symmetrical improvements in both orienting the Reach and closing the Grasp prior to target contact at increasingly older ages. Alternatively, visual guidance may mature at different rates for the Reach vs. the Grasp, in which case infants would show asymmetrical improvements in orienting the Reach vs. closing the Grasp prior to target contact, with the movement that is more tightly coupled to vision showing improvements in anticipatory movement control earlier.

To investigate these hypotheses, infants aged 4 to 24 months and healthy adults were filmed at high speed as they reached for a vertical rod placed on a table in front of them. Infants always reached with vision whereas adults reached without vision (NV) and with vision (V). Frame-by-frame 3D video analysis and linear kinematics were used to quantify the temporal structure of the movement components that comprise reaching, hand orientation at contact, hand aperture at contact, and overall grasping strategy in order to determine the extent to which visual vs. non visual inputs were used to orient the Reach vs. close the Grasp in each group.

Materials and Methods

Participants

Adults. Eighteen young adults (9 male, 9 female, mean age = 21.6 ± 0.87 years) were recruited from a second year class at the University of Lethbridge. All participants provided informed consent and were self-reported to have no history of sensory, motor, or neurological disorders. All participants were selected because they were right-handed for writing and had normal or corrected-to-normal vision.

Infants. Thirty-nine infants (21 male, 18 female) were recruited through an online advertisement (www.kijiji.ca) and were assigned to 5 age groups: 4 to 6 months of age (n = 8, mean age = 170 ± 8 days), 7 to 8 months of age (n = 8, 237 ± 5 days), 9 to 10 months of age (n = 9, 291 ± 5 days), 11 to 12 months of age (n = 7, 355 ± 9 days), and 24 months of age (n = 7, 754 ± 13 days). All parents provided informed consent and reported that infants were full term (born within 7 days of due date) and had no known sensory, motor, or neurological disorders. The University of Lethbridge Human Subject Research Committee approved the study.

Procedures

Setup. Prior to testing adults were seated in a comfortable upright position on an armless chair in front of a table that bent at a 90º angle at the participant's midline. The height of the chair was adjusted so that the participant's hands could rest comfortably on the table with the elbows bent at approximately 135º. Participants then placed their hands in an open and comfortable position on the dorsal aspect of their upper thighs in preparation for the first reaching trial. Infants were seated in a similar manner, but on the mother's lap (Fagard, 2000). If necessary, the mother stabilized the infant by holding his/her waist with both hands.

Targets. Two custom made vertical rods, 20.5 cm in height, were used as reaching targets. Each rod was made of clear acrylic and filled with plastic sea glass pebbles and reflective ribbon to attract the infants' attention. A 0.5 cm acrylic protrusion was attached to the bottom of each rod so that the rod could be secured in a vertical position on an acrylic receptacle located on the table in front of the participant. Adults reached for a rod that measured 3.25 cm in diameter; infants reached for a rod that measured 1.75 cm in diameter.

Adult Reaching Experiment. Adult participants assumed the "start" position by placing both hands in an open and relaxed posture on the dorsal aspect of their upper leg (see figure 5.1). They were shown the general location at which the target object would be placed before putting on plastic goggles that occluded target, which was placed on the table at a distance that allowed for complete extension of the participant's arm. Participants were instructed to wait for a verbal 1, 2, 3, GO command, after which they were to reach out as naturally as possible, pick up the target object with the right hand, pass it back to the experimenter, and then return their hand to the start position in

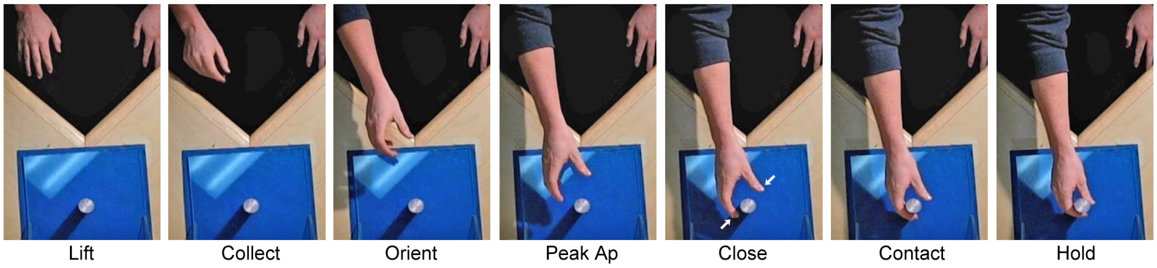


Figure 5.1 Movement components in a healthy sighted adult. *Lift*, the hand begins to lift from the substrate. *Collect*, the digits flex and close as the hand is transported towards the target. *Orient*, the arm and hand supinate to orient to the target. *Peak Aperture*, maximum opening of the index finger and thumb . *Close*, the digits begin to close to grasp. *Contact*, the hand contacts the target. *Hold*, digit closure is complete as the hand holds the target.

preparation for the next trial. Because of the occluding goggles, participants did not know the exact size, shape, or location of the reaching target on their first No Vision reach attempt. Adults performed 5 No Vision trials, followed by 5 Vision trials with the goggles removed. To control for learning effects in the No Vision condition (Karl et al., 2013) only the first trial in each viewing condition was subject to analysis.

Infant Reaching Experiment. A similar design was used for the infant reaching experiment, with some differences. Infants were encouraged by their mother to start each trial with their hands placed on the table in front of them, although, infants in the two youngest age groups did not begin with the hands in this position on a minority of trials. Infants were not able to follow a verbal 1, 2, 3, GO command and simply reached for the target whenever they were ready. Infants were not blindfolded. After grasping the target, infants were allowed time (approximately 30 to 60 seconds) to explore and/or play with the target before the mother retrieved it and handed it back to the experimenter who then placed it back at the target location in preparation for the next trial.

Infants reached for a maximum of twenty minutes or until they began to fuss. Eight reaches per infant were analyzed, although some trials were excluded due to incomplete data capture. A total of 274 (out of a potential 312) infant reaches were subject to kinematic and behavioural analysis with only one infant providing as few as 4 successful reaches.

Data Collection and Analysis

Two high-speed digital video cameras (Casio Exilim Ex-F1: http://www.exilim.eu /euro/exilimhighspeed/exf1/video/), operating at 300 frames/s, were positioned to record a reach-side view and top-down view of the participant. A lamp containing four 55 watt fluorescent light bulbs was used to illuminate the scene. Before testing, a 3D cubic calibration frame (http://www.motus10.com/motion-capture/calibration.aspx) was placed on the table in front of the participant and the experimenter touched the frame with her index finger. The two video records were time-synchronized offline using Final Cut Pro (http://www.apple.com/final-cut-pro/). The time-synchronized video records were imported into Peak Motus Motion Analysis Software (http://www.motus10.com/) and points of interest on the arm and hand were manually digitized by clicking on them in both video views for each reaching trial. These time-synchronized 2D coordinate points were then transformed into 3D scaled coordinates using the 3D calibration frame as a spatial reference. Offline, frame-by-frame analysis of the time-synchronized high-speed video record was used to score further behavioural measures.

Movement Components. The movement components analyzed are based on a conceptual framework derived from Eshkol-Wachman Movement Notation (EWMN; Eshkol and Wachman, 1958), which has been used to describe reaching behaviour in healthy infants, healthy adults, and adults with sensorimotor disorders (see Sacrey et al., 2012; Whishaw et al., 2002). The standard reaching analysis was modified to describe the point in time at which specific movement components occurred. This was achieved by stepping frame-by-frame through the video records and noting the individual frame at which a movement component occurred. Frames numbers were converted to seconds and plotted as a function of total movement time. The movement components of interest to the present study are depicted in figure 5.1, which also shows the temporal organization of these movement components in an adult reaching with vision.

1. Lift was defined as the time point at which the hand made its first discernable movement away from the leg (or table) and toward the target object that resulted in contact with the target. If the infant did not begin with the hands placed on the table, *lift* was defined as the first movement towards the target resulting in contact.

2. Collect was defined as the time point at which flexion and closure of the digits resulted in the smallest distance between the tips of the index finger and the thumb prior to target contact.

3. Orient was defined as the time point at which supination of the forearm and hand was complete, such that the orientation of the hand reached the smallest angle relative to the vertical target object, which could be achieved either before or after target contact.

4. Peak Aperture was defined as the time point at which the distance between the tips of the index finger and thumb reached the largest aperture prior to target contact.

5. Close was defined as the time point at which the tip of the index finger and/or thumb first began to close, resulting in a successful grasp of the target.

6. Contact was defined as the time point at which the hand made first contact with the target.

7. Hold was defined as the time point at which digit closure was complete, resulting in successful holding of the target.

Total Movement Time was defined as the duration of time from *Lift* to *Hold*.

Inter-Rater Reliability of Movement Component Timings. Three reaches per infant age group, 3 adult Vision reaches, and 3 adult No Vision reaches were scored by three independent experimenters (N = 21 reaches or 105 movement components). Inter-rater reliability was assessed using intraclass correlation co-efficients (ICC) with absolute agreeability for individual movement components. For *Lift* ICC = 0.999 (95% confidence interval 0.990 – 1.000), *Collect* = 0.963 (0.765 – 0.987), *Orient* = 0.992 (0.942 – 0.997), *Peak Aperture* = 0.965 (0.779 – 0.988), *Close* = 0.991 (0.930 – 0.997), *Contact* = 1.000 (0.998 – 1.000), and *Hold* = .999 (0.991 – 1.000), suggesting very high reliability.

Contact, Orientation, and Aperture Kinematics. The time-synchronized video records were paused on the frame at which the hand made first contact with the target. Figure 5.2 shows the kinematic measures derived from the Peak Motus Motion Analysis software at this time point.

1. First Contact. The hand was arbitrarily divided into 20 sections corresponding to *distal contact locations* (distal digital phalanges) and *proximal contact locations (*middle and proximal digital phalanges + metacarpophalangeal (MCP) joints 2 to 5 + the thenar space between the thumb and index finger). Inspection of the video record was used to determine which section of the hand made first contact (visualized as a green dot in figure 5.2).

2*. Extra Contacts*. A reach movement was considered to contain an *extra contact* if, between first contact and final hold, the participant released and re-established contact.

3. Orientation at First Contact. The orientation of the hand at first contact was

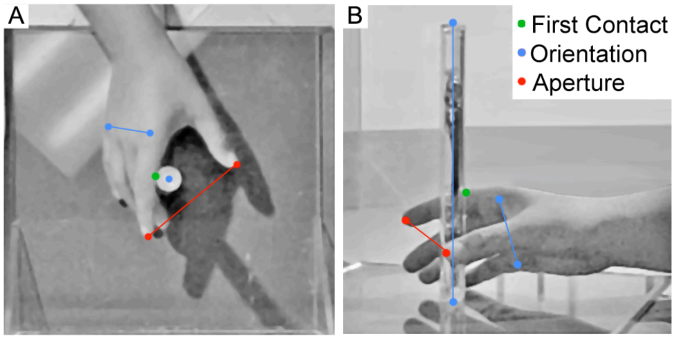


Figure 5.2 Aperture (red) and orientation (blue) of hand at first contact (green). A. Dorsal view. B. Lateral view.

determined by measuring the vector angle between two line segments, the hand (visualized as a blue line segment joining the second and fifth metacarpophalangeal joints in figure 5.2) and the vertical rod (visualized as a blue line segment joining the top and the bottom of the rod in figure 5.2). A hand orientation of 0° indicated that the hand was vertically oriented, parallel to the vertical rod, whereas an orientation of 90° indicated that the hand was horizontally oriented, perpendicular to the vertical rod.

4. Aperture at First Contact. The distance between the index finger and thumb at first contact was measured (visualized as a red line segment joining the tip of the index finger and the tip of the thumb) and divided by the participant's hand length (from tip of middle finger to center of wrist) to correct for differences in hand size across participants.

5. Kinematic Profiles. For a subset of reaches, change in hand orientation and change in hand aperture were plotted as functions of normalized time. Only trials on which infants began the reaching trial with the hands place on the table in front of them were included in this analysis.

Grasp Strategy. The grasp strategy used to acquire the target was scored using previously defined methods (Hall et al., 2014; Karl et al., 2012a). A visual grasp strategy was identified as one in which the digits preshaped in an over grasp before object contact, closed to a grasping configuration on approach to the object, and grasped the object directly without making adjustments as it was contacted. This is termed a *preshape* strategy and is illustrated in Figure 5.3A.

A grasp strategy was considered to be haptic if the hand did not preshape and close on approach to the target and/or featured adjustments to hand orientation, hand shape, or digit contact locations after first contact. Haptic strategies included a *touch & release*, in which the hand touched the object and then withdrew contact in order to adjust contact locations, re-orient, re-shape, and close the hand to grasp (Figure 5.3B); a *capture*, in which a digit or the palm of an open hand contacted the object while the remaining digits closed from a very large aperture to grasp it (Figure 5.3); an *adjust*, in which the target was grasped and then slightly released and grasped again in order to establish different contact points; and a *manipulate*, in which the target was moved and/or manipulated by one or more digits before being grasped (Karl et al., 2012a).

Infants often employed a combination of strategies such as a *touch & release* strategy followed by a *manipulate* strategy. For this reason, only the first strategy employed in each reach trial was counted for analysis.

Statistical Analysis

The results of the adult experiment were evaluated using a repeated measures ANOVA with the computer software SPSS (V.19). Visual Condition (NO VISION vs. VISION) served as a within-subjects factor when analyzing Movement Components (*collect, orient, peak ap, close, contact*), Total Movement Time, Extra Contacts, Time from Orient to Contact, Time from Close to Contact, Orientation at Contact, and Aperture at Contact. Results reported as proportions or frequencies such as Hand Contact (*proximal vs. distal hand*) and Grasping Strategy (*preshape, touch & release, capture*) were evaluated using the McNemar non-parametric statistical test.

To accommodate uneven subject and trial numbers, the results of the infant

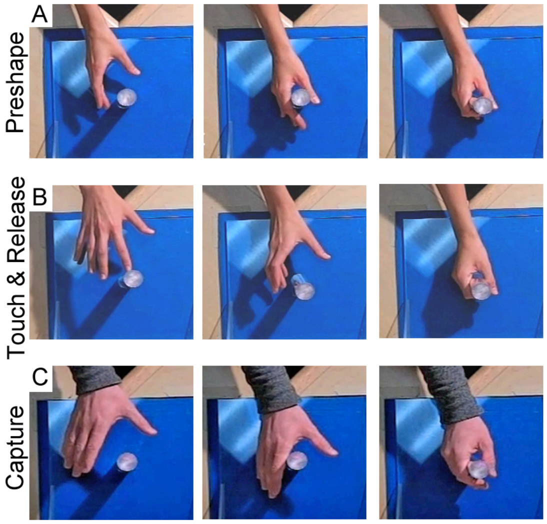


Figure 5.3 Grasping Strategies. A. *preshape,* digits gradually close to grasp at first contact B.,C., The digits do not gradually close to grasp at first contact. After touching the target the hand releases contact as the digits orient, shape, and close to grasp it (B, *Touch & Release*), or the hand maintains contact with the target as the remaining digits either close to grasp it (C, *Capture*) or manipulate the target in order to grasp it (not shown).

experiment were evaluated using a repeated measures mixed linear model (MLM) in SPSS (Heck et al., 2014). Age (4-6, 7-8, 9-10, 11-12, and 24 MONTHS) served as a between-subject factor and Trial (1, 2, 3, 4, 5, 6, 7, and 8) served as a within-subjects factor when analyzing Movement Components (*collect, orient, peak ap, close, contact*), Total Movement Time, Extra Contacts, Time from Orient to Contact, Time from Close to Contact, Orientation at Contact, and Aperture at Contact. Results reported as proportions or frequencies such as Hand Contact (*proximal vs. distal hand*) and Grasping Strategy (*preshape, touch & release, capture*) were normally distributed and evaluated using an one-way ANOVA using the Brown-Forsythe test to correct for unequal variances when necessary.

Adult vs. infant comparisons were made by converting infant repeated measures to the mean and treating adult Visual Condition (NO VISION vs. VISION) as a between-subjects factor. Because the data were normally distributed, statistical comparisons were made using an one-way ANOVA using the Brown-Forsythe test to correct for unequal variances when necessary.

A p value of < 0.05 was considered significant. Follow-up pairwise comparisons and post hoc analyses were subjected to Bonferroni correction. Unless a non-significant effect was of interest, only significant effects are reported. Results are reported as the mean ± standard error.

Results

Results Summary

In young infants, movement component organization resembled that of adults in the No Vision condition. At older ages, however, movement organization came to resemble that of adults in the Vision condition. At the youngest ages, infants failed to orient the Reach or close the Grasp prior to target contact. Thus, they required more time to complete these movements after the hand touched the target. The Reach and the Grasp followed different developmental profiles. Between 9 and 24 months, infants were able to transport and orient the Reach as accurately as adults in the Vision condition, but they persisted in using an open Grasp to contact the target, similar to adults in the No Vision condition. Infants of different ages also favoured different grasping strategies. Younger infants favoured a *touch & release* strategy, whereas older infants favoured a *capture* strategy. All infants differed from adults in the Vision condition who favoured the *preshape* strategy.

Movement Components

Figure 5.4 illustrates the time at which each movement component occurred as a function of total reaching time. Figures 4A and G show that the adult reaching movement is organized differently depending on whether or not vision is available. In the No Vision condition, *peak aperture* and target *contact* occur relatively early in the movement (~50% and 54% of the way through the movement, respectively) and hand *close* and *orient* are relatively delayed, occurring after *contact* (~74%, 78%, and 55% of the way through the movement, respectively). This differs from the adult Vision condition in which *peak aperture* occurs in the later half of the movement (~ 67%) and hand *orient* and *close* precede *contact*, (~50%, 74%, and 88%, respectively). Thus, reaching in the No Vision condition did not reflect a simple modification of the kinematics of visually guided reaching. Rather, the organizational structure of the movement was fundamentally different depending on whether or not vision was available. These differential movement structures can be described as follows:

Adult No Vision: Lift → Collect → Peak Ap → Contact → Orient/Close → Hold
Adult Vision: Lift → Collect → Orient → Peak Ap → Close → Contact → Hold

Infants aged 4 to 12 months (figures 5.4B,C,D,E) display the same reaching structure as adults in the No Vision condition. By 24 months, however, the structure of the reaching movement (figure 5.4F) approaches that of adults in the Vision condition. The adult results were confirmed by repeated measures ANOVAs that gave a significant effect of Visual Condition for *collect* [$F(1,17) = 56.961$, $p < 0.001$], *orient* [$F(1,17) = 51.642$, $p < 0.001$], *peak ap* [$F(1,17) = 29.527$, $p < 0.001$], and *contact* [$F(1,17) = 99.497$, $p < 0.001$], but not *close* [$F(1,17) = 2.388$, $p > 0.05$]. The infant results were confirmed by repeated measures MLMs that gave a significant effect of Age for *collect* [$F(4, 30.388) = 6.978$, $p < 0.001$], *orient* [$F(4, 27.206) = 11.582$, $p < 0.001$], *peak ap* [$F(4, 25.583) = 16.041$, $p < 0.001$], *close* [$F(4,26.909) = 5.903$, $p < 0.001$], and *contact* [$F(4,24.305) = 25.133$, $p < 0.001$].

Timing of Reach Orientation, Grasp Closure, and Total Movement Time

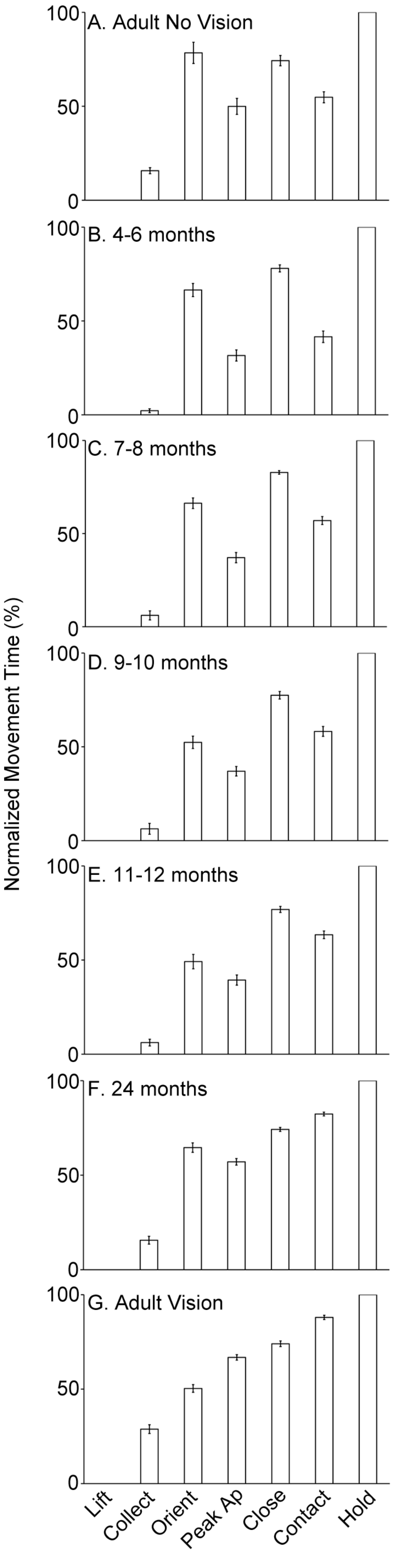


Figure 5.4 Temporal organization of reaching movement components. Reach movement components (mean ± se, lift, collect, orient, peak aperture, close, contact, and hold) averaged across all trials and subjects for each group and plotted against normalized time. *Note:* reaching component organization of young infants is similar to unsighted adults but transitions to resemble sighted adults in older infants.

Reach Orientation. Figure 5.5A illustrates time at which the hand finished orienting to the target relative to the time of target contact (0.0 seconds). Younger infants and adults in the No Vision condition failed to finish orienting the hand prior to target contact. Instead they completed hand orientation ~ 0.55s (4 to 6 month infants, NV adults) and 0.16s (7 to 8 month infants) after target contact. In contrast, infants aged 9 months and older finished orienting the hand anywhere from 0.14s to 0.24s prior to contact, similar to adults in the Vision condition.

These result were confirmed by a repeated measures ANOVA that gave a significant effect of Visual Condition [$F(1,17) = 54.542$, $p < 0.001$] for adults and a repeated measures MLM that gave a significant effect of Age [$F(4, 240.906 = 16.042$, $p < 0.001$] for infants. Adult vs. infant comparisons were confirmed by an one-way ANOVA that gave a significant effect of Group [$F(6, 35.995) = 26.821$, $p < 0.001$]. Pairwise comparisons revealed that in the No Vision condition adults did not differ from 4 to 6 month old infants, but did differ from all other groups ($p < 0.001$). In the Vision condition adults differed from 4 to 6 month old infants ($p < 0.001$) and 7 to 8 month old infants ($p < 0.01$).

Grasp closure. Figure 5.5B illustrates the time at which the digits began to close to Grasp relative to the time of target contact (0.0 seconds). On average, young infants, like adults in the No Vision condition, did not start closing the digits to Grasp until 0.84 to 0.20 seconds after target contact. With increasing age, infants required less time after contact to begin closing the digits to Grasp and between 12 and 24 months infants began to close the digits prior to contact, similar to adults in the Vision condition.

These results were confirmed by a repeated measures ANOVA that gave a

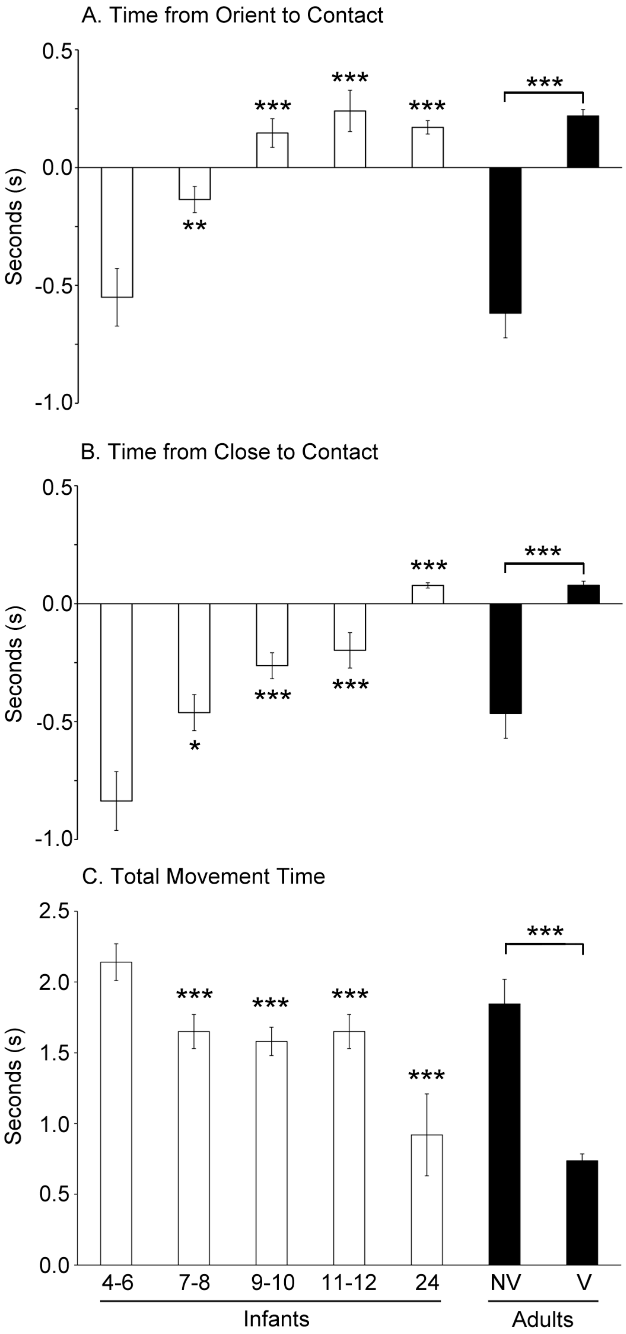


Figure 5.5 Timing of *orientation*, *aperture closure*, and *hold*. A. Time of orientation completion relative to first contact (mean ± se). B. Time of aperture closure onset relative to first contact (mean ± se) C. Total movement time from *lift* to *hold* (mean ± se) averaged across all trials and subjects for each group. *Note:* From 9 months of age and older infants finish orienting the hand prior to contact. At 12 months of age infants do not initiate hand closure until after object contact, but by 24 months they initiate hand closure prior to object contact, similar to sighted adults. Younger infants (4 to 12 months) and unsighted adults take significantly longer to complete the reach movement compared to older infants (24 months) and sighted adults (*** $p < 0.001$ vs. 4-6 month infants).

significant effect of Visual Condition [F(1,17) = 30.236, $p < 0.001$] for adults and a repeated measures MLM that gave a significant effect of Age [F(4,157.066 = 19.759, $p < 0.001$] for infants. Adult vs. infant comparisons were confirmed by an one-way ANOVA that gave a significant effect of Group [F(6,35.252) = 14.194, $p < 0.001$]. Pairwise comparisons revealed that in the No Vision condition adults differed from 4 to 6 month ($p <0.001$), 24 month ($p < 0.001$), and 11 to 12 month old infants ($p < 0.05$). In the Vision condition adults differed from all groups ($p < 0.001$, 0.01, 0.5) except 24 month old infants.

Total movement time. Figure 5.5C illustrates the total amount of time required to complete the reaching movement. Adults took significantly longer to complete the reaching movement in the No Vision condition compared to the Vision condition. Younger infants also took longer to complete the movement but total movement duration decreased as a function of increasing infant age such that 24 month old infants took about the same amount of time as adults in the Vision condition to complete the reaching movement.

These results were confirmed by a repeated measures ANOVA that gave a significant effect of Visual Condition [F(1,17) = 55.987, $p < 0.001$] for adults and a repeated measures MLM that gave a significant effect of Age [F(4,195.510, $p < 0.001$] for infants. Adult vs. infant comparisons were confirmed by an one-way ANOVA that gave a significant effect of Group [F(6,34.311) = 12.127, $p < 0.001$]. Pairwise comparisons revealed that in the No Vision condition adults differed only from 24 month old infants ($p < 0.001$) whereas in the Vision condition adults differed from all infants ($p < 0.001$) except 24 month old infants.

Contact Location and Extra Contacts

Contact Location. Figure 5.6A illustrates the part of the hand adults used to make first contact with the target in the No Vision and Vision conditions. Adults made contact with a larger range of distal digit segments in the No Vision condition compared to the Vision condition. The distal digit segment of the middle finger was the most common part of the hand to make first contact in the No Vision condition, whereas the proximal segment of the index finger was the most common part of the hand to make first contact in the Vision condition.

Figure 5.6B illustrates the part of the hand infants used to make first contact with the target. There was a general tendency for younger infants to make contact with distal portions of the hand and for older infants to make contact with proximal portions of the hand, especially between the index finger and thumb. The most common part of the hand to make first contact was the distal segment of the index finger in 4 to 6 month old infants; the distal segment of the thumb in 7 to 8 and 9 to 10 month old infants; the proximal segment and metacarpophalangeal joint of the index finger in 11 to 12 month old infants; and the thenar space between the index finger and thumb in 24 month old infants.

These results were confirmed by a McNemar test which showed that adults used the proximal part of the hand to contact the target significantly more in the Vision compared to No Vision condition ($p < 0.01$, 2-tailed) and an one-way ANOVA that gave a significant effect of Age [$F(4,34) = 6.139$, $p < 0.001$] for infants. Pairwise comparisons revealed that 24 month old infants made contact with proximal parts of the hand more

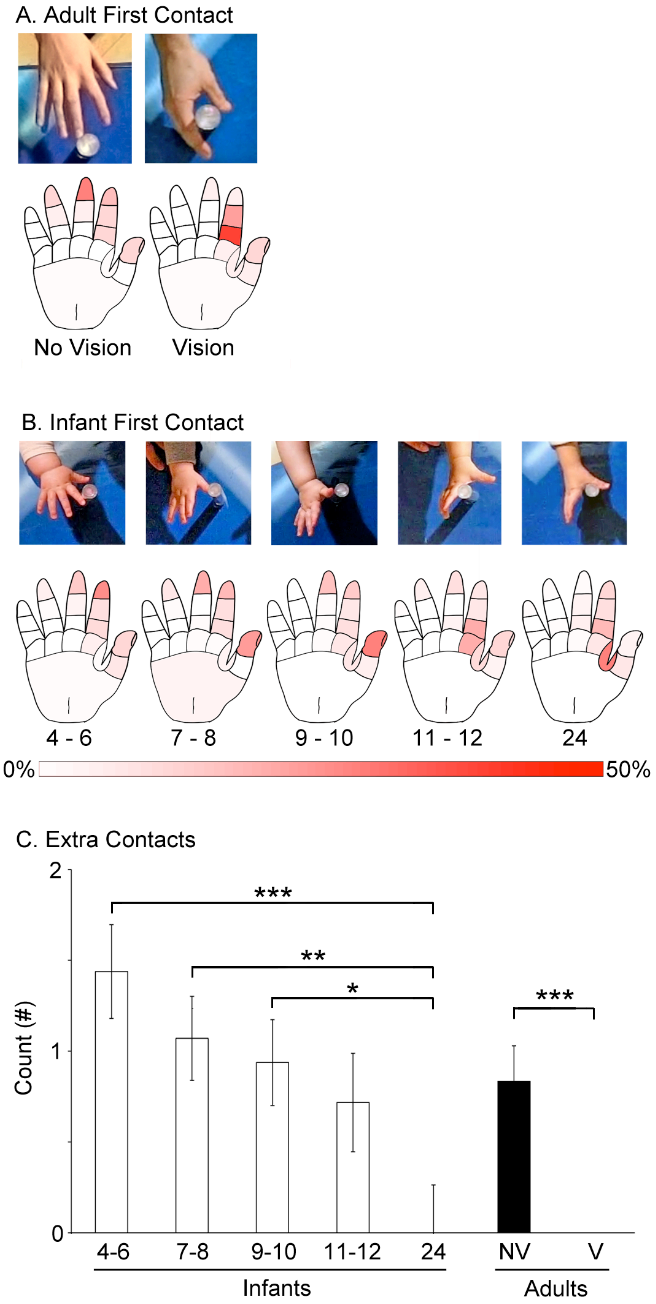


Figure 5.6 First contact and extra contacts. A.,B. Photographs and heat maps (averaged across all trials and subjects for each group) indicate which portion of the hand was most likely to make first contact with the target in unsighted and sighted adults (A) and infants (B). C. Number of extra target contacts (mean ± se) averaged across all trials and subjects for each group. *Note:* Younger infants (4 to 12 months) and unsighted adults are more likely to make first contact with a distal portion of the hand whereas older infants (24 months) and sighted adults tend to make contact with the thenar space or the proximal phalange of the index finger, respectively. Younger infants and unsighted adults also make extra contacts between first contact and final hold whereas older infants (24 months) and sighted adults do not (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

often than infants aged 4 to 6 months ($p < 0.01$), 7 to 8 months, ($p < 0.001$), and 9 to 10 months ($p < 0.01$); and 11 to 12 month old infants made contact with proximal parts of the hand more often than 7 to 8 month old infants ($p < 0.01$). Adult vs. infant comparisons were confirmed by an one-way ANOVA that gave a significant effect of Group [$F(6,62.446) = 7.029$, $p < 0.001$] and pairwise comparisons revealed that in the No Vision condition adults used the distal part of the hand to contact the target more than 24 and 11 to 12 month old infants ($p < 0.01$, 0.05), whereas in the Vision condition adults used the proximal part of the hand to contact the target more than 4 to 6, 7 to 8, and 9 to 10 month old infants ($p < 0.01$).

Extra Contacts. Figure 5.6C illustrates the number of extra contacts (and subsequent releases) made between the hand and target before the hand fully closed to grasp it. Adults made an average of one extra contact in the No Vision condition, whereas they never made any extra contacts in the Vision condition. The youngest infants also made extra contacts, but this decreased with increasing infant age.

These results were confirmed by a repeated measures ANOVA that gave a significant effect of Visual Condition [$F(1,17) = 55.987$, $p < 0.001$] for adults and a repeated measures MLM that gave a significant effect of Age [$F(4,28) = 4.225$, $p < 0.01$] for infants. Adult vs. infant comparisons were confirmed by an one-way ANOVA that gave a significant effect of Group [$F(6,68) = 8.578$, $p < 0.001$]. Pairwise comparisons revealed that in the No Vision condition adults differed only from 24 month old infants ($p < 0.01$) whereas in the Vision condition adults differed from all infants ($p < 0.001$, 0.01, 0.05).

Reach Orientation at First Contact

Figure 5.7 illustrates the orientation of the hand upon making first contact with the target. For adults, the angle between the hand and the vertical target was significantly greater in the No Vision condition compared to the Vision condition. This indicates that adults were more accurate at matching the orientation of their hand to the target before contact in the Vision condition. The youngest infants resembled adults in the No Vision condition in that the orientation of their hand did not match the target by the time of contact; however, the ability to match hand orientation to target orientation prior to contact gradually improved with increasing infant age.

The adult results were confirmed by a repeated measures ANOVA that gave a significant effect of Visual Condition for *orientation angle at contact* [F(1,17) = 80.257, $p < 0.001$]. The infant results were confirmed by a repeated measures MLM that gave a significant effect of Age for *orientation angle at contact* [F(4,35.614) = 23.574, $p < 0.001$]. Adult vs. infant comparisons were confirmed by an one-way ANOVA that gave a significant effect of Group [F(6,52.395) = 28.179, $p < 0.001$]. Pairwise comparisons revealed that in the No Vision condition adults differed from all infants except 4 to 6 month old infants ($p < 0.001$). In the vision condition adults differed from 4 to 6 ($p < 0.001$), 7 to 8 ($p < 0.001$) and 9 to 10 ($p = 0.05$) month old infants, but not 11 to 12 or 24 month old infants.

Kinematic Profiles of Hand Orientation

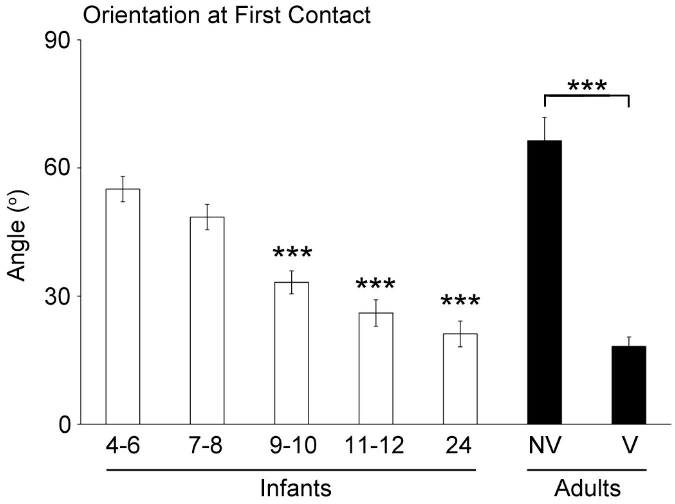


Figure 5.7 Orientation angle at first contact (mean ± se). *Note:* the accuracy of hand orientation at contact gradually improves with age and approaches that of sighted adults between 11 and 12 months of age (**p < 0.01, ***p < 0.001 vs. 4-6 month infants).

Figure 5.8 shows sample kinematic profiles of changing hand orientation as a function of total movement time for a 6 month old infant, 24 month old infant, an adult in the No Vision condition, and an adult in the Vision condition. The 6 month old infant, like the unsighted adult, contacts the target approximately half way through the movement and only finishes orienting the hand to the target after contact. In contrast, the 24 month old infant and the sighted adult finish orienting the hand prior to target contact, which occurs relatively later in the movement.

Grasp Aperture at First Contact

Figure 5.9 illustrates hand aperture (corrected for hand size) upon making first contact with the target. Adults contacted the target with a larger hand aperture in the No Vision condition compared to the Vision condition. Infants also contacted the target using a large hand aperture. Between 9 and 24 months, hand aperture at contact was proportionately larger even than that of adults in the No Vision condition. The use of a wide hand aperture at first contact was a consistent feature of grasping in all infant age groups and did not change with increasing age.

These results were confirmed by a repeated measures ANOVA that gave a significant effect of Visual Condition [$F(1,17) = 4.520$, $p < 0.05$] for adults and a repeated measures MLM that gave no significant effect of Age [$F(4,34.851) = 1.565$, $p > 0.05$] for infants. Adult vs. infant comparisons were confirmed by an one-way ANOVA that gave a significant effect of Group [$F(6,68) = 6.314$, $p < 0.001$]. Pairwise comparisons revealed that in the No Vision condition adults differed from 9 to 10 ($p < 0.01$), 11 to 12

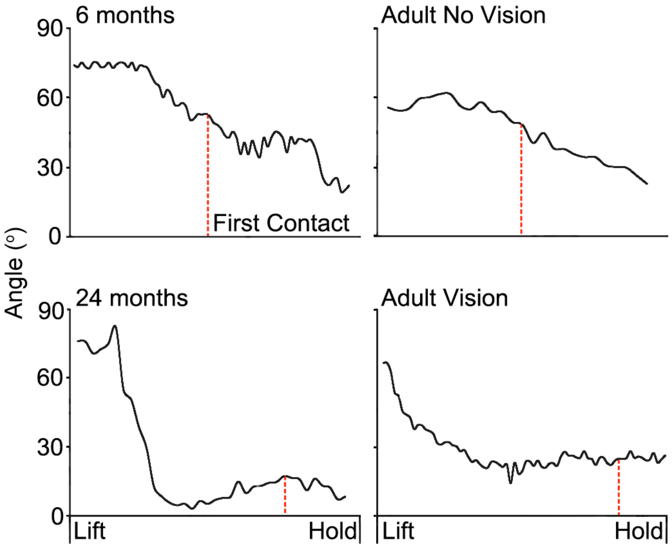


Figure 5.8 Sample kinematic profiles of hand orientation from *lift* to *hold*. Dashed red line indicates first contact with the target. *Note*: 4-6 month infants and unsighted adults continue to orient the hand to the target after first contact. 24 month infants and sighted adults complete hand orientation prior to target contact.

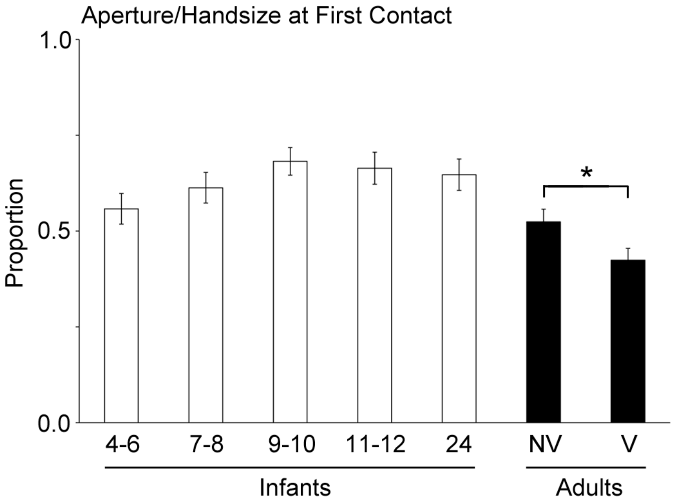


Figure 5.9 Index-thumb aperture, as a function of hand size, at first contact (mean ± se). *Note:* Infants show no improvement in aperture accuracy, even at 24 months, and use an exaggerated hand opening at object contact, similar to unsighted adults (* $p < 0.05$, ***$p < 0.0001$ vs. 4-6 month infants).

($p < 0.01$), and 24 ($p < 0.05$) month old infants. In the Vision condtion adults differed from all infant age groups except 4 to 6 month old infants ($p < 0.001$)

Kinematic Profiles of Hand Aperture

Figure 5.10 shows sample kinematic profiles of changing hand aperture (corrected for hand size) as a function of time for a 6 month old infant, 24 month old infant, an adult in the No Vision condition, and an adult in the Vision condition. The 6 month old infant and unsighted adult did not start closing the hand to grasp until after contact, which occurred about half way through the movement. The 24 month old infant only closed the hand a small amount before making contact, whereas the sighted adult closed the hand a significant amount before making contact. Infants of both ages opened the hand proportionately larger than adults.

Grasping Strategies

Figure 5.11 illustrates the frequency with which the 3 most prominent grasping strategies were used by infants and adults in the No Vision and Vision conditions.

Figure 5.11A illustrates the frequency with which a visual *preshape* strategy was used. Adults favored a *preshape* strategy in the Vision condition, but never used this strategy in the No Vision condition. Infants rarely employed a *preshape* strategy, but 24 month old infants used it more than younger infants.

These results were confirmed by a McNemar test which showed that adults used

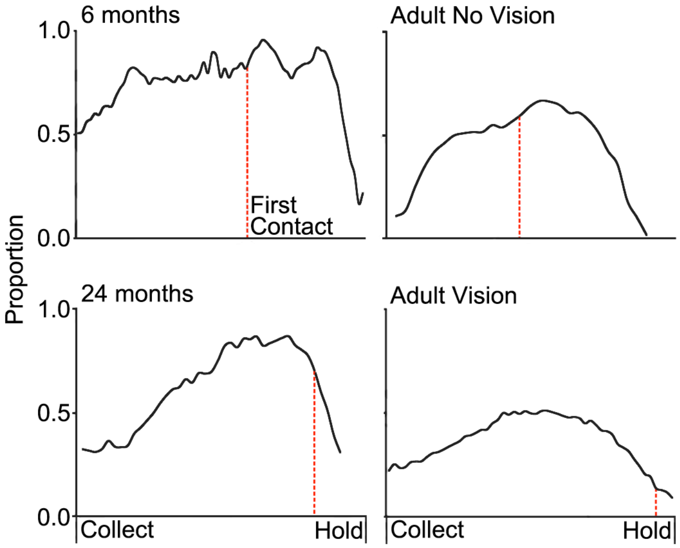


Figure 5.10 Sample kinematic profiles of aperture from *collect* to *hold.* Dashed red line indicates first contact. *Note*: 4-6 month old infants and unsighted adults initiate aperture closure after first contact, 24 month old infants at about the time of first contact, and sighted adults prior to target contact. Infants at all ages display an exaggerated opening of hand aperture prior to and at first contact compared to adults.

the preshape strategy significantly more in the Vision compared to No Vision condition ($p < 0.001$, 2-tailed) and an one-way ANOVA that gave a significant effect of Age [$F(4,34) = 8.680$, $p < 0.001$] for infants. Adult vs. infant comparisons were confirmed by a one-way ANOVA that gave a significant effect of Group [$F(6,68) = 18.542$, $p < 0.001$]. Pairwise comparisons revealed that adults differed only from 24 month old infants ($p < 0.001$) in the No Vision condition, but they differed from all infants ($p < 0.001$) in the Vision condition.

Figure 5.11B illustrates the frequency with which a haptic *touch & release* strategy was used. Adults slightly favored this strategy in the No Vision condition, but never used it in the Vision condition. This was also the preferred strategy among 4 to 6 month old infants, but decreased with increasing age.

These results were confirmed by a McNemar test which showed that adults used the touch & release strategy significantly more in the No Vision compared to Vision condition ($p < 0.01$, 2-tailed) and a one-way ANOVA that gave a significant effect of Age [$F(4,34) = 9.647$, $p < 0.001$] for infants. Adult vs. infant comparisons were confirmed by a one-way ANOVA that gave a significant effect of Group [$F(6,68) = 8.347$, $p < 0.001$]. Pairwise comparisons revealed that adults differed only from 24 month old infants ($p < 0.001$) in the No Vision condition whereas they differed from all infants ($p < 0.001$, 0.01, 0.05) except 24 month old infants in the Vision condition.

Figure 5.11C illustrates the frequency with which a haptic *capture* strategy was used. Adults employed this strategy 30% to 40% of the time in both Vision and No Vision conditions. While this strategy was not particularly prominent in the youngest

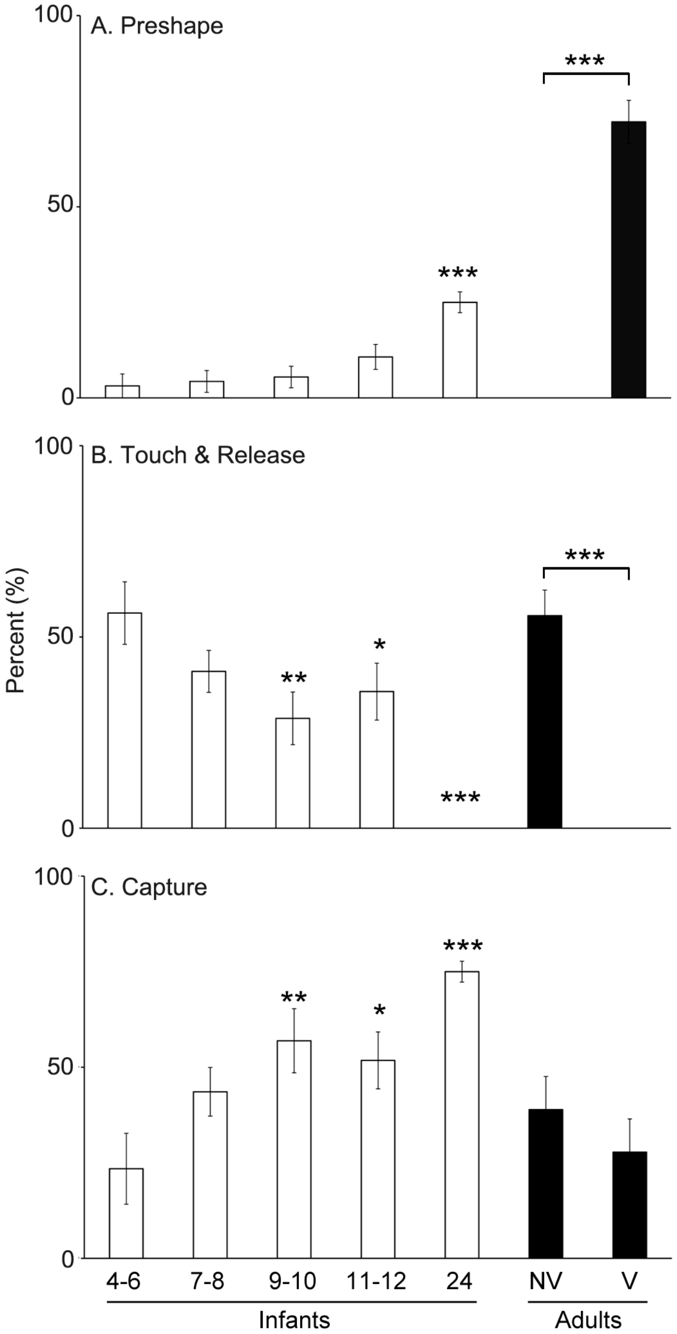


Figure 5.11 Grasping strategies. Percentage of trials (mean ± se) on which subjects used a visual *preshape* strategy (A), a haptic *touch & release* strategy (B), or a haptic *capture* strategy (C). The frequency of *adjust* and *manipulate* strategies are not plotted as their occurrence was minimal (* $p < 0.05$, **$p < 0.01$, *** $p < 0.001$ vs. 4-6 month infants).

infants, it’s use increased with age to become the dominant strategy in 24 month old infants.

These results were confirmed by a McNemar test which showed that the frequency with which adults used the capture strategy did not differ between the No Vision and Vision conditions ($p > 0.05$, 2-tailed) and a one-way ANOVA that gave a significant effect of Age [$F(4,34) = 6.201$, $p < 0.001$] for infants. Adult vs. infant comparisons were explored by an one-way ANOVA, which found a significant effect of Group [$F(6,58.734) = 3.134$, $p < 0.01$]. Pairwise comparisons revealed that in both the No Vision ($p < 0.05$) and Vision ($p < 0.01$) conditions, adults differed from 24 month old infants.

Discussion

Previous work has not fully clarified the relative use of visual guidance for Reach and Grasp movements in early infancy. While many studies have compared reaching in infants and sighted adults, the present study is the first to compare infant reaching to both visual and non visual reaching in adults. Participants were filmed as they reached to grasp a vertical rod. Movement component organization, hand orientation, hand aperture, and grasping strategy were analyzed to determine the extent to which vision was used to orient the Reach vs. close the Grasp prior to target contact. At the youngest ages, infant reaching resembled non visual reaching in adults, suggesting that when young infants first start reaching, they rely on non visual, haptic, inputs to guide both the Reach and the Grasp. Between 9 and 24 months, infant Reach orientation accurately anticipated target contact but Grasp closure did not, suggesting that older infants use vision to guide the Reach but still rely on haptics to guide the Grasp. Thus, the main finding indicates that infants transition from using a *Touch & Release* strategy in early infancy, characterized by temporal dissociation of the Reach and the Grasp, to a *Capture* strategy in later infancy, characterized by partial integration of the Reach and Grasp. The uncoupling of the Reach and the Grasp in early infancy appears related to their differential transition from somatosensory to visual guidance throughout development.

The present experiment used a number of innovative measures to compare movement organization, hand orientation, hand aperture, and grasping strategies across infants of different developmental ages and adults with and without vison. The movements were recorded using synchronized highspeed video cameras and analyzed using Peak Motus 3D video software. This technique avoids the application of physical markers or wires to the infant's arms and hands, which can influence infant reaching behaviour (Domellöf et al., 2007). This methodology also allowed the experimenters to evaluate deviations from normal visually guided reaching (e.g., extra contacts, manipulatory hand movements prior to grasping of the target, etc.), which are difficult to interpret from kinematic data derived solely from infrared emitting diodes taped to the skin. Visual and haptic grasping strategies were also categorized using previously defined methods (Karl et al., 2012a), which have been validated by producing inter-rater reliability scores of greater than 96% among 263 naïve raters (Hall et al., 2014).

Some caveats must be made with respect to the procedures used. First, on a minority of trials, infants in the 2 youngest age groups did not always initiate reaching with the hand placed on the table. On such trials reaching was often initiated with the hand positioned somewhat closer to the target, which could have slightly reduced the proportion of time required to get the hand to the target; however, the effect on overall movement time was likely minimal compared to the additional time required by young infants to make multiple contacts with the target and who used haptic grasping strategies. Second, preliminary work from our lab suggested that adults show a natural tendency to orient the hand in the horizontal plane when reaching without vision. To avoid an inflation in measures of orientation accuracy related to this tendency, only a vertical rod was used as a target. Third, our initial intention was to study infants up to 12 months old, which is sometimes considered the upper limit of reaching maturation (Halverson, 1931); however, our preliminary results indicated that maturity for this behavior exceeds 12 months, and so a 24 month group was added. This introduced an age gap between the two oldest infant groups. Future work should further clarify the developmental changes that take place between 12 and 24 months and beyond 24 months of age. Finally, total hand size (from tip of the middle finger to center of the wrist) was used to normalize measures of hand aperture across groups. There may be other measures that could be applied, e.g., absolute maximum aperture, but the measure used did reveal relative differences in the extent to which infants vs. adults opened the hand prior to target contact.

Movement component analyses revealed that adult reaching is structured differently depending on whether or not it is guided by vision. This difference provided insights into the changing structure of infant reaching throughout development. Early infant reaching resembles that of unsighted adults whereas later infant reaching resembles that of sighted adults. When vision is available, adults organize reaching in a temporally efficient manner: the hand lifts, collects, forms a peak aperture, orients to the target, and begins to close before touching the target. Consequently, the target is securely grasped almost immediately after contact. In contrast, in young infants and unsighted adults the hand lifts and forms a large peak aperture, contacts the target, and only then orients and closes to grasp. Consequently, young infants and unsighted adults spend a significant amount of time adjusting the orientation and aperture of the hand after target contact before they are able to achieve a secure grasp. These results show that adults flexibly re-structure the reaching movement depending on the availability of visual feedback. They also indicate that very young infants structure their reaching movements similar to unsighted adults, suggesting that non visual guidance dominates both Reach and Grasp control in early infancy

In addition to using a non visual reaching structure, both young infants and unsighted adults use a number of hand adjustments associated with haptic contact with the target. First, they tend to contact the target with distal, rather than proximal, parts of the hand, which is not conducive to immediate grasping. Second, they often make extra contacts, releasing and then re-establishing contact with the target before they grasp it. Third, release after contact is often associated with e-positioning the hand, so that a more *appropriate* target contact can be made (i.e., one in which the thumb and index finger are positioned on opposite sides of the vertical target and either the palm or thenar space contacts the target). Fourth, although not directly quantified, young infants appeared to delay the onset of digit closure until an *appropriate* contact with the target is established. The introduction of these post-contact adjustments results in an increase in total movement time, especially in the latter portion of the movement. At older ages, both the frequency of post-contact adjustments and total movement time decrease. Together, these results suggest that, like unsighted adults, young infants use haptic feedback associated with target contact to facilitate corrections in hand position, orientation, and aperture after initial target contact. At older ages, infants rely more on visual information to adjust hand orientation and to direct an appropriate part of the hand towards the target prior to contact.

Hand orientation and hand aperture at the time of contact reveal that visual guidance develops at different rates for the Reach vs. the Grasp. First, 4 to 6 month old infants and unsighted adults fail to align the hand to the target prior to contact. Anticipatory hand orientation improves gradually with increasing infant age and by 11 months infants do orient the hand prior to target contact with an accuracy equivalent to that of sighted adults. This result replicates previous work (Hofsten and Fazel-Zandy, 1984; Lockman et al., 1984; Morrongiello and Rocca, 1989; Schum et al., 2011; Wentworth eth al., 2000; Witherington, 2005) and suggests that visual control of the Reach develops gradually and is largely mature by 11 to 12 months of age. Second, 4 to 6 month old infants and unsighted adults fail to initiate Grasp closure before target contact. At older ages, infants begin to close the Grasp earlier, but it is not until 12 to 24 months that Grasp closure begins to anticipate target contact. Even so, 24 month old infants substantially attenuate Grasp closure compared to sighted adults, and continue to complete the majority of Grasp closure after target contact. These results are in line with previous work (Barrett & Needham, 2008; Hofsten & Rönnqvist, 1988; Schum et al., 2011) and suggest that visual control of the Grasp is substantially delayed and continues to mature beyond 24 months of age even though visual guidance of the Reach is largely mature at 11 to 12 months.

Infant Reach and Grasp configurations resemble the haptic grasping strategies that adults use when reaching without vision. Very young infants tend to use a *touch & release* strategy, which is characterized by a temporal dissociation of the Reach and the Grasp. That is, the two movements are executed in sequence, rather than in synchrony. The Reach is performed first and is associated with an open hand, which serves to establish haptic contact with the target. After contact, haptic feedback guides re-orienting of the hand, re-directing of the digits to appropriate contact locations, and re-shaping of the hand to Grasp. Thus, the use of a *touch & release* strategy seems to reflect a high reliance on non visual inputs, especially touch, for guiding both the Reach and the Grasp in early infancy. At older ages, infants transition to favouring a *capture* strategy in which the Reach and the Grasp partially synchronize. At these ages, the hand usually orients prior to target contact and contact is made with an appropriate part of the hand. Nevertheless, a wide hand aperture is maintained until target contact and Grasp closure is completed largely after contact. In infants, the use of a capture strategy seems to reflect an increased use of visual guidance for the Reach, but not the Grasp, which continues to rely on tactile feedback associated with target contact. Even at 24 months, infants rarely use a *preshape* strategy, in which the Reach and the Grasp are fully synchronized under visual control such that the hand orients, preshapes, and closes prior to target contact.

The present results are in agreement with a number of previous studies (Berthier and Carrico, 2008; Carrico and Berthier, 2010; Fagard, 2000; Konczak and Dichgans, 1997; Perris and Clifton, 1988; Robin et al, 1996; and Corbetta and Snapp-Childs, 2009; Schum et al., 2011) in suggesting that touch contributes to the early development of the Reach and the Grasp and that visual guidance of these movements continues to develop into early childhood. The present results also extend this work in a number of ways. First, they show that the structure of reaching in early infancy is fundamentally different from that of visually guided reaching in healthy adults; however, it features a general organization and additional movement adjustments characteristic of adult reaching without vision. Second, the present results suggest that visual guidance of the Reach vs. the Grasp develop at different rates, with the development of visual guidance for the Reach preceding that of the Grasp – a proposition that is also supported by neuroanatomical (Gharbawie et al., 2010, 2011) and behavioural work (Karl et al., 2013). Elsewhere Karl and Whishaw (2013) have suggested that the Reach is more dependent on vision than the Grasp, at least in primates. Third, developmental changes in reaching structure appear to be related to the use of different grasping strategies, which capitalize on different sensory inputs at different stages of development. Specifically, there appears to be a transition from strategies that capitalize almost entirely on somatosensation in early infancy, to strategies that use mixed control – vision for the Reach and touch for the Grasp – in later infancy.

An early dependence on haptic inputs for guiding separate Reach and Grasp movements may be developmentally advantageous for a number of reasons. First, haptic feedback may be more reliable than vision due to the ongoing development of postural control (Bertenthal and Hofsten, 1998; Hadders-Algra, 2013; Thelen and Spencer, 1998; Van Der Fits and Hadders-Algra, 1998), reaching synergies (Konczak and Dichgans, 1997), visual inputs to the dorsal stream (Loenneker et al., 2010), and the ability to re-weight visual and proprioceptive inputs to determine limb location (Bremner et al., 2013). Second, haptic dissociation of the Reach and the Grasp may facilitate successful acquisition of the target despite significant kinematic inconsistencies within individual Reach and Grasp components prior to 24 months of age (Konczak and Dichgans, 1997). Third, behavioural dissociation of the Reach and the Grasp under haptic control likely facilitates the refinement of distinct Reach vs. Grasp circuits in parietofrontal cortex through differential experience (Thelen et al., 1993). In this way, a delay in the onset of visual guidance may prevent overly tight coupling between the Reach and the Grasp.

Neurobehavioural separation of the Reach and the Grasp seems important as it allows for the two movements to be flexibly recombined depending on the sensory and cognitive demands of various situations. For instance, a variety of pincer, precision, power, or hook grasps could be combined with any variety of one handed reaches, two handed reaches, swats, pushes, or pulls (Karl and Whishaw, 2013). Thus, separation of the Reach and the Grasp, via differential haptic and visual control in early infancy likely supports the development of a more diverse behavioural repertoire compared to a developmental process that would favour the formation of a singular Reach-to-Grasp movement under the control of a single, visual, modality. Interestingly, recent evidence suggests that dorsal stream Reach and Grasp pathways develop in the absence of visual input in congenitally blind adults (Fiehler et al., 2009; 2010). Thus, future work aimed at describing the Reach and Grasp configurations of these patients should reveal whether or not they retain and utilize the same haptic grasping strategies as young infants and temporarily blind adults.

The present results should not be interpreted as suggesting that vision does not influence the Reach and the Grasp at all during early development, just that it does not appear to contribute in the same way that it does in adulthood. Clearly reaching in early infancy can be visually elicited and under a minority of conditions 24 month old infants appear to preshape the hand prior to target contact. In addition, previous work (Sacrey et al., 2012; Schum et al., 2011; Siddiqui, 1995) shows that 12 month old infants can select an appropriate grip posture prior to target contact, i.e. a pincer grip for a cheerio vs. a power grip for a plastic toy. We suggest, however, that early grip selection, as has been proposed for early selection of Reach orientation (McCarty et al., 2001), could be mediated by perceptual mechanisms in the ventral visual stream, while dorsal visual control mechanisms, which are needed to accurately synchronize Grasp closure with Reach termination (Goodale and Milner, 1992), continue to develop into early childhood. Such a proposition is supported by the fact that older infants in the present study selected not just a power grip, but an exaggerated power grip, compared even to unsighted adults, and also by recent neuroimaging work indicating that connectivity within the dorsal visual stream continues to mature beyond 7 years of age (Loenneker et al., 2010). Along this line of thinking, one might also consider that visual control of the Reach might developmentally precede the Grasp because young children favor vision for discriminating object orientation vs. haptics for discriminating object size, at least on perceptual tasks (Gori et al., 2008).

It has generally been accepted that the development of reaching features a progression from reflexive whole hand grasping to visually guided reaching using power then precision and pincer grips (Butterworth et al., 1997; Halverson, 1931). The present results, however, in combination with other work from our lab (Thomas et al., in prep; Wallace and Whishaw, 2003), suggests an alternative developmental progression based on the sensory control of discrete Reach and Grasp movements (Table 5.1). In stage 1, separate motor control systems for the Reach vs. the Grasp are expressed as vacuous preReach and preGrasp movements. In stage 2, separate preReach and preGrasp movements become self-directed and are reinforced through haptic feedback from the infant's own body. In stage 3, Reach and Grasp movements are directed towards external targets (which may or may not be visual, see Perris and Clifton, 1988; Robin et al., 1996), but they are sequentially executed so that haptic feedback associated with target contact can guide each movement separately. In stage 4, partially synchronized Reach and Grasp movements are directed towards external targets as visual control of the Reach ensures proper orienting of the hand prior to contact, but haptic control of the Grasp delays hand closure until after target contact. Finally, in stage 5, fully synchronized Reach and Grasp movements are directed towards external targets under foveal visual control.

In summary, the present results support the postulate of the Dual Visuomotor Channel theory that the Reach and the Grasp are distinct and derived from different neural origins. The present results additionally support the fourth hypothesis of the present thesis in suggesting that haptic inputs contribute to the guidance of early Reach and Grasp movements and that it is likely these, rather than visual inputs, that shape the initial development of separate Reach and Grasp pathways in parietofrontal cortex. Developmental changes in infant Reach and Grasp configurations also reflect changes in the extent to which haptic vs. visual inputs guide prehension. Specifically, they reveal a transition from a dependence on haptic cues for both the Reach and the Grasp in early infancy to a dependence on visual cues for the Reach vs. haptic cues for the Grasp in later infancy. In this way, sequential Reach and Grasp movements, mediated by different sensory inputs, may provide a developmental transition from the discrete preReach and

Table 5.1 Developmental progression of sensory control for discrete Reach and Grasp movements

Stage	Age	Movements	Sensory Control	Temporal Organization
1	Birth to 3 months	preReach & preGrasp (vacuous)	Spontaneous, visually/haptically elicited, and ballistic	Discrete
***2**	3 to 4 months	preReach & preGrasp (self-directed)	Haptically reinforced	Discrete or Sequential (Reach → Grasp)
3	4 to 9 months	Touch & Release	Reach = Haptically guided Grasp = Haptically guided	Sequential (Reach → Grasp)
4	9 to >24 months	Capture	Reach = Visually guided Grasp = Haptically guided	Partially Synchronized
5	? to adulthood	**Preshape	Reach = Visually guided Grasp = Visually guided	Fully Synchronized

* Stage 2 is described in Thomas et al., in prep.
** Adults also employ Touch & Release and Capture configurations in situations where vision is unavailable (Karl et al., 2012a) or degraded (Hall et al., 2014).

preGrasp movements of early infancy to the fully synchronized and visually guided Reach and Grasp movements of adulthood. Finally, complete integration of the Reach and the Grasp into a single prehensile act likely depends on a number of factors, including the maturation of visual inputs from the dorsal stream to separate Reach and Grasp circuits in parietofrontal cortex.

Chapter 6

Discussion

Abstract

Behavioural results from the present thesis support the postulate of the DVC theory that the Reach and the Grasp are separate movements mediated by different neural pathways. Nevertheless, they additionally suggest that modifications to the DVC theory are warranted in order to account for the finding that both vision and somatosensation likely access the Reach and Grasp pathways. This new model for the neural substrates of prehension leads to interesting questions concerning the evolutionary origins of the Reach and the Grasp. Specifically, is there a single evolutionary antecedent for prehension, or two different evolutionary antecedents, one for the Reach and one for the Grasp? Furthermore, did the antecedent(s) to prehension originate under visual or non-visual control? The purpose of the present review is to re-examine previous neuropsychological, developmental, and comparative evidence in light of the findings from the present thesis with the aim of determing the evolutionary origins of prehension. First, work from the present thesis is reviewed to show that the removal of vision in healthy adults causes prehension to decompose into its constituent Reach and Grasp components, which are then executed in sequence or isolation. Second, evidence is reviewed to show that similar decomposition occurs in optic ataxic patients following cortical injury to the Reach and the Grasp pathways and after corticospinal tract lesions in non-human primates. Third, combined evidence from the present thesis and previous work is presented to show that during development early nonvisual PreReach and PreGrasp movements develop into mature Reach and Grasp movements but are only integrated under visual control after a prolonged developmental period. Finally, a review of comparative studies reveals many

behavioural and neuroanatomical similarities between stepping movements and the Reach and between food handling movements and the Grasp. Together, the evidence suggests that the Reach and the Grasp are derived from different evolutionary antecedents and originated under non-visual control. The evidence is discussed in relation to the ideas that dual visuomotor channels in primate parietofrontal cortex emerged as a result of distinct evolutionary origins for the Reach and Grasp; that foveated vision in primates serves to integrate haptic Reach and Grasp movements into a single prehensile act; and, that flexible recombination of discrete Reach and Grasp movements under various forms of sensory and cognitive control can produce adaptive behavior.

Introduction

Prehension, the act of reaching to grasp an object, is used for many everyday functions, one of the most common of which is to retrieve a food item and place it in the mouth for eating. Prehension is performed with little conscious effort and appears as a seamless act. Thus, it is not surprising that it is sometimes considered a single movement in experimental research (Desmurget et al., 1996; Grol et al., 2007; Mon-Williams and McIntosh 2000; Smeets and Brenner 1999) or that it is proposed to have a single evolutionary origin, possibly derived from walking (Georgopoulos & Grillner, 1989), climbing through tree branches (Jones 1916; Le Gros Clark 1963), digging (Bracha et al., 1989), or capturing prey (Cartmill, 1974).

Nonetheless, distinctive changes in prehension have been reported after brain injury as some patients display curious impairments in hand preshaping for grasping despite being able to accurately transport the hand to the location of a visual target. To explain this phenomenon Jeannerod (1981) proposes that prehension actually consists of two distinct but temporally integrated movements, a Reach and a Grasp, each mediated by different neural pathways projecting from visual to motor cortex via the parietal lobe. The Dual Visuomotor Channel Theory (Arbib, 1981; Jeannerod, 1981) has received support from electrophysiological, neuroanatomical, brain imaging, and now behavioural studies (for reviews see Culham et al., 2006; Jeannerod et al., 1995; Davare et al., 2011; Schmidt and Lee, 2011; present thesis). Nevertheless, behavioural results from the present thesis argue that vision does not have privileged access to the Reach and Grasp pathways in parietofrontal cortex, but rather that non-visual inputs, such as somatosensation, also access these pathways in order to produce Reach and Grasp movements in the absence of vision (Dijkermann and de Haan, 2007; Fiehler et al., 2009, 2010; Karl et al., 2012a,b, 2013; Karl and Whishaw 2013).

This modification of the original DVC theory raises new questions concerning the evolutionary origins of prehension. Specifically, how did the Reach and Grasp come to be mediated by different neural substrates and did they originate under visual or non-visual control? Various animal species display a wide range of Reach and Grasp specializations using the tongue, mouth, neck, tail, trunk, or hand, each of which can be guided by various sensory modalities including olfaction, audition, somatosensation, and vision (Iwaniuk and Whishaw, 2000; Sustaita et al, 2013). Thus, evolutionary pressures favoring either the Reach or the Grasp could explain differences in forelimb specialization in different phylogenetic lineages. As an extreme example, the third digit is specialized for stepping in the horse (MacFadden, 1992) versus foraging and prey capture in the aye-aye (Lhota et al., 2008; Milliken et al., 1991). In primates, the Reach and the Grasp appear to have co-evolved and are put to integrated use in the many movements that comprise prehension. Nevertheless, distinct functional, biomechanical, and neuroanatomical features of the Reach and Grasp suggest that each has its own evolutionary history.

The Dual Visuomotor Channel Theory is described first. Behavioural results from the present thesis are then reviewed in order to reaffirm the contribution of non-visual somatosensory inputs to the production of independent Reach and Grasp movements in the absence of vision in healthy adults (Experiments 1, 2, and 3). Neuropsychological evidence is presented next, which suggests that when visual inputs to the cortical Reach and Grasp pathways are disrupted via brain injury, prehension again decomposes into discrete Reach and Grasp components. Developmental evidence is then presented to show that independent Reach and Grasp movements are initially established under haptic control in early infancy, before being integrated together under vision following a prolonged developmental time period (Experiment 4). Finally, comparative evidence is presented to show that independent Reach and Grasp movements are not only identifiable in the forelimb movements of primates, but also in many non-primate species. Collectively, the evidence suggests that the Reach and the Grasp are derived from different evolutionary origins and were only recently, in phylogenetic terms, integrated together under visual control in primates.

The Dual Visuomotor Channel Theory

The Dual Visuomotor Channel Theory has its origins in the proposal that pointing has two phases. A ballistic movement brings the forelimb to the general location of a target and then a visually guided corrective movement positions the hand on the target (Woodworth, 1899). Indeed, dual phase guidance may be a general feature of animal movement (Hamilton et al, 2004). The distinctive contribution of the Dual Visuomotor Channel Theory is that it describes prehension in ethological terms: the Reach serves to bring the hand into contact with the target by transporting it to the appropriate location whereas the Grasp serves to shape the hand for target purchase. As distinct behaviors, the Reach and the Grasp may be subject to different evolutionary pressures and adaptive specializations that can be analyzed by comparative methods.

Table 6.1 Reach and Grasp Components of the DVC Theory

	Reach	Grasp
1. Musculature	Proximal (Upper Arm)	Distal (Lower Arm & Hand)
2. Function	Transport Hand to Target	Shape Hand for Target Purchase
3. Spatial Properties	Extrinsic (Location & Orientation)	Intrinsic (Size & Shape)
4. Spatial Coordinates	Egocentric	Ego- and Non-egocentric
5. Visuomotor Channel	Dorsomedial Parietofrontal Cortex	Dorsolateral Parietofrontal Cortex

Distinctive features of the Reach and the Grasp are summarized in Table 6.1. The Reach transports the hand to the location of the target so that the digits align with appropriate contact points on the target. It is produced largely by proximal musculature of the upper arm, is guided by the extrinsic properties of the target (location and orientation), and is coded in egocentric coordinates relative to the reacher. The Grasp preshapes the digits by first opening them to a peak aperture that scales to target size, then gradually closes them on approach to the target, and finally closes them completely for target purchase. The Grasp is produced mainly by distal musculature of the hand and digits, is guided by the intrinsic properties of the target (size and shape), and can be coded in spatial coordinates intrinsic to the hand irrespective of the hand's location relative to the body.

The Reach and the Grasp are subserved by largely segregated visuomotor pathways in occipitoparietofrontal cortex (Figure 6.1). The dorsomedial Reach pathway projects through the superior parietal lobule via the parietal reach region (PRR), which includes the superior parieto-occipital cortex (SPOC/V6A), medial intraparietal sulcus (mIPS), and anterior precuneous (aPCu). It then projects to dorsal premotor cortex (PMd), and finally to primary motor cortex (M1). The dorsolateral Grasp pathway projects through the anterior intraparietal sulcus (aIPS) to ventral premotor cortex (PMv) and from there to M1 (Cavina-Pratesi et al., 2010b; Culham and Valyear 2006; Davare et al. 2011; Filimon 2010; Jeannerod et al., 1995; Rizzolatti and Luppino, 2001). Long-train intracortical microstimulation of the dorsomedial pathway elicits reaching movements in awake and anesthetized monkeys, whereas microstimulation of the dorsolateral pathway

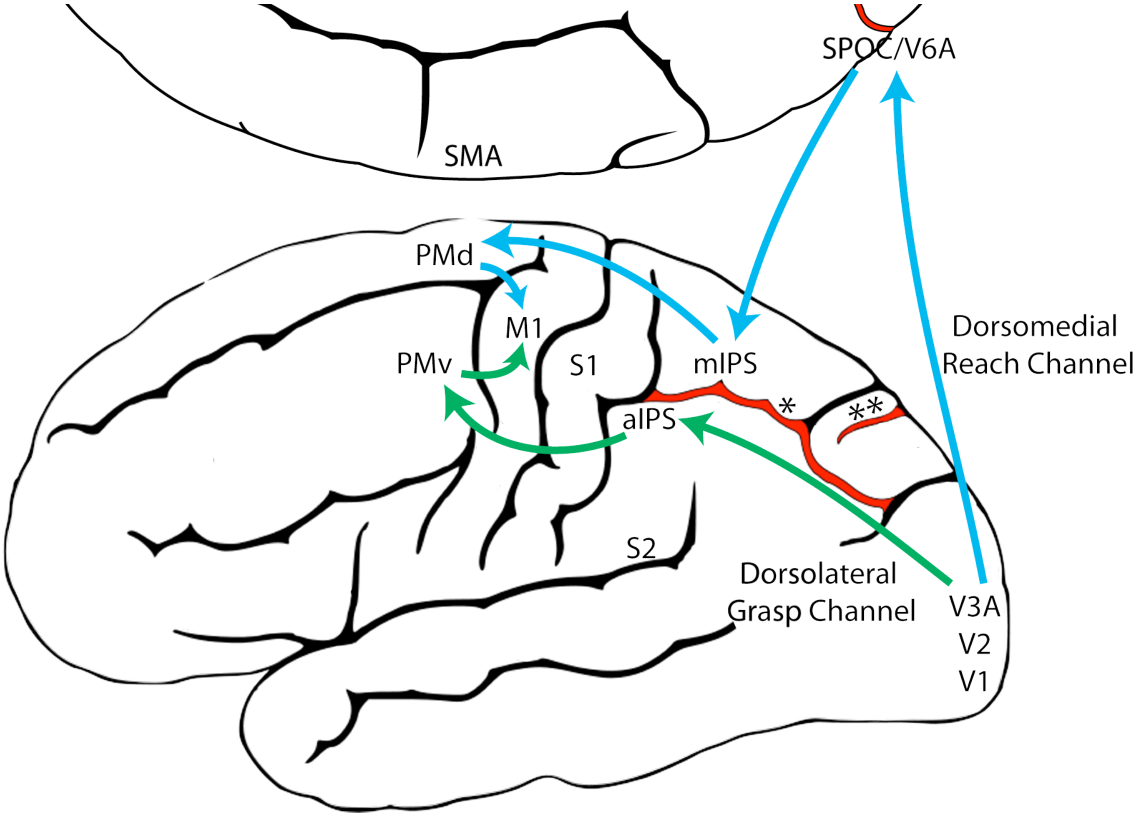


Figure 6.1 The dorsomedial Reach pathway (Blue) and the dorsolateral Grasp pathway (Green), adapted from Grafton, 2010 (aIPS – Anterior Intraparietal Sulcus, M1 – Primary Motor Cortex, mIPS – Medial Intraparietal Sulcus, PMd – Dorsal Premotor Cortex, PMv – Ventral Premotor Cortex, S1 – Primary Somatosensory Cortex, S2 – Secondary Somatosensory Cortex, SMA – Supplementary Motor Area, SPOC – Superior Parieto-Occipital Cortex, V1 – Primary Visual Cortex, V2 – Secondary Visual Cortex, V3A – Visual Area 3A, V6A – Visual Area 6A, * - Intraparietal Sulcus, ** - Parieto-Occipital Sulcus).

elicits grasping and/or manipulatory movements (Kaas et al., 2012; Gharbawie et al. 2011; Graziano et al., 2005).

The Dual Visuomotor Channel Theory posits that concurrent visual inputs to the dorsomedial and dorsolateral pathways allow the Reach and the Grasp to be simultaneously executed as a single integrated act (Figure 6.2A). The preeminent role of vision is illustrated by the act of foveating the target from movement onset until target contact (Sacrey and Whishaw, 2012). This visual attention is essential for identifying the terminal point of the Reach, i.e., contact locations on the target, and also for coordinating closure of the hand on approach to the target. Nevertheless, nonvisual and cognitive inputs may act through the visuomotor Reach and Grasp pathways in order to acquire targets in the absence of visual guidance (Cohen et al., 2009), to produce pantomime Reach and Grasp movements (Goodale et al., 1994; Milner and Goodale, 2008), and also to produce spontaneous Reach and Grasp gestures associated with speech (Whishaw et al., 2010b).

Visual Occlusion Dissociates the Reach and Grasp in Healthy Adults

One approach to dissociating the Reach and the Grasp is to manipulate the relative extrinsic or intrinsic properties of a single visual target, but this manipulation has produced ambiguous results. For example, Jeannerod (1981) finds that when the size of a visible target is changed unexpectedly, the Grasp is altered but the Reach is not. In contrast, Jakobson and Goodale (1991) find that both the Reach and the Grasp are altered. The difficulty in dissociating the Reach and the Grasp with this approach is that when the shape or location of the visual target is changed, both extrinsic and intrinsic target properties are altered resulting in concurrent adjustments in both the Reach and the Grasp.

An alternative way to dissociate the Reach and the Grasp is to remove vision, such that the extrinsic and intrinsic properties of the target must be determined nonvisually. Karl et al. (2012a – Experiment 1) asked blindfolded participants to reach for targets of varying size: a blueberry, doughnut ball, and orange slice. Targets were randomly presented, one at a time, on a pedestal in front of the participants so that they would not know which target they were reaching for on any given trial. In performing the task, participants advanced an open hand above and then down onto the target, often palpitating in the region of the target until touching it. The dorsal trajectory and open digits appeared to enhance the chances of target contact. After touching the target, the participants used haptic cues to shape the digits for grasping. Sometimes the hand released contact with the target before the digits preshaped and closed to Grasp. Other times, the target was stabilized or manipulated by some digits while the remaining digits shaped to Grasp. Hand scaling after target contact was equal to that of visually guided hand preshaping. Thus, when the extrinsic and intrinsic properties of the target cannot be visually determined, the prehensile act decomposes into sequential Reach and Grasp movements, each guided by somatosensation. The Reach, likely mediated by proprioception, is performed first and serves to locate the target by touching it. Only after contact do the hand and digits shape to haptic cues in order to Grasp the target. This two-staged act is termed a Touch-then-Grasp strategy and is illustrated in Figure 6.2B.

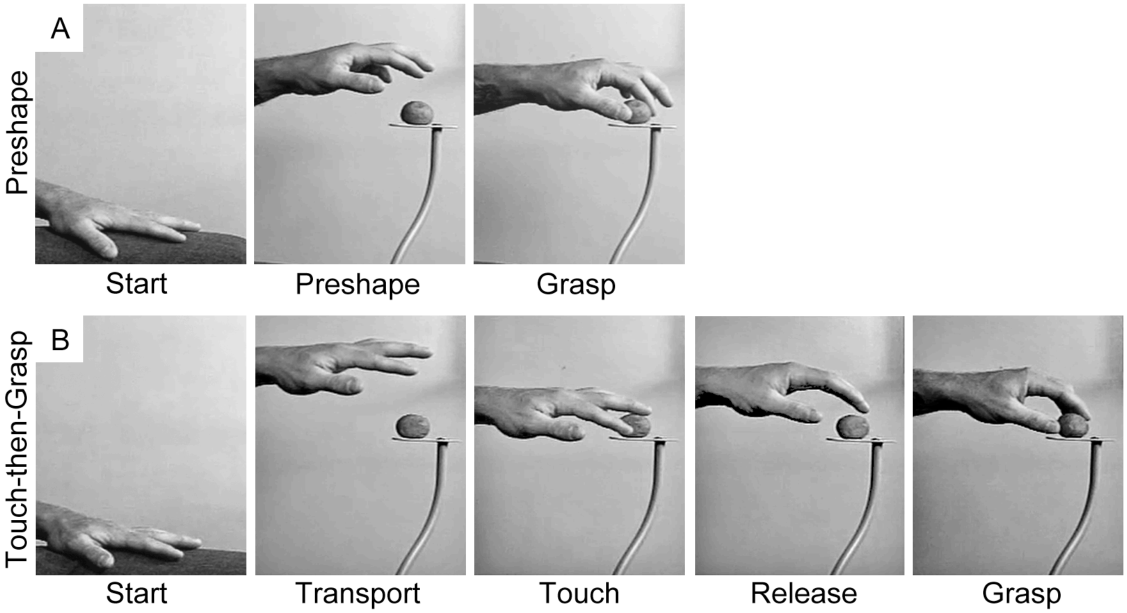


Figure 6.2 Representative still frames illustrating (A) the Preshape strategy used to acquire a visible target and (B) the Touch-then-Grasp strategy used to acquire an unseen and unknown or uncertain target. Note: For the Preshape strategy the Reach and the Grasp are temporally integrated such that the hand preshapes and orients to the intrinsic properties of the target before touching it. For the Touch-then-Grasp strategy the Reach and the Grasp are temporally dissociated such that the hand does not shape to the intrinsic properties of the target until after touching it.

A variation of this experiment had participants learn about the extrinsic and intrinsic properties of the target through repeated nonvisual experience (Karl et al. 2013 – Experiment 2). Blindfolded participants reached 50 times for a doughnut ball. Although initially unknown, both the location and size of the target could be learned through repetition. As was found in the unknown target experiment, participants persisted in using a dorsal Reach trajectory, in which the hand approached the target from above and an open hand and digits were used to locate the target by touching it. Nevertheless, within a few trials the participants began to preshape hand aperture to the size of the target before touching it. Scaling of hand aperture became indistinguishable from that of sighted participants. Thus, previous nonvisual experience had differential effects on the Reach and Grasp such that a dorsal Reach trajectory became coupled with a preshaped Grasp. Another experimental variation had participants perform the task using peripheral vision, a manipulation that provided enough visual information to identify each target while still degrading information about target size and location (Hall et al., 2013). Similar results were obtained, participants maintained a dorsal Reach trajectory but could scale hand aperture to target size before touching it.

The finding that previous somatosensory experience can instruct accurate hand preshaping for the Grasp raises the question of whether online haptic inputs could produce fully integrated Reach and Grasp movements similar to that of visually guided prehension (Karl et al., 2012b – Experiment 3). Online haptic feedback is known to be available in acts such as reaching for a part of the body or objects on the body. Thus, participants were asked to reach for one of three different sized food targets that were randomly placed in their mouth by the experimenter. When reaching to grasp the target, participants preshaped and oriented the hand prior to target contact, closed the digits in anticipation of target contact, and successfully grasped the target on the first attempt. Scaling of hand aperture was as accurate, and for some food items, more accurate, than that of visually guided grasping. Thus, online haptic information from a target held in the mouth is as informative as online vision for guiding integrated Reach and Grasp movements.

The behaviors called upon in these studies resemble many everyday actions in which people reach for and manipulate objects under degraded visual conditions. Such acts include reaching for objects in the dark, reaching for objects contacting the body (Edwards et al., 2005), or sequential reaching acts in which one object is grasped while visual attention is directed to a subsequent target. Collectively, these studies support the idea that somatosensation and vision both have access to the Reach and Grasp pathways (Dijkerman and de Haan, 2007; Fiehler et al., 2007a,b, 2008, 2010). As will be discussed below, this conclusion further suggests that somatosensation may have been formative in the evolution of distinct Reach and Grasp movements and their underlying neural substrates.

Visuomotor Impairment Dissociates the Reach and Grasp after Brain Injury

The Reach and the Grasp are also dissociated after localized brain injury that disrupts visual input to one or both of the visuomotor pathways. Patients with such injury display optic ataxia; an impairment in visually guided hand movements despite normal visual perception (Balint, 1909; Jakobson et al., 1991). Recent work with optic ataxic patients support the postulate of the Dual Visuomotor Channel Theory that the visuomotor pathways of the Reach and the Grasp are subject to a double dissociation.

A number of patients with damaged visual inputs to the Grasp, but not Reach, pathway have been described (Binkofski et al., 1998; Jeannerod et al., 1994). These patients have no problem reaching to the location of a visual target and consistently touch it on the first attempt; however, they use an open hand to do so and only close their digits to grasp the target after touching it. Thus, these patients seemingly adopt a modified Touch-then-Grasp strategy. They use vision to determine the target's extrinsic properties (location) but are unable to use vision to determine the target's intrinsic properties (size and shape) and thus cannot preshape the hand to Grasp prior to target contact. Instead they rely on haptic cues after target contact to shape their digits to the contours of the target in order to Grasp it.

Cavina-Pratesi and colleagues (2010a) describe the reverse condition, in which a patient cannot perform a visually guided Reach but can perform a visually guided Grasp. The patient, M.H., suffered an anoxic episode, disrupting visual inputs to the Reach but not the Grasp pathway. M.H. accurately opens, preshapes, and closes his hand to Grasp a visual target, but only if the target is located adjacent to his hand; i.e., if he doesn't have to Reach for it. If he does have to Reach for it, he must first locate it by touch before shaping his hand to Grasp it: "Presumably M.H., wittingly or unwittingly, compensates for the direction and distance errors resulting from his damaged visual reaching network, by habitually opening his hand widely: the wider the hand aperture, the higher the probability of successfully acquiring the object." M.H.'s visually guided Reach movements are inaccurate regardless of whether the movement is directed inward (towards his body) or outward (away from his body), indicating that his deficit is related to visual guidance of the Reach and not the location of the target within egocentric space. Thus, M.H. can use vision to guide his hand in relation to the intrinsic (size and shape) but not extrinsic (location) properties of a target.

The neural substrates that integrate the Reach and the Grasp under visual control may extend beyond the cortex into the spinal cord. Karl and Whishaw (2013a) re-examined the Reach and the Grasp movements of monkeys with bilateral corticospinal tract (CST) lesions, first described by Lawrence and Kuypers (1968). The analysis suggests that these monkeys may also use a Touch-then-Grasp strategy to acquire visual targets. They Reach towards the target using an open and extended hand and often miss the target on the first attempt. They then palpitate the hand in the vicinity of the target until they touch it. After initial contact, the hand releases contact with the target, re-shapes, re-orients, and finally closes to Grasp the target (Figure 6.3). Impairments in hand preshaping have also been reported following more selective corticospinal tract lesions in monkeys (Alstermark and Isa, 2012; Isa et al., 2007; Pettersson et al., 2007)

Taken together these lesion studies suggest that the visuomotor pathways of the Reach and the Grasp are separate. They also suggest that if brain injury deprives a subject of visual information, somatosensory mediated Reach and Grasp movements are adopted. Finally, it is possible that direct corticomotoneurons in primates mediate the motor output for visual control of the Reach and the Grasp pathways. It is instructive that direct corticomotoneurons and the dorsal visual stream evolved concurrently in the primate lineage.

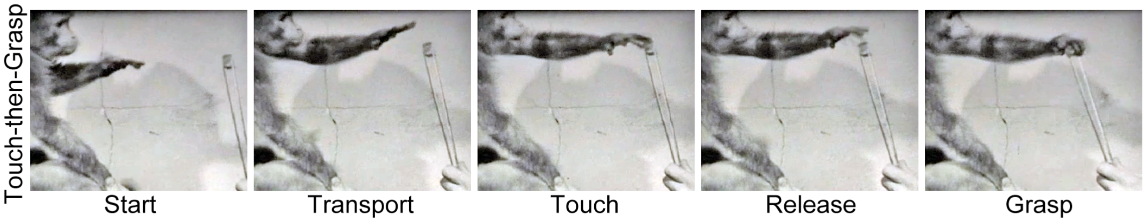


Figure 6.3 Representative still frames illustrating the Touch-then-Grasp strategy used by a macaque monkey to acquire a visible target 5 months after a bilateral corticospinal tract lesion. Note: even though vision is available the monkey advances an open hand towards the target, and only shapes and closes the hand to grasp the target after it has been touched (videos provided by D.G. Lawrence; Lawrence and Kuypers, 1968a).

Dissociation of the Reach and Grasp in Early Infancy

At about 5 months of age human infants begin to haphazardly reach for visual targets, gradually becoming more accurate at bringing a single hand to the target, and finally developing precision grips to grasp (Berthier et al., 1999; Bower, 1974; Halverson, 1931; Sacrey et al., 2012; Twitchell, 1970; Wimmers et al., 1998). We have re-examined the development of infant reaching in order to determine whether the Reach and the Grasp have different developmental profiles. Our results show that the Reach and the Grasp emerge independently as PreReach and PreGrasp movements in early development and require a significant length of time to become fully integrated under visual control.

Young infants produce a variety of PreReach movements before they can direct a single hand to the location of a visual target. From birth infants can orient the eyes and head to a visual target (Greenman, 1963; Kremenitzer et al., 1977). Soon after, they reach for the target with the mouth by thrusting the head forward and flexing the abdominals (Foroud and Whishaw, 2012; Supplementary Video 1), eventually they use a fisted hand to swipe and wave at a target (White et al., 1964). Consummation of these PreReach movements into a targeted, visually guided Reach only emerges at about 5 months of age. Initially an open hand advances along a jerky trajectory to make imprecise contact with the target (Sacrey et al., 2012). This ability develops equally whether the infant has sight of their hand or not and successful contact with the target is signaled by haptic rather than visual feedback (Clifton et al., 1993; Schlesinger and Parisi, 2001). However, by 7 to 9 months, visual control of the Reach improves significantly such that the location and orientation of the open hand accurately reflects the extrinsic properties of the target at the moment of target contact (Karl & Whishaw, 2014; Lockman et al., 1984; von Hofsten and Fazel-Zandy, 1984).

Young infants also produce a variety of PreGrasp movements before they can preshape the hand and digits to match the contours of a visual target. At birth the digits display a closed and flexed posture, but by one month they adopt a collected posture in which the hand is relaxed and partially open (Sacrey and Whishaw, 2010). Nevertheless, newborn infants will close the digits on an object that makes haptic contact with the palm (Twitchell, 1965) and by at least 4 months of age infants can use haptic cues to shape the hand to match the contours of an object (Newell et al., 1989). By 2 months of age infants start "hand babbling", producing a variety of spontaneous but complex digit movements that form a variety of Grasp configurations. Movements include extension and flexion of individual digits, sequential digit movements, and pressing individual digit pads together to form vacuous pincer and precision grips (Wallace and Whishaw, 2003; supplementary video 2). At 4 months, these movements become self-directed and are used to grasp the infant's own body or clothing. In performing these movements, infants do not look at their hands, suggesting that the movements are shaped by somatosensation rather than by vision.

Not only do the Reach and the Grasp emerge independently in early development, but they require a long developmental period to be integrated under online visual control. When infants first start to Reach to visual targets, they advance an open hand along a jerky trajectory, often missing the target on the first attempt or making multiple contacts between the open hand and target before closing to Grasp it. Thus, they do not preshape the hand to the target and use a Touch-then-Grasp strategy similar to that described above for unsighted adults. As infants age, they become more accurate at using vision to direct an open handed

Reach to the target on the first attempt; however, they do not preshape the hand and haptic contact with the target continues to instruct shaping of the Grasp, similar to the first set of optic ataxic patients described above (Figure 6.4; Clifton et al., 1993; McCarty et al., 2003). Thus, the Reach and the Grasp are dissociated in early development and complete integration of the two movements under visual control, such that the hand accurately preshapes prior to target contact, does not appear to be complete until at least 2 years of age (Karl and Whishaw, 2014 – Experiment 4).

In summary, analyses on the development of prehension provide evidence that the Reach and the Grasp follow independent developmental profiles. Initially, both the Reach and the Grasp emerge under somatosensation and only later come under visual control. Even then, visual guidance of the Reach develops before visual guidance of the Grasp. Finally, integration of the Reach and the Grasp under visual control only appears after a protracted developmental time course lasting into early childhood.

Comparative Evidence for Distinct Evolutionary Origins for the Reach and Grasp

The preceding lines of evidence show that somatosensory and visual information have equal access to the neural pathways that control the Reach and the Grasp. When vision is removed or limited, as occurs with visual occlusion, brain injury, or early in development, the Reach and the Grasp are dissociated by a Touch-then-Grasp strategy that maximizes the use of haptic feedback for guiding each movement independently. Nevertheless, the Reach and the Grasp can be integrated under nonvisual control, similar to visually guided prehension, if online haptic feedback concerning the target is available. In the following section we will

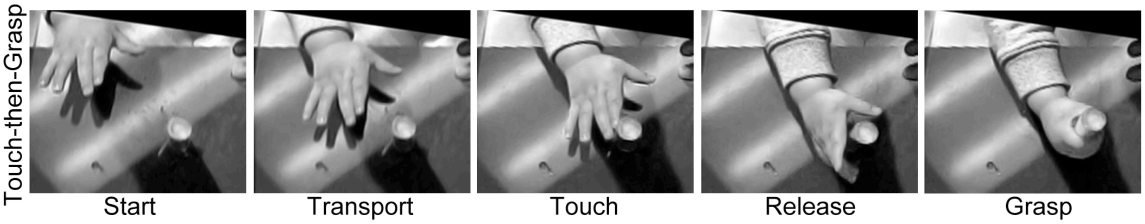


Figure 6.4 Representative still frames illustrating the Touch-then-Grasp strategy used by a 7 month old human infant in order to acquire a visible target. Note: even though vision is available the infant advances an open hand towards the target, touches the target, and then re-orients, shapes, and closes, the hand to Grasp it.

consider evidence that haptically mediated Reach and Grasp movements are phylogenetically older than those guided by vision.

In phylogenetically early quadrupeds, the neural control of the forelimbs and hindlimbs is tightly coupled to subserve locomotion, but even when stepping a forelimb has independence. Forelimb stepping is achieved by first flexing the forelimb to release contact with the substrate and then extending it to re-establish contact at another location (Grillner, 1975). Semi-independent control of a single forelimb likely evolved to allow animals to circumvent obstacles and to navigate over uneven terrain (Armstrong, 1988; Beloozerova and Sirota, 1993; Georgopoulos and Grillner, 1989; Krouchev and Drew, 2013). Complete independence of a single forelimb allowed the stepping movement to be adapted for a variety of non-locomotor functions such as pushing, swatting, or digging. For instance, a polar bear may flex and extend a single forelimb in order to pin a slippery fish to the ground, a cat may flex and extend a single forelimb to swat at a fly, or a boar may flex and extend a single forelimb to uncover a food item covered by soil. Thus, the wide range of independent forelimb movements produced by various animals, including Reach movements, may be derived from a common origin, stepping.

Our behavioral and kinematic analyses reveal similarities between forelimb stepping and the Reach movement which support the idea of common origin (Figure 6.5). We have examined a variety of movements in rodents and primates, including walking in rats, crawling in humans, and climbing and reaching in both species. In all of these behaviors, the forelimb movement is initiated by flexing the elbow and *lifting* the hand from the substrate. The digits then flex and close in a *collected* posture as the limb is transported forward. The digits then open and *extend* as they approach the target. The

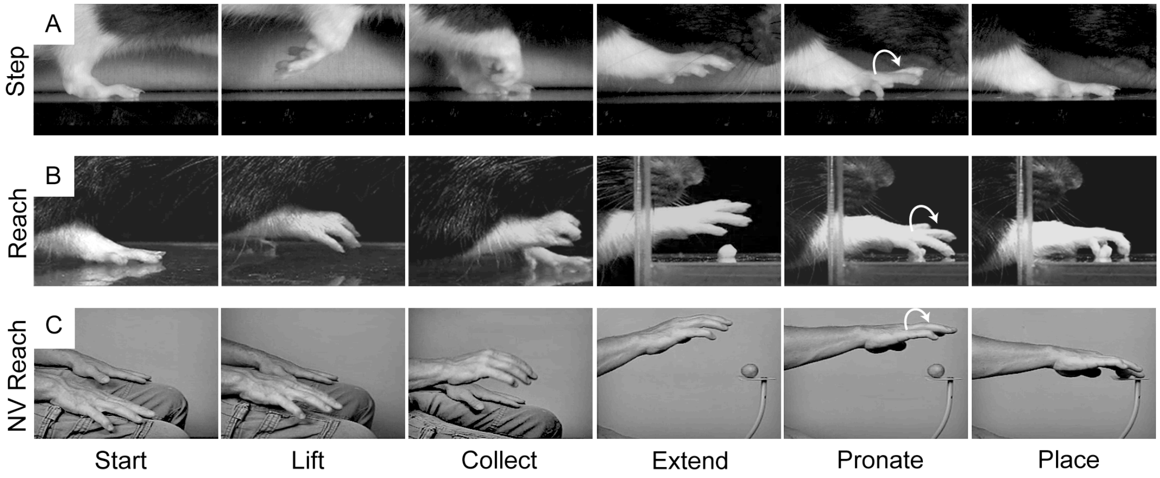


Figure 6.5 Representative still frames illustrating the kinematic structure of (A) a rat forelimb stepping movement, (B) a rat Reach movement, and (C) a human nonvisual Reach movement. Note: all three movements share a common kinematic structure in which the hand is first *lifted* from the underlying substrate, the digits *collect* and *extend* as the arm is advanced forward, and the hand *pronates* before being *placed* on the new substrate. Adapted from Whishaw et al., 2010 and Karl et al., 2012a.

hand then *pronates* in the lateral to medial direction and is finally *placed* on the target or substrate (Karl et al., 2012; Sacrey et al., 2009; Whishaw et al., 2010a). Thus a number of kinematic similarities shape both forelimb stepping and the Reach movement.

For movements of stepping and its derivatives, vision is not essential. Vision is usually directed ahead of the limb's target (Patla and Vickers, 2003; Wilkson and Sherk, 2005). Thus, the step is performed in the absence of online sensory control until it receives haptic confirmation associated with limb placement. A rat may use vibrissae cues to signal where to step (Whishaw et al., 2010a) but in its forward movement, this sensory signal precedes the step. Likewise, a rat may use olfactory cues to locate a food item that it will retrieve with a Reach, but the animal must displace its head in order to clear a path for the hand to the target (Whishaw and Tomie, 1989). As a result, rats perform both stepping and Reach movements in the absence of online visual control (Hermer-Vazquez et al., 2007; Whishaw et al., 2010a). Thus, like a blindfolded human reaching for an unknown target, the rat does not preshape the hand prior to target contact and cannot learn to do so even with extended training (Metz and Whishaw, 2000). Detailed information on the sensory control of the forelimb for most actions in most animal species is not available, but available evidence suggests that visual guidance is not prominent in species other than primates. Taken together, comparative evidence for kinematic similarities in the structure of forelimb transport, collection, and lateral to medial pronation, coupled with the distinct absence of hand preshaping, argues that only the Reach movement, not an integrated Reach-to-Grasp movement, is derived from forelimb stepping.

The Grasp action, especially grasping a food item, is a common forelimb movement in many vertebrate orders (Iwaniuk & Whishaw, 2000; Reghem et al., 2011; Sustaita et al., 2012). Grasping not only involves holding a food item and bringing it to the mouth with a hand, but taking an item from the mouth with a hand or taking it from one hand with the other hand, as well as manipulating the item in preparation for consumption. Furthermore, in various non-primate species, specialized hand and digit movements may be used to Grasp and remove the hard shell from a sunflower seed, the spiky legs from a cricket, or the fleshy peel from an orange (Allred et al., 2008; Ivanco et al., 1996; Whishaw et al., 1998; Whishaw and Coles, 1996). In all of its manifestations these Grasp movements are guided by hapsis. Thus, the demands of a diverse diet have led to the evolution of dexterous and haptically sensitive hands (Dominy, 2004; Iwaniuk et al., 2000; Whishaw, 2003).

The many manipulations made by the hand in handling food require preshaping by both the hand and the mouth to receive the food item (Whishaw et al., 1992). These preshaping movements are the likely origin of hand preshaping for the primate Grasp. Comparisons of rat and human hand preshaping prior to retrieving a food item from the mouth are illustrated in Figures 6.6 and 6.7. The human is blindfolded and the location of the rodent's eyes prevent it from observing its hands. For both species, online haptic feedback from the food in the mouth guides hand preshaping in order to Grasp the food item. The movement is initiated by *lifting* the hand from a substrate, *preshaping* the hand to the size of the target, and closing the digits on approach to the target in order to *Grasp* it (Figure 6.6). Even though rodents are unable to preshape the hand when reaching to a distal target; they, like primates, are able to use oral hapsis to scale hand aperture to the size of a target in the mouth (Figure 6.7), which is also similar to visually guided hand

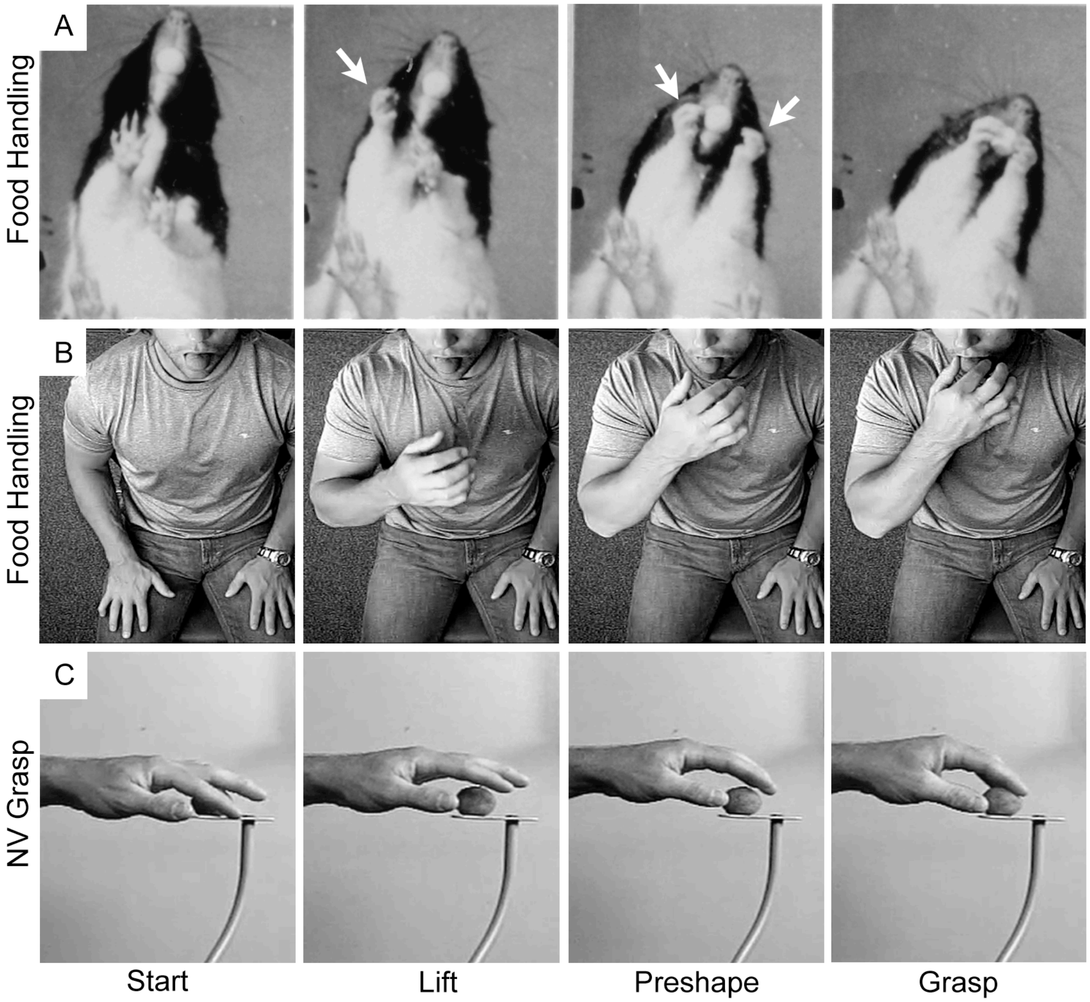


Figure 6.6 Representative still frames illustrating the kinematic structure of (A) a rat food handling movement and (B) a human food handling movement. Note: both movements share a common kinematic structure in which the hand is first *lifted* from the substrate, then digits then *preshape* to the target, and finally the digits close on approach to the target in order to *grasp* it. White arrows indicate hand preshaping in the rat. Adapted from Whishaw et al., 1992 and Karl et al., 2012a,b.

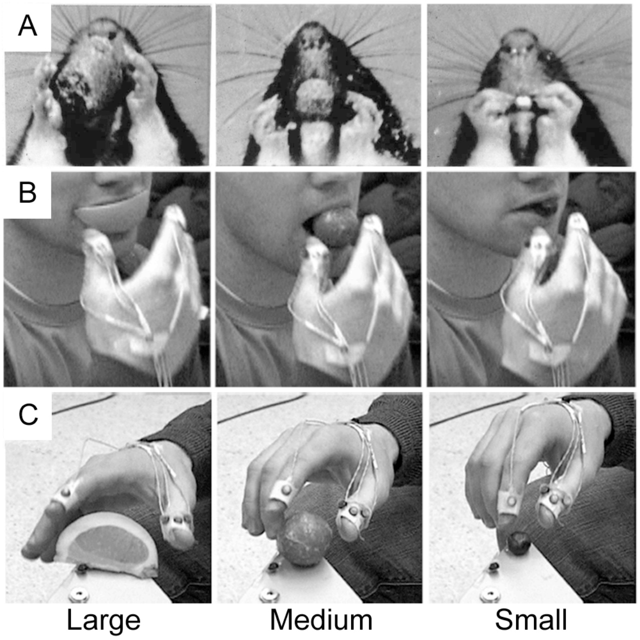


Figure 6.7 Representative still frames illustrating hand preshaping before touching the target in (A) rat food handling movements, (B) human food handling movements, and (C) human visually guided Grasp movements. Note: in all three situations online haptic (food handling) or visual (Grasp) information is available to guide hand preshaping such that a large peak hand aperture is used to Grasp a large food item, an intermediate peak hand aperture is used to Grasp a medium-sized food item, and a small peak hand aperture is used to Grasp a small food item. Adapted from Whishaw et al., 1992 and Karl et al., 2012b.

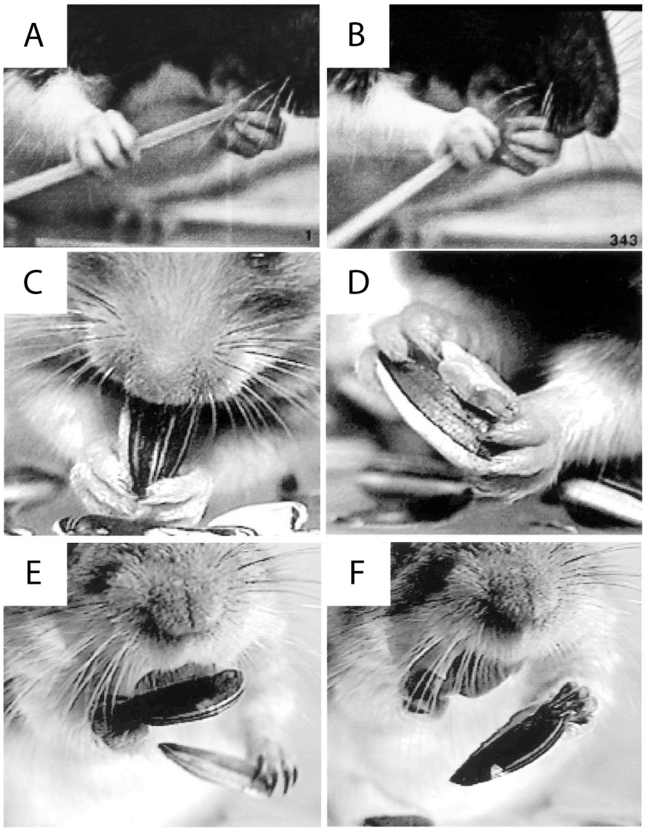


Figure 6.8 Representative still frames illustrating specialized grip configurations and independent digit movements in rodents during food handling. (A-B) A rat eating spaghetti, the left hand holds the pasta near the mouth with the digit tips (a modified precision grip) while the right hand uses a scissor grip between digits 4 and 5 to push the pasta towards the mouth. (C-D) A hamster eating a sunflower seed, both hands hold the seed in a modified precision grip between digit 1 (the thumb) and digits 2 and 3 as the mouth bites into the shell. Two objects can also be held at once, the seed is held in a modified (bilateral) pincer grip between digits 1 and 2, the shell is held in a bilateral power grip between the palm and digits 3 and 4, while digit 5 is positioned on the ventral surface of the seed, likely to stabilize the grip on both objects. (E-F) A Mongolian gerbil eating a sunflower seed. A bite from the incisors is used to open the shell (not shown). The bottom half of the shell is held in the digit tips as the left hand uses a precision grip to grasp and discard the top portion of the shell. The left hand then grasps the bottom half of the shell in the digit tips (precision grip) and discards it as the right hand uses a precision grip to hold the seed in the mouth. Adapted from Whishaw et al., 1996, 1998.

preshaping displayed by primates (Karl et al., 2012b; Whishaw et al., 1992).

After the target is grasped a variety of specialized grip configurations and independent digit movements may be used to manipulate, explore, or stabilize the food item (Figure 6.8). For further descriptions in nonprimates see (Whishaw and Coles, 1996; Whishaw et al., 1992, 1998; Ivanco et al., 1996 Sustaita et al., 2012). For descriptions in primates see (Elliot and Connolly, 1984; Lederman and Klasky, 1998; Macfarlane and Graziano, 2009). That both rodents and primates use haptic information to Grasp a food item in the mouth suggests that haptically guided hand preshaping, as well as a manipulatory digit movements, predate visually guided Grasp movements in primates (Karl et al., 2012b; Whishaw 2003).

Distinct Neuroanatomical Origins for the Reach and Grasp

In addition to classic work (Georgopoulos & Grillner, 1989), recent electrophysiological and brain imaging studies in non-human primates and humans support the notion that cortical control of the Reach could be derived from a pre-existing locomotion pathway in parietofrontal cortex. Like the Reach, stepping appears to be mediated by a dorsomedial pathway in parietofrontal cortex. Electrical stimulation of this pathway elicits bilateral movements of the forelimbs and hindlimbs that resemble spontaneous running or leaping in monkeys (Gharbawie et al., 2011; Graziano et al., 2005; Kaas et al., 2012; Stepniewska et al., 2009). In humans, regions of dorsomedial posterior parietal cortex (PPC) mediate reaching to visible targets with the arms and hands, but also subserve pointing and stepping movements to visible targets with the foot (Cavina-Pratesi et al., 2013; Evans et al., 2013; Heed et al., 2011; Hollnagel et al., 2011;

Michel & Henaff, 2004; Rondot et al., 1977). Although the stepping and Reach pathways overlap in dorsomedial PPC, they appear to diverge in frontal cortex. Thus, regions of overlap (SPOC/V6A, mIPS) may code for a specific behavioral function; i.e., transport of a limb to a different spatial location, whereas regions of divergence (PMd/SMA and M1) might specify the body part used to execute that behavior, i.e., the foot (stepping) or the hand (forelimb stepping/Reach; Heed et al., 2011).

Food handling, like grasping, may be mediated by a dorsolateral pathway in parietofrontal cortex. Electrical stimulation of this dorsolateral pathway elicits hand-to-mouth movements, in which the hand is lifted towards an open mouth and the digits shape to Grasp (Gharbawie et al., 2011; Graziano et al., 2005; Kaas et al., 2012; Stepniewska et al., 2009). In humans, a similar region in the inferior parietal lobule is activated when performing grasping movements with either the mouth or hands (Castiello et al., 1999). Futhermore, aIPS, the parietal region of the dorsolateral Grasp pathway, receives strong somatosensory inputs (Borra et al., 2008; Gharbawie et al. 2010, 2011; Lewis and Van Essen, 2000) and mediates grasping and manipulatory digit movements directed towards both visual and haptic targets (Binkofski et al., 1999; Fiehler 2007a,b, 2008; Gardner et al., 2007). Thus, it is possible that, like the stepping and Reach pathways, the food handling and Grasp pathways may overlap in parietal cortex (aIPS), which might code for a specific behavioral function, i.e., shaping a body part to grasp/manipulate a target, whereas regions of divergence (M1) could specify the body part used to execute that behavior, i.e., the mouth (bite) or the hand (Grasp).

Interestingly, lesions to V6A, a crucial node in the dorsomedial Reach pathway, disrupt both Reach and Grasp movements (Battaglini et al., 2002), although, as demonstrated by Cavina-Pratesi et al., (2010a), the Grasp impairments could emerge as a secondary consequence of misreaching. Nevertheless, V6A receives inputs from AIP (the macaque homologue of human aIPS; Borra et al., 2007; Gamberini et al., 2009) and contains orientation- and grip-selective neurons (Fattori et al., 2009, 2010; Galletti et al., 2003). Thus, V6A could have originally evolved to serve the Reach, but through its connections with AIP, it may also monitor preshaping of the Grasp as the hand is advanced towards the target. Thus, primate V6A may serve as a visuoproprioceptive "integrator", ensuring that visually guided Reach and Grasp movements unfold in temporal synchrony (Fattori et al., 2010). Indeed, the neural substrate that integrates the Reach and the Grasp must emerge early in the visuomotor pathways in order to integrate the two movements from action onset. One way to determine whether the grip-selective properties of neurons in V6A are intrinsic to this cortical area, or emerge in response to inputs from AIP, would be to selectively lesion AIP while observing the effect on grip-selective neurons in V6A.

Although non-primate species do not display visually guided hand preshaping during reaching, behavioral evidence suggests that the sensorimotor representations of the Reach and the Grasp should be similar to that of primates with respect to motor control. For instance, the rat has a well-developed forelimb representation in anterior motor cortex consisting of a relatively smaller rostral forelimb area (RFA) and a larger caudal forelimb area (CFA; for a reviews see Neafsey et al, 1986; Wise and Donoghue, 1986). Microelectrical stimulation of these regions produces brief movements of distal and proximal regions of the contralateral forelimb, respectively. Longer train electrical stimulation in the RFA is more likely to elicit movements involving the hands, including grasping, whereas stimulation in the CFA elicits whole limb movements (Bonazzi et. al, 2013), some of which resemble reaching. Inactivation of these regions disrupts Grasp and Reach movements respectively (Brown and Teskey, in preparation). Additionally, results from brainstem stimulation in freely moving rats suggest separate subcortical regions mediate the Reach (stepping movements) and the Grasp (food handling movements). For example, forced forelimb movements are obtained by electrical stimulation in the region of nucleus gigantocelluralis whereas fictive eating (the rats sits on its haunches and engages in food handling and eating without food) from the region of the locus coerulelus (Robinson, 1978).

It is also suggested that descending projections from cortical motor regions may form the efferent control of the cortical visuomotor Reach and Grasp pathways. The direct projections of the corticospinal tract are distinctive in primates (Kuypers, 1981) but have been associated with the production of independent digit movements (Lawrence and Kuypers, 1968a,b; Courtine et al., 2007). Yet there are many difficulties with the independent digit theory, including definitional difficulties related to independent digit movements as well as evidence that deficits following cortical injury are related to movement synergies, not independent digit control (Ben Hamed et al., 2007; Schieber and Santello, 2004). Independent digit movements are also distinctive in the hand babbling movements of infants as young as two months of age (Wallace and Whishaw, 2003), well before maturation of the direct connections of the corticospinal tract is complete (Armand et al., 1994; Olivier et al., 1997). In the earliest stages of development and following corticospinal tract lesions in primates, prehension resembles optic ataxia in that the Reach and the Grasp do not appear to integrate under visual control, but are characterized instead by a distinct absence of hand preshaping as well as the use of a Touch-then-Grasp strategy. The prolonged developmental period required to integrate the Reach and the Grasp also seems to parallel the long maturational period characteristic of the direct projections of the corticospinal tract. Taken together, this evidence seems to suggest that, in primates, visual control of the Reach and Grasp co-evolved with direct corticospinal projections from motor cortex.

Collectively, anatomical studies confirm predictions from behavioral work that separate pathways should subserve the Reach and the Grasp in non-primate species and that these species could be further examined to identify the neural origins of primate Reach and Grasp movements. Specifically, it is proposed that the neural circuits for stepping are the evolutionary antecedent for the Reach whereas the neural circuits for food handling are the evolutionary antecedent for the Grasp. Early in their evolution these movements were importantly dependent on nonvisual guidance, including somatosensation and olfaction, whereas visual control of the Reach and Grasp appears to have emerged later as a primate specialization. The proposition that visually guided Reach and Grasp movements might be derived from pre-existing nonvisual stepping and food handling circuits fits well with recent evidence that movement representations in primate parietofrontal cortex are both effector- and modality-independent (Heed et al., 2011; Sabes, 2011).

Conclusion

Healthy adults use vision to integrate the Reach and Grasp into a unified prehensile act by preshaping the hand and digits to the size and shape of a target as the hand is advanced towards it. This behavior is critically dependent on foveal vision. Nevertheless, when visual inputs are limited or disrupted as occurs during early development, under visual occlusion, or following brain injury, prehension decomposes into its constituent movements: a Reach that advances an open hand in order to haptically locate the target and a haptically guided Grasp that shapes the hand and digits for target purchase.

The independence of the Reach and the Grasp under nonvisual control supports the proposition of the Dual Visuomotor Channel Theory that the neural substrates of the Reach and the Grasp are distinct and derived from different evolutionary origins. Collective evidence suggests that the primate Reach is one of a number of species-specific adaptations derived from forelimb stepping, whereas the primate Grasp is one of a number of species-specific adaptations derived from food handling. Thus, distinct motor circuits for the “Reach” and the “Grasp” may have emerged relatively early in evolution and were likely influenced more by nonvisual than visual inputs. Expansion of the primate visual system would have given rise to a number of new connections between occipital and parietofrontal cortex, allowing vision to harness these pre-existing “Reach” and “Grasp” circuits resulting in multiple visuomotor pathways from occipital to parietofrontal cortex (Figure 6.9). No longer constrained by the necessity of haptic control, the Reach and Grasp could be executed simultaneously, rather than sequentially, giving primates the unique ability to preshape the hand to the intrinsic properties of a visual target before touching it.

Finally, distinct neural and evolutionary origins for the Reach and the Grasp would allow for a multiplicity of Grasp movements including various single handed pincer, precision, or power grasps, as well as any combination of two handed grasps to be combined with a multiplicity of Reach movements including single handed reaches, two handed reaches, pushes, throws, or swats, all of which can executed under various forms of sensory or cognitive control. Thus, the proposition that distinct motor circuits for the Reach and the Grasp evolved separately and only came under visual control late in the evolutionary process supports the idea that the Reach and the Grasp pathways in parietofrontal cortex are accessed not only by vision, but also by a variety of nonvisual and cognitive inputs in order to produce a diverse repertoire of adaptive behaviours upon which natural selection may act.

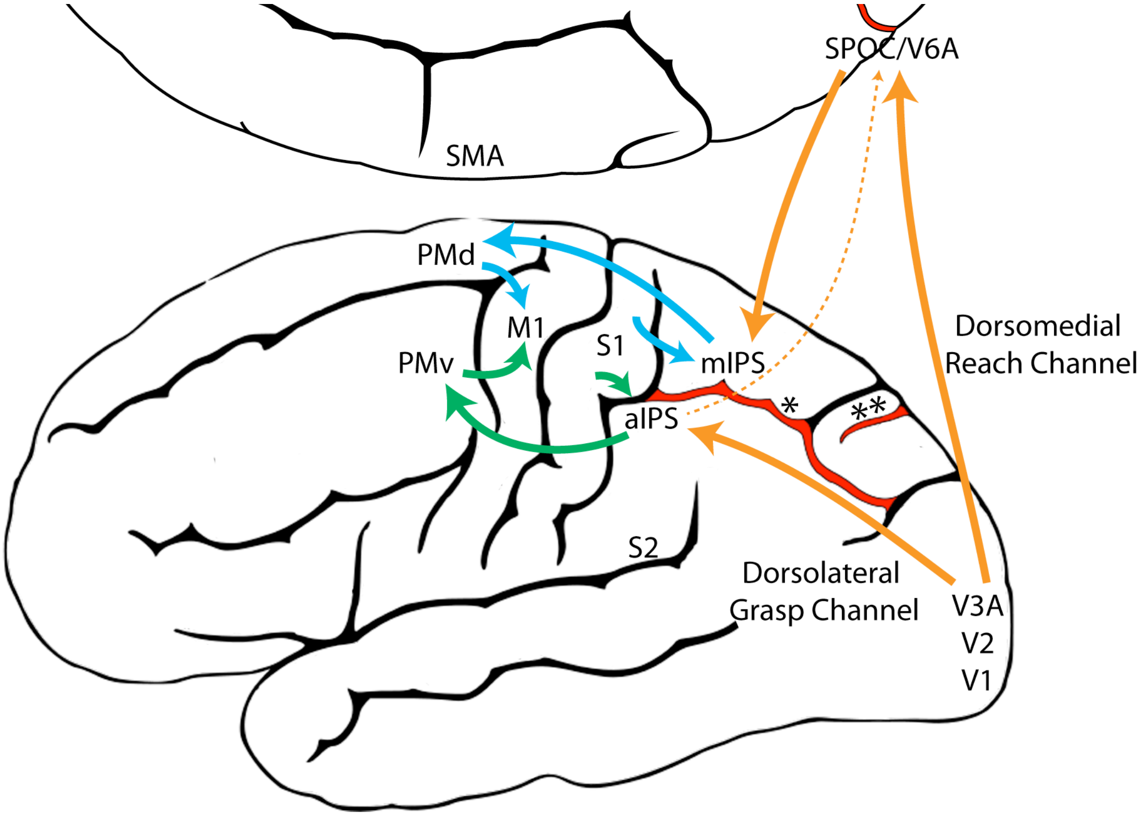


Figure 6.9 A model illustrating the proposed evolutionary origins for dual visuomotor Reach and Grasp channels in primate parietofrontal cortex. The original dorsomedial stepping/Reach circuit (blue) and the dorsolateral food handling/Grasp circuit (Green) evolved first and were subsequently harnessed by the primate visual system (Orange) through neural re-use (Anderson, 2010). (aIPS – Anterior Intraparietal Sulcus, M1 – Primary Motor Cortex, mIPS – Medial Intraparietal Sulcus, PMd – Dorsal Premotor Cortex, PMv – Ventral Premotor Cortex, S1 – Primary Somatosensory Cortex, S2 – Secondary Somatosensory Cortex, SMA – Supplementary Motor Area, SPOC – Superior Parieto-Occiptal Cortex, V1 – Primary Visual Cortex, V2 – Secondary Visual Cortex, V3A – Visual Area 3A, V6A – Visual Area 6A, * - Intraparietal Sulcus, ** - Parieto-Occipital Sulcus).

References

Abraira VE, Ginty DD (2013) The sensory neurons of touch. Neuron 79:618-639

Abdollahi RO, Jastorff J, Orban GA (2013) Common and segregated processing of observed actions in human SPL. 23:2734-2753

Ageranioti-Belanger SA, Chapman CE (1992) Discharge properties of neurons in the hand area of primary somatosensory cortex in monkeys in relation to the performance of an active tactile discrimination task. II. Area 2 as compared to areas 3b and 1. Exp Brain Res 91:207-228

Allred RP, Adkins DL, Woodlee MT, Husbands LC, Maldonado MA, Kane JR, Schallert T, Jones TA (2008) The Vermicelli Handling Test: A simple quantitative measure of dexterous forepaw function in rats. J Neurosci Methods 170:229–244

Alstermark B, Isa T (2012) Circuits for skilled reaching and grasping. Ann Rev Neurosci 35:559-578

Amaral DG (2013) The functional organization of perception and movement. In Kandel, Jessel, Siegelbaum, Huspeth (Eds.) *Principles of Neural Science, Fifth Edition* (pp. 356-368). United States of America: McGraw-Hill

Anderson ML (2010). Neural reuse: A fundamental organizational principle of the brain. Behav Brain Sci 33:245–266

Andersen RA, Andersen KN, Hwang EJ, Hauschild M (2014) Optic ataxia: from Balint's syndrome to the parietal reach region. Neuron 81:967-983

Anema HA, van Zandvoort MJE, de Haan EH, Kappelle LJ, de Kort PLM, Jansen BPW, Dijkerman HC (2009) A double dissociation between somatosensory processing for perception and action. Neuropsychologia 47:1615-1620

Ansuini C, Giosa L, Turella L, Altoe G, Castiello U (2008) An object for an action, the same object for other actions: effects on hand shaping. Exp Brain Res 185:111-119

Ansuini C, Santello M, Massaccessi S, Castiello U (2006) Effects of end-goal on hand shaping. J Neurophysiol 95:2456-2465

Arbib MA (1981) Perceptual structures and distributed motor control. In: Brooks VB (ed) *Handbook of Physiology, Section 1, Vol 2, Part 2*, William & Wukjubsm Baltimore, pp 1449-1480

Armand J, Edgley SA, Lemon RN, Olivier E (1994) Protracted postnatal development of corticospinal projections from the primary motor cortex to hand motoneurones in the macaque monkey. *Exp Brain Res* 101:178-82

Armstorng DM (1988) The supraspinal control of mammalian locomotion. J Physiol 405:1-37

Bakola S, Gamberini M, Passarelli L, Fattori P, Galletti C (2010) Cortical connections of parietal field PEc in the macaque: linking vision and somatosensation for the control of limb action. Cereb Cortex 20:2592-604

Bakola S, Passarelli, Gamberini M, Fattori P, Galletti C (2013) Cortical connectivity suggests a role in limb coordination for macaque area PE of the superior parietal cortex. J Neurosci 33:6648-6658

Balint R (1909). Seelenlahmung des “schauens,” optische Ataxie, raumliche Storung der Aufmersamdeit. Monatsschrift Psychiat Neurol 25:57-81

Barrett TM, Needham A (2008) Developmental differences in infants’ use of an object’s shape to grasp it securely. Dev Psychobiol 50:97-106

Bates JAV, Ettlinger G (1960) Posterior biparietal ablations in the monkey. Arch Neurol 3:177-192

Batista AP, Snthanam G, Yu BM, Ryu SI, Sfshar A, Shenoy KV (2007) Reference frames for reach planning in macaque dorsal premotor cortex. J Neurophysiol 98:966-983

Battaglia-Mayer A, Mascaro M, Caminiti R (2007) Temporal evolution and strength of neural activity in parietal cortex during eye and hand movements. Cereb Cortex 17:1350-1363

Battaglini PP, Muzur A, Galletti C, Skrap M, Brovelli A, Fattori P (2002) Effects of lesions to area V6A in monkeys. Exp Brain Res 144:419-422

Begliomini C, Wall MB, Smith AT, Castiello U (2007) Differential cortical activity for precision and whole-hand visually guided grasping in humans. Eur J Neurosci 25:1245-1252

Beurze SM, Toni I, Pisella L, Medendorp WP (2010) Reference frames for reach planning in human parietofrontal cortex. J Neurophysiol 104:1736-1745

Beloozerova IN, Sirot MG (1993) The role of the motor cortex in the control of accuracy of locomotor movements in the cat. J Physiol 461:1-25

Ben Hamed S, Schieber MH, Pouget A (2007) Decoding M1 neurons during multiple finger movements. J Neurophysiol 98:327-333

Bernier PM, Grafton ST (2010) Human posterior parietal cortex flexibly determines reference frames for reaching based on sensory context. Neuron 68:776-788

Bertenthal B, Hofsten von C (1998) Eye, head, and trunk control: the foundation for manual development. Neurosci Biobehav Rev 22:515-20

Berthier NE, Carrico RL (2010) Visual information and object size in infant reaching. Infant Behav Dev 33:555-66

Berthier NE, Clifton RK, Gullapalli V, McCall DD, Robin DJ (1996) Visual information and object size in the control of reaching. J Mot Behav 28:187-197

Berthier NE, Keen R (2006) Development of reaching in infancy. Exp Brain Res 169:507-518

Bingham G, Coats R, Mon-Williams M (2007) Natural prehension in trials without haptic feedback but only when calibration is allowed. Neuropsychologia 45:288-294

Binkofski F, Buccino G, Posse S, Seitz RJ, Rizzolatti G, Freund H (1999a) A fronto-parietal circuit for object manipulation in man: evidence from an fMRI-study. Eur J Neurosci 11:3276-3286

Binkofski F, Buccino G, Stephan KM, Rizzolatti G, Seitz RJ, Freund HJ (1999b) A parieto-premotor network for object manipulation: evidence from neuroimaging. Exp Brain Res 128:210-213

Binkofski F, Dohle C, Posse S, Stephan KM, Hefter H, Seitz RJ, Freund HJ (1998) Human anterior intraparietal area subserves prehension: a combined lesion and functional MRI activation study. Neurology 50:1253-1259

Blangero A, Ota H, Delporte L, Revol P, Vindras P, Rhode G, Boisson D, Vighetto A, Rossetti Y, Pisella L (2007) Optic ataxia is not only ‘optic’: impaired spatial integration of proprioceptive information. Neuroimage. 36 Suppl 2:T61-T68

Blum (1985) Manipulation reach and visual reach neurons in the inferior parietal lobule of the rhesus monkey. Behav Brain Res 18:167-173

Boivie J and Boman K (1981) Termination of a separate (proprioceptive?) cuneothalamic tract from external cuneate nucleus in monkey. Brain Res 224:235-46

Bonazzi L, Viaro R, Lodi E, Canto R, Bonifazzi C, Franchi G (2013) Complex movement topography and extrinsic space representation in the rat forelimb motor cortex as defined by long-duration intracortical microstimulation. J Neurosci 33:2097-107

Borra E, Belmalih A, Calzavara R, Gerbella M, Murata A, Rozzi S, Luppino G (2008) Cortical connections of the macaque anterior intraparietal (AIP) area. Cerebral Cortex 18:1094-1111

Bower TGR (1974) *Development in infancy*. San Francisco: Freeman

Bowlanowski SJ, Pawson L (2003) Organization of Meissner corpuscles in the glabrous skin of monkey and cat. Somatosens Mot Res 20:223-231

Bracha V, Zhuravin IA, Bures J (1990). The reaching reaction in the rat: a part of the digging pattern? Behav Brain Res 36:53-64

Bremner LR, Andersen RA (2012) Coding of the reach vector in parietal area 5d. Neuron 75:342-351

Breveglieri R, Galletti C, Gamberini M, Passarelli L, Fattori P (2006) Somatosensory cells in area PEc of macaque posterior parietal cortex. J Neurosci 26:3679-3684

Breveglieri R, Galletti C, Monaco S, Fattori P (2008) Visual, somatosensory, and bimodal activities in the macaque parietal area PEc. Cereb Cortex 18:806-816

Brinkman C (1981) Lesions in supplementary motor area interfere with a monkey's performance of a bimanual coordination task. Neurosci Lett 27:267-270

Brisben AJ, Hsiao SS, Johnson KO (1999) Detection of vibration transmitted through an object grasped in the hand. J Neurophysiol 81:1548-58

Brown, A.R. and Teskey. G.C. (In press). Functionally segregate movement encoding in rat neocortical forelimb motor areas

Burbaud P, Doegle C, Gross C, Bioulac B (1991) A quantitative study of neuronal discharge in areas 5, 2, and 4 of the monkey during fast arm movements. J Neurophysiol 66:429-443

Butterworth G, Verweij E, Hopkins B (1997) The development of prehension in infants: Halverson revisited. Brit J Dev Psychol 15:223-236

Bremner AJ, Hill EL, Pratt M, Rigato S, Spence C (2013) Bodily illusions in young children: Developmental change in visual and proprioceptive contributions to perceived hand position. PloS One 8:e51887

Caminiti R, Chafee MV, Battaglia-Mayer A, Averbeck BB, Crowe DA, Georgopoulos AP (2010) Understanding the parietal lobe syndrome from a neurophysiological evolutionary perspective. Eur J Neurosci 31:2320-2340

Caminiti R, Genovesio A, Marconi B, Mayer AB, Onorati P, Rerraina S, Mitsuda T, Giannetti S, Squatrito S, Maioli MG, Molinari M (1999) Early coding of reaching: frontal and parietal association connections of parieto-occipital cortex. Eur J Neurosci 11:3339-45

Carrico RL, Berthier NE (2008) Vision and precision reaching in 15-month-old infants. Infant Behav Dev 31:62-70

Cartmill M (1974) Rethinking primate origins. Science 184:436-443

Caselli RJ (1991) Rediscovering tactile agnosia. May Clin Proc 66:129-142

Castiello U (1997) Arm and mouth coordination during the eating action in humans: a kinematic analysis. Exp Brain Res 115:552-556

Castiello U, Bennett KM, Egan GF, Tochon-Danguy HJ, Kritikos A, Dunai J (2000) Human inferior parietal cortex ‘programs’ the action class of grasping. Cogn Syst Res 2:22-30

Castiello U, Bennett KM, Mucignat C (1993) The reach to grasp movement of blind subjects. Exp Brain Res 96:152-162

Cavina-Pratesi C, Connolly JD, Milner AD (2013) Optic ataxia as a model to investigate the role of the posterior parietal cortex in visually guided action: evidence from studies of patient M.H. Front Hum Neurosci 7, 366, doi:10.3389/fnhum.2013.00336

Cavina-Pratesi C, Ietswaart M, Humphreys GW, Lestou V, Milner AD (2010a) Impaired grasping in a patient with optic ataxia: primary visuomotor deficit or secondary consequence of misreaching? Neuropsychologia 48:226-34

Cavina-Pratesi C, Monaco S, Fattori P, Galletti C, McAdam TD, Quinlan DJ, Goodale MA, Culham JC (2010b) Functional magnetic resonance imaging reveals the neural substrates of arm transport and grip formation in reach-to-grasp actions in humans. J Neurosci 30:10306-10323

Chapman CS, Gallivan JP, Wood DK, Milne JL, Culham JC, Goodale MA (2010) Reaching for the unknown: multiple target encoding and real-time decision-making in a rapid reach task. Cognition 116:168-176

Chen LM, Friedman RM, Ramsden BM, LaMotte RH, Roe AW (2001) Fine-scale organization of SI (area 3b) in the squirrel monkey revealed with intrinsic optical imaging. J Neurophysiol 86:3011-29

Cisek P, Kalaska JF (2005) Neural correlates of reaching decisions in dorsal premotor cortex: specification of multiple direction choices and final selection of action. Neuron 45:801-814

Clifton RK, Muir DW, Ashmead DH, Clarkson MG (1993) Is visually guided reaching in early infancy a myth? Child Development 64:1099–1110

Cohen NR, Cross ES, Tunik E, Grafton ST, Culham JC (2009) Ventral and dorsal stream contributions to the online control of immediate and delayed grasping: a TMS approach. Neuropsychologia 47:1553-1562

Courtine G, Bunge MB, Fawcett JW, Grossman RG, Kaas JH, Lemon R, Maier I, Martin J, Nudo RJ, Ramon-Cueto A, Rouiller EM, Schnell L, Wannier T, Schwab ME, Edgerton VR (2007) Can experiments in nonhuman primates expedite the translation of treatments for spinal cord injury in humans? Nat Med 13:561-566

Crawford JD, Medendorp WP, Marotta JJ (2004) Spatial transformations for eye-hand coordination. J Neurophysiol 92:10-19

Culham JC, Cavina-Pratesi C, Singhal A (2006) The role of parietal cortex in visuomotor control: what have we learned from neuroimaging? Neuropsychologia 44:2668-2684

Culham JC, Danckert SL, DeSouza JF, Gati JS, Menon RS, Goodale MA (2003) Visually guided grasping produces fMRI activation in dorsal but not ventral stream brain areas. Exp Brain Res 153:180-189

Culham JC, Valyear KF (2006) Human parietal cortex in action. Curr Opin Neurobiol 16:205-212

Cusick CG, Steindler DA, Kaas JH (1985) Corticocortical and collateral thalmocortical connections of postcentral somatosensory cortical areas in squirrel monkeys: a double-labeling study with radiolabeled wheetgerm agglutinin and wheatgerm Agglutinin conjugated to horseradish peroxidase. Somatosens Res 3:1-31

Darian-Smith C, Ciferri MM (2005) Loss and recovery of voluntary hand movements in the macaque follosing a cervical dorsal rhizotomy. J Com Neurol 491:27-45

Darian-Smith C and Darian-Smith I (1993) Thalamic projections to 3a, 4b, and 4 in the sensorimotor cortex of the mature and infant macaque monkey. J Comp Neurol 335:173-199

Davare M, Andres M, Cosnard G, Thonnard JL, Olivier E (2006) Dissociating the role of ventral and dorsal premotor cortex in precision grasping. J Neurosci 26:2260-2268.

Davare M, Kraskov A, Rothwell JC, Lemon RN (2011) Interactions between areas of the cortical grasping network. Curr Opin Neurobiol 21:565–570

de Bruin N, Sacrey LA, Brown LA, Doan J, Whishaw IQ (2008) Visual guidance for hand advance but not hand withdrawal in a reach-to-eat task in adult humans: Reaching is a composite movement. J Mot Behav 40:337-346

Della Sala S, Francescani A, Spinnler H (2002) Gait apraxia after bilateral supplementary motor area lesion. J Neurol Neurosurg Psychiatry 72:77-85

de Ryck M, Van Reempts J, Duytschaever H, Van Deuren B, Clincke G (1992) Neocortical localization of tactile/proprioceptive limb placing reactions in the rat. Brain Res 573:44-60

de Santis L, Spierer L, Clarke S, Murray MM (2007) Getting in touch: Segregated somatosensory what and where pathways in humans revealed by electrical neuroimaging. NeuroImage, 37:890-903

Desmurget M, Prablanc C (1997) Postural control of three dimensional prehension movements. J Neurophysiol 77:452-464

Desmurget M, Prablanc C, Arzi M, Rossetti Y, Paulignan Y, Urquizar C (1996) Integrated control of hand transport and orientation during prehension movements. Exp Brain Res 110:265-278

Desmurget M, Reilly KT, Richard N, Szathmari A, Mottolese C, Sirigu A (2009) Movement intention after parietal cortex stimulation in humans. Science 324:811-813

Desmurget M, Richard N, Harquel S, Baraduc P, Szathmari A, Mottolese C, Sirigu A (2014) Neural representations of ethologically relevant hand/mouth synergies in the human precentral gyrus. Proc Natl Acad Sci USA. 111:5718-5722

Diamond ME (2010) Texture sensation through the fingertips and the whiskers. Curr Opin Neurobiol 20:319-327

Dijkerman HC, de Haan EH (2007) Somatosensory processes subserving perception and action. Behav Brain Sci 30:189-201

Domellöf E, Hopkins B, Francis B, Rönnqvist L (2007) Effects of finger markers on the kinematics of reaching movements in young children and adults. J Appl Biomech 23:315-321

Dominy NJ (2004) Fruits, fingers, and fermentation: the sensory cues available to foraging primates. Integr Comp Biol 44:295–303

Drew T, Andujar JE, Lajoie K, Yakovenko S (2008) Cortical mechanisms involved in visuomotor coordination during precision walking. Brain Res Rev 57:199-211

Edin BB (1992) Quantitative analysis of static strain sensitivity in human mechanoreceptors from hairy skin. J Neurophysiol 67:1105-13

Edin BB and Johansson N (1995) Skin strain patterns provide kinaesthetic information to the human central nervous system. J Physiol (Lond) 487:243-251

Edwards MG, Wing AM, Stevens J, Humphreys GW (2005) Knowing your nose better than your thumb: measures of over-grasp reveal that face-parts are special for grasping. Exp Brain Res 161:72-80

Elliot JM, Connolly KJ (1984) A classification of manipulative hand movements. Dev Med Child Neurol 26:283-296

Eshkol N, Wachman A, (1958) Movement Notation. Weidenfeld and Nicholson, London

Ettlinger G and Wegener J (1958) Somaesthetic alternation, discrimination and orientation after frontal and parietal lesions in monkeys. Q J Exp Psychol 10:177-186

Evans C, Milner AD, Humphreys GW, Cavina-Pratesi C (2013) Optic ataxia affects the lower limbs: Evidence from a single case study. Cortex 49:1229–1240

Fagard J (2000) Linked proximal and distal changes in the reaching behavior of 5- to 12-month-old human infants grasping objects of different sizes. Infant Behav & Dev 23:317-329

Fattori P, Breveglieri R, Marzocchi N, Filippini D, Bosco A, Galletti C (2009) Hand orientation during reach-to-grasp movements modulates neuronal activity in the medial posterior parietal area V6A. J Neurosci 29:1928-1936

Fattori P, Kutz DF, Breveglieri R, Marzocchi N, Galletti C (2005) Spatial tuning of reaching activity in the medial parieto-occipital cortex (area V6A) or macaque monkey. Eur J Neurosci 22:956-972

Fattori P, Raos V, Breveglieri R, Bosco A, Marzocchi N, Galleti C (2010) The dorsomedial pathway is not just for reaching: Grasping neurons in the medial parieto-occipital cortex of the macaque monkey. J Neurosci 30:342-349

Faul F, Erdfelder E, Lang A-G, Buchner A (2007) G*Power 3: A flexible statistical power analysis program for the social, behavioural, and biomedical science. Behav Res Methods 39:175-191

Ferrari PF, Gallese V, Rizzolatti G, Fogassi L (2003) Mirror neurons responding to the observation of ingestive and communicative mouth actions in the monkey ventral premotor cortex. Eur J Neurosci, 17:1703-1714

Ferri F, Campione GC, Dalla Volta R, Gianelli C, Gentilucci M (2010) To me or to you? When the self is advantaged. Exp Brain Res 203:637-646

Fiehler K, Bannert MM, Bischoff M, Blecker C, Stark R, Vaitl D, Franz VH, Rosler F (2011) Working memory maintenance of grasp-target information in the human posterior parietal cortex. NeuroImage 54:2401-2411

Fiehler K, Burke M, Bien S, Röder B, Rösler F (2009) The human dorsal action control system develops in the absence of vision. Cereb Cortex 19:1-12

Fiehler K, Burke M, Engel A, Bien S, Rosler F (2007a) Kinesthetic Working Memory and Action Control within the Dorsal Stream. Cereb Cortex 18:243–253

Fiehler K, Engel A, Rosler F (2007b) Where are somatosensory representations stored and reactivated? Behav Brain Sci 30:206-207

Fiehler K, Rösler F (2010). Plasticity of multisensory dorsal stream functions: evidence from congenitally blind and sighted adults. Restor Neurol Neurosci 28:193–205

Filimon F (2010) Human cortical control of hand movements: parietofrontal networks for reaching, grasping, and pointing. Neuroscientist 16:388-407

Filimon F, Nelson JD, Huang RS, Sereno MI (2009) Multiple parietal reach regions in humans: cortical representations for visual and proprioceptive feedback during on-line reaching. J Neurosci 29:2961-2971

Fitzgerald PJ, Lane JW, Thakur PH, Hsiao SS (2004) Receptive field properties of the macaque second somatosensory cortex: evidence for multiple functional representations. J Neurosci 24:11193-11204

Fogassi L, Gallese V, Buccino G, Graighero L, Fadiga L, Rizzolatti G (2001) Cortical mechanism for the visual guidance of hand grasping movements in the monkey. A reversible inactivation study. Brain 124:571-586

Foroud A, Whishaw IQ (2012) The consummatory origins of visually guided reaching in human infants: a dynamic integration of whole-body and upper-limb movements. Behav Brain Res 231:343-355

Frey SH, Vinton D, Norlund R, Grafton ST (2005) Cortical topography of human anterior intraparietal cortex active during visually guided grasping. Brain Res Cogn Brain Res 23:397-405

Fried I, Katz A, McCarthy G, Sass KJ, Williamson P, Spencer SS, Spencer DD (1991) Functional organization of human supplementary motor cortex studied by electrical stimulation. J Neurosci 11:3656-3666

Gallese V, Murata A, Kaseda M, Niki N, Sakata H (1994) Deficit of hand preshaping after muscimol injection in monkey parietal cortex. Neuroreport 5:1525-1529

Galletti C, Fattori P, Kutz DF, Battaglini P (1997) Arm movement-related neurons in the visual area V6A of the macaque superior parietal lobule. Eur J Neur 9:410-413

Gamberini M, Galletti C, Bosco A, Breveglieri R, Fattori P (2011) Is the medial posterior parietal area V6A a single functional area? J Neurosci 31:5145-5157

Gamberini M, Passarelli L, Fattori P, Zuchelli M, Bakola S, Luppino G, Galletti C (2009) Cortical connections of the visuomotor parietooccipital area V6Ad of the macaque monkey. J Comp Neurol 513:622-642

Gardner EP, Babu KS, Reitzen SD, Ghosh S, Brown AS, Chen J, Hall AL, Herslinger MD, Kohlenstein JB, Ro JY (2007) Neurophysiology of prehension. I. Posterior parietal cortex and object-oriented hand behaviors. J Neurophysiol 97:387-406

Gentilucci M, Benuzzi F, Gangitano, Grimaldi S (2001) Grasp with hand and mouth: a kinematic study on healthy subjects. J Neurophysiol 86:1685-1699

Gentilucci M, Caselli L, Secchi C (2003) Finger control in the tripod grasp. Exp Brain Res 149:351-360

Gentilucci M, Daprati E, Gangitano M, Saetti C, Toni I (1996) On orienting the hand to reach and grasp an object. Neuroreport 7:589-592

Gentilucci M, Negrotti A, Cangitano M (1997) Planning an action. Exp Brain Res 115:116-128

Georgopoulos AP, Grillner S (1989) Visuomotor coordination in reaching and locomotion. Science 245:1209-1210

Gerbella M, Belmalih A, Borra E, Rozzi S, Luppion G (2011) Cortical connections of the anterior (F5a) subdivision of the macaque ventral premotor area F5. Brain Struct Funct 216:43-65

Gharbawie OA, Stepniewska I, Burish MJ, Kaas JS (2010) Thalamocortical connections of functional zones in posterior parietal cortex and frontal cortex motor regions in New World monkeys. Cereb Cortex 20:2391-2410

Gharbawie OA, Stepniewska I, Kaas JH (2011a) Cortical connections of functional zones in posterior parietal cortex and frontal cortex motor regions in New World monkeys. Cereb Cortex 21:1981-2002

Gharbawie OA, Stepniewska I, Kaas JH (2011b) Multiple parietal-frontal pathways mediate grasping in macaque monkeys. J Neurosci 31:11660-11677

Gonzalez-Alvares C, Subramanina A, Pardhan S (2007) Reaching and grasping with restricted peripheral vision. Ophthal Physiol Opt 27:265-274

Goodale MA (1998) Visuomotor control: where does vision end and action begin? Curr Biol 2:R489-91

Goodale MA, Jakobson LS, Keillor JM (1994a) Differences in the visual control of pantomimed and natural grasping movements. Neuropsychologia 32:1159-1178

Goodale MA, Meenan JP, Bulthoff HH, Nicolle DA, Murphy KJ, Racicot CI (1994) Separate neural pathways for the visual analysis of object shape in perception and prehension. Curr Biol, 4:604-610

Goodale MA, Milner AD (1992) Separate visual pathways for perception and action. Trends Neurosci 15:20-25

Goodale MA, Murphy KJ, Meenan J-P, Racicot CI, Nicholle DA (1993) Spared object perception but poor object-calibrated grasping in a patient with optic ataxia. Soc Neurosci Abstr 19:775

Goodale MA, Westwood DA, Milner AD (2004) Two distinct modes of control for object-directed action. Prog Brain Res 144:131-144

Goodwin AW, Browning AS, Wheat HE (1995) Representation of curved surfaces in responses of mechanoreceptive afferent fibers innervating the monkey's fingerpad. J Neurosci 15:798-810

Goodwin AW, Wheat HE (1999) Effects of nonuniform fiber sensitivity, innervation geometry, and noise on information relayed by a population of slowly adapting type 1 primary afferents from the fingerpad. J Neurosci 19:8057-8070

Gori M, Del Viva M, Sandini G, Burr DC (2008) Young children do not integrate visual and haptic form information. Curr Biol 18:694-698

Graziano M (2009) The Intelligent Movement Machine. Oxford, New York

Graziano M (2006) The organization of behavioral repertoire in motor cortex. Annu Rev Neurosci, 29:105-34

Graziano MS, Aflalo TN, Cooke DF (2005) Arm movements evoked by electrical stimulation in the motor cortex of monkeys. J Neurophysiol 94:4209-4223

Greenman GW (1963) Visual behavior of newborn infants. In: *Modern perspectives in child development,* Solnit AJ, Provence SA(Eds.) New York, NY: Hallmark

Grefkes C, Fink GR (2005) The functional organization of the intraparietal sulcus in humans and monkeys. J Anat 207:3-17

Grillner S (1975). Locomotion in vertebrates: central mechanisms and reflex interaction. Physiol Reviews 55:247–304

Grol MJ, Majdandzic J, Stephan KE, Verhagen L, Dijkerman HC, Bekkering H, Verstraten FA, Toni I (2007) Parieto-frontal connectivity during visually guided grasping. J Neurosci 27:11877-11887

Hadders-Algra M (2013) Typical and atypical development of reaching and postural control in infancy. Dev Med Child Neurol,55 Suppl 4:5-8

Hall LA, Karl JM, Thomas BL, Whishaw IQ (2014) Reach and Grasp reconfigurations reveal that proprioception assists reaching and hapsis assists grasping in peripheral vision. Exp Brain Res DOI: 10.1007/s00221-014-3945-6

Halverson HM (1931) An experimental study of prehension in infants by means of systematic cinema records. Genet Psychol Monogr 10:107-286

Hamilton DA, Rosenfelt CS, Whishaw IQ (2004) Sequential control of navigation by locale and taxon cues in the Morris water task. Behav Brain Res 154:385-397

Harrison TC, Ayling OG, Murphy TH (2012) Distinct cortical circuit mechanisms for complex forelimb movement and motor map topography. Neuron 74:397-409

Heck RH, Thomas SL, Tabata LN (2014) Examining individual change with repeated measures data. In*: Multilevel and Longitudinal Modeling with IBM SPSS, 2nd Ed*. Routledge, New York, NY

Heed T, Beurze SM, Toni I, Roder B, Medendorp WP (2011) Functional rather than effector-specific organization of human posterior parietal cortex. J Neurosci 31:3066-3076

Hermer-Vazquez L, Hermer-Vazquez R, Chapin JK (2007) The reach-to-grasp-food task for rats: a rare case of modularity in animal behavior? Behav Brain Res 177:322-328

Hermsdorfer J, Elias Z, Cole JD, Quaney BM, Nowak DA (2008) Preserved and impaired aspects of feed-forward grip force control after chronic somatosensory deafferentation. Neurorehabil Neural Repair 22:374-384

Hofsten von C (1982) Eye-hand coordination in the newborn. Dev Psychol 18:450-461

Hofsten von C (1984) Developmental changes in the organization of prereaching movements. Dev Psychol 3:378-388

Hofsten von C (1991) Structuring of early reaching movements: a longitudinal study. Journal of Motor Behav 23:280-292

Hofsten von C, Fazel-Zandy S (1984) Development of visually guided hand orientation in reaching. J Exp Child Psychol 38:208-219

Hofsten von C, Rönnqvist L (1988) Preparation for grasping an object: A developmental study. J Exp Psychol 14:610-621

Hofsten von C, Rosander K (1997) Development of smooth pursuit tracking in young infants. Vision Res 37:1799-1810

Hollnagel C, Brugger M, Vallery H, Wolf P, Dietz V, Kollias S, Riener R (2011) Brain activity during stepping: a novel MRI-compatible device. J Neurosci Methods 201, 124-130

Holmes G (1918) Disturbances of visual orientation. Br J Opthalmol 2:449-468, 506-516

Hsiao SS (2008) Central mechanisms of tactile shape perception. Curr Opin Neurobiol 18:418-424

Hu Y, Eagleson R, Goodale MA (1999) The effects of delay on the kinematics of grasping. Exp Brain Res 126:109-116

Huffman KJ, Krubitzer L (2001) Thalamo-cortical connections of areas 3a and M1 in marmoset monkeys. J Comp Neurol, 435:291-310

Hwang EJ, Hauschild M, Wilke M, Andersen RA (2012) Inactivation of the parietal reach region causes optic ataxia, impairing reaches but not saccades. Neuron 76:1021-9

Hyvarinen J (1982) Posterior parietal lobe of the primate brain. Physiol Rev 62:1060-1129

Iberall T, Bingham G, Arbib MA (1986) Opposition space as a structuring concept for the analysis of skilled hand movements. In: Heuer H, Fromm C (eds) Generation and Modulation of Actions Patterns. Experimental Brain Research Series Vol. 15, Springer-Verlag, Berlin, pp 158-173

Ingram JM, Howard IS, Flanagan JR, Wolpert DM (2010) Multiple grasp-specific representations of tool dynamics mediate skillful manipulation. Curr Biol 20:618-623

Isa T, Ohki Y, Alstermark B, Pettersson L-G, Sasaki S. (2007) Direct and indirect cortico-motoneuronal pathways and control of hand/arm movements. Physiology 22:145-152

Ishida H, Fornia L, Grandi LC, Umilta MA, Gallese V (2013) Somato-motor haptic processing in posterior inner perisylvian region (SII/plC) of the macaque monkey. PLoS One 8:e69931

Ivanco TL, Pellis SM, Whishaw IQ (1996) Skilled forelimb movements in prey catching and in reaching by rats (*Rattus norvegicus*) and opossums (*Monodelphis domestica*): relations to anatomical differences in motor systems. Behav Brain Res 79:163-181

Iwamura Y, Iriki A, Tanaka M (1994) Bilateral hand representation in the postcentral somatosensory cortex. Nature 369:554-556

Iwamura Y, Tanaka M (1978) Postcentral neurons in hand region of area 2: their possible role in the form discrimination of tactile objects. Brain Res 15:662-666

Iwamura Y, Tanaka M, Sakamoto M, Hikosaka O (1993) Rostrocaudal gradients in neuronal receptive field complexity in the finger region of the alert monkey's postcentral gyrus. Exp Brain Res 92:360-368

Iwaniuk AN, Pellis SM, Whishaw IQ (2000) The relative importance of body size, phylogeny, locomotion, and diet in the evolution of forelimb dexterity in fissiped carnivores (Carnivora). Can J Zool 78:1110–1125

Iwaniuk AN, Whishaw IQ (2000) On the origin of skilled forelimb movements. Trends Neurosci 23:372-376

Jackson JH (1870) Remarks on non-protrusion of the tongue in some cases of aphasia. In *Selected Writings of John Hughlings Jackson*, J Taylor (Ed.) pp. 716, Hodder & Stoughton, London

Jacobs S, Danielmeier C, Frey SH (2010) Human anterior intraparietal and ventral premotor cortices support representations of grasping with the hand or a novel tool. J Cogn Neurosci 22:259-2608

Jacobsen C, Sperling, L (1976) Classification of the hand-grip: A preliminary study. J Occup Med 18:395-398

Jakobson LS, Archibald YM, Carey DP, Goodale MA (1991) A kinematic analysis of reaching and grasping movements in a patient recovering from optic ataxia. Neuropsychologia 29:803-309

Jakobson LS, Goodale MA (1991) Factors affecting higher-order movement planning: a kinematic analysis of human prehension. Exp Brain Res 86:199-208

James TW, Humphrey GK, Gati JS, Servos P, Menon RS, Goodale MA (2002) Haptic study of three-dimensional objects activates extrastriate visual areas. Neuropsychologia 40:1706-1714

Jeannerod M (1981) Intersegmental coordination during reaching at natural visual objects. In: Long J, Baddeley A (eds) Attention and Performance, Erlbaum, Hillsdale, pp 153-168

Jeannerod M (1984) The timing of natural prehension movements. J Mot Behav 16:235-254

Jeannerod M (1986) The formation of finger grip during prehension. A cortically mediated visuomotor pattern. Behav Brain Res 19:99-116

Jeannerod M (1999) Visuomotor channels: Their integration in goal-directed prehension. Hum Mov Science 18:201-218

Jeannerod M, Arbib MA, Rizzolatti G, Sakata H (1995) Grasping objects: the cortical mechanisms of visuomotor transformation. Trends Neurosci 18:314-20

Jeannerod M, Decety J, Michael F (1994) Impairment of grasping movements following bilateral posterior parietal lesion. Neuropsychologia 32:369-380

Jeannerod M, Paulignan Y, Weiss P. (1998) Grasping an object: one movement, several components. Novartis Found Symp 218:16-20

Johansson RS and Flanagan JR (2009) Coding and use of tactile signals from the fingertips in object manipulation tasks. Nature Reviews Neuroscience 10 345-359

Johansson RS, Vallbo AB (1983) Tactile sensory coding in the glabrous skin of the human hand. Trens Neurosci 6:27-32

Johnson KO (2001) The roles and functions of cutaneous mechanoreceptors. Curr Opin Neurobiol 11:455-461

Johnson KO, Yoshioka T, Vega-Bermudez F (2000) Tactile functions of mechanoreceptive afferents innervating the hand. J Clin Neurophysiol 17:539-58

Johnson PB, Ferraina S, Bianchi L, Caminiti R (1996) Cortical networks for visual reaching: physiological and anatomical organization of frontal and parietal lobe arm regions. Cereb Cortex 6:102-119

Jones EG (1986) Extent of the ipsilateral representation in the ventral posterior medial nucleus of the monkey thalamus. Exp Brain Res 63:310-320

Jones EG, Coulter JD, Hendry SH (1978) Intracortical connectivity of architectonic fields in the somatic sensory, motor and parietal cortex of monkeys. 181:291-347

Jones FW (1916) Arboreal Man. London: Edward Arnold

Kaas AL, van Mier H, Goebel R (2007) The neural correlates of human working memory for haptically explored object orientations. Cereb Cortex 17:1637-49

Kaas JH (2004) Evolution of somatosensory and motor cortex in primates. Anat Rec A Discov Mol Cell Evol Biol 281:1148-56

Kaas JH (2008) The somatosensory thalamus and associated pathways. In JH Kaas, EP Gardner (eds.) *The Senses: A Comprehensive Reference, Vol 6 Somatosensation*, pp. 117-141. Oxford: Elsevier

Kaas JH, Gharbawie OA, Stepniewska I (2013) Cortical networks for ethologically relevant behaviors in primates. Am J Primatol 75:407-14

Kaas JH, Gharbawie OA, Stepniewska I (2011) The organization and evolution of dorsal stream multisensory motor pathways in primates. Front Neuroanat 5:1-7

Kaas JH, Nelson RJ, Sur M, Lin CS, Merzenich MM (1979) Multiple representations of the body within the primary somatosensory cortex of primates. Science, 204:521-523

Kaas JH, Qi HX, Iyengar S (2006) Cortical network for representing the teeth and tongue in primates. Anat Rec A Disco Mol Cell Evol Biol 288:182-190

Kalil K (1981) Projections of the cerebellar and dorsal column nuclei upon the thalamus of the rhesus monkey. J Comp Neurol 195:25-50

Kapandji IA (1982) The physiology of the joints, Vol 1. Upper Limb, 5th edn. Churchill Livingstone, Edinburgh

Karl JM, Sacrey LA, Doan JB, Whishaw IQ (2012a) Hand shaping based on hapsis resembles visually guided hand shaping. Exp Brain Res 219:59-74

Karl JM, Sacrey LA, Doan JB, Whishaw IQ (2012b) Oral hapsis guides accurate hand preshaping for grasping food targets in the mouth. Exp Brain Res 221:223-240

Karl JM, Schneider LR, Whishaw IQ (2013). Nonvisual learning of intrinsic object properties in a reaching task dissociates grasp from reach. Exp Brain Res 225:465-477

Karl JM, Whishaw IQ (2013) Different evolutionary origins for the Reach and the Grasp: An explanation for dual visuomotor channels in primate parietofrontal cortex. Front Neurol 4:208

Karl JM, Whishaw IQ (2013) Reach and grasp movements are similarly altered after corticospinal tract lesions vs. the removal of visual feedback: Could the direct corticospinal pathway have evolved as the terminal output of the dorsal stream for visual control of reach-to-grasp movements in primates? Society for Neuroscience Abstact.

Karl JM, Whishaw IQ (2014) Haptic grasping configurations in early infancy reveal different developmental profiles for visual guidance of the Reach versus the Grasp. Exp Brain Res (Epub ahead of print)

Karnath HO, Perenin MT (2005) Cortical control of visually guided reaching: evidence from patients with optic ataxia. Cereb Cortex 15:1561-1569

Konczak J, Dichgans J (1997) The development toward stereotypic arm kinematics during reaching in the first 3 years of life. Exp Brain Res 117:346-354

Konen CS, Mruczek EB, Montoya JL, Kastner S, (2013) Functional organization of human posterior parietal cortex: grasping- and reaching-related activations relative to topographically organized cortex. J Neurophys 109:2897-2908

Kremeriitzer JP, Vaughan HG, Kurtzberg D, Dowling K (1979). Smooth-pursuit eye movements in the newborn infant. Child Dev 50:442-448

Krouchev N, Drew T (2013) Motor cortical regulation of sparse synergies provides a framework for the flexible control of precision walking. Front Comput Neurosci 7:83–83

Kuypers HGJM (1981) Anatomy of the descending pathways. In *Handbook of physiology: The nervous system Vol. 2, Part 1*, JM Brookhart, VB Mountcastle (Eds.) pp 579-666. Baltimore: Williams and Wilkins

Lacey S, Sathian K (2011) Multisensory object representation: Insights from studies of vision and touch. In: Green AM, Chapman CE, Kalaska JF, Lepore F (Eds.) *Progress in Brain Research* pp: 165-176, Elsevier

Lawrence DG, Kuypers HG (1968a) The functional organization of the motor system in the monkey. I. The effects of bilateral pyramidal lesions. Brain 91:1-14

Lawrence DG, Kuypers HG (1968b) The functional organization of the motor system in the monkey. II. The effects of lesions of the descending brain-stem pathways. Brain 91:15-36

Lederman SJ, Klatzky RL (1998) The hand as a perceptual system. In: *The psychobiology of the hand*, K Connolly (Ed.), pp 16-35, London: MacKeith Press

Lee JH and van Donkelaar (2006) The human dorsal premotor cortex generates on-line error corrections during sensorimotor adaptation. J Neurosci 26:3330-3334

Le Gros Clark WE (1959) The antecedents of man. New York: Harper and Row

Leinonen L, Hyvarinen J, Nyman G, Linnankoski I (1979) I. Functional properties of neurons in lateral part of associative area 7 in awake monkeys. Exp Brain Res 34: 299-320

Leinonen L, Nyman G (1979) II. Functional properties of cells in anterolateral part of area 7 associative face area of awake monkeys. Exp Brain Res 34:321-333

Lewis JW, Van Essen DC (2000) Corticocortical connections of visual, sensorimotor, and multimodal processing areas in the parietal lobe of the macaque monkey. J Comp Neurol 428, 112-137

Lhota S, Junek T, Bartos L, Kubena AA (2008) Specialized use of two fingers in free-ranging aye-ayes (Daubentonia madagascariensis). Am J Primatol 70:786-795

Li L, Rutlin M, Abraira VE, Cassidy C, Kus L, Gong S, Jankowski MP, Luo W, Heintz N, Koerber HR, Woodbury CJ, Ginty, DD (2011) The functional organization of cutaneous low-threshold mechanosensory neurons. Cell 147:1615-1627

Lockman JJ, Ashmead DH, Bushnell EW (1984) The development of anticipatory hand orientation during infancy. J Exp Child Psychol 37:176-186

Loenneker T, Klaver P, Bucher K, Lichtensteiger J, Imfeld A, Martin E (2010) Microstructural development: Organizational differences of the fiber architecture between children and adults in dorsal and ventral visual streams. Hum Brain Mapp 32:935-946

Loucks J, Sommerville JA (2012) The role of motor experience in understanding action function: The case of the precision grasp. Child Dev 83: 801-809

Luppino G, Matelli M, Camarda RM, Gallese V, Rizzolatti G (1991) Multiple representations of body movements in mesial area 6 and the adjacent cingulate cortex: an intracortical microstimulation study in the macaque monkey. J Comp Neurol 311:463-482

Luppino G, Matelli M, Camarda R, Rizzolatti G (1993) Corticortical connections of area F3 (SMA-proper) and area F6 (pre-SMA) in the macaque monkey. J Comp Neurol 338:114-140.

Luppino G, Murata A, Govoni P, Matelli M (1999) Largely segregated parietofrontal connections linking rostral intraparietal cortex (areas AIP and VIP) and the ventral premotor cortex (areas F5 and F4). Exp Brain Res 128:181-187

Macefield VG, Hager-Ross C, Johansson RS (1996) Control of grip force during restraint of an object held between finger and thumb: responses of cutaneous afferents from the digits. Exp Brain Res 108:155-171

MacFadden BJ (1992) Fossil Horses: Systematics, Paleobiology, and Evolution of the Family Equidae. New York: Cambridge University Press

Macfarlane NBW, Graziano MSA (2009) Diversity of grip in Macaca mulatta. Exp Brain Res 197, 255–268

MacKenzie CL, Iberall T (1994a). Prehension. In: The Grasping Hand, CL MacKenzie CL, T Iberall T (Eds.), pp 15-46, Amsterdam: Elsevier/North Holland

MacKenzie CL, Iberall T (1994a). Prehension. In: The Grasping Hand, CL MacKenzie CL, T Iberall T (Eds.), pp 30, Amsterdam: Elsevier/North Holland

Makin TR, Holmes NP, Zohary E (2007) Is that near my hand? Multisensory representation of peripersonal space in human intraparietal sulcus. J Neurosci 27:731-740

Mamassian P (1997) Prehension of objects oriented in three-dimensional space. Exp Brain Res 114:235-245

Marconi B, Genovesio A, Battaglia-Mayer A, Ferraina S, Squatrito S, Molinari M, Lacquaniti F, Caminiti R (2001) Eye-hand coordination during reaching. I. Anatomical relationships between parietal and frontal cortex. Cereb Cortex 11:513-27

Margulies DS, Vincent JL, Kelly C, Lohmann G, Uddin LQ, Biswal BB, Villringer A, Castellanos FX, Milham MP, Petrides M (2009) Precuneus shares intrinsic functional architecture in humans and monkeys. Proc Nat Acad Sciences 106:20069-20074

Marigold DS, Drew T (2011) Contribution of cells in the posterior parietal cortex to the planning of visually guided locomotion in the cat: effects of temporary visual interruption. J Neurophysiol 105:2457-2470

Mars RB, Jbabdi S, Sallet J, O'Reilly JX, Croxson PL, Olivier E, Noonan MP, Bergmann C, Mitchell AS, Baxter MG, Behrens TE, Johnsen-Berg H, Tomassini V, Miller KL, Rushworth MF (2011) Diffusion-weighted imaging tractography-based parcellation of the human parietal cortex and comparison with human and macaque resting-state functional connectivity. J Neurosci 31:4087-4100

Matelli M, Govoni P, Galletti C, Kutz DF, Luppino G (1998) Superior area 6 afferents from the superior parietal lobule in the macaque monkey. J Comp Neurol 402:327-352

Marteniuk RG, Leavitt JL, MacKenzie CL, Athenes S (1990) Functional relationships between grasp and transport components in a prehension task. Hum Mov Sci 9:149-176

Matsuzaka Y, Aizawa H, Tanji J (1992) A motor area rostral to the supplementary motor area (presupplementary motor area) in the monkey: neuronal activity during a learned motor task. J Neurophysiol 68:653-662

McCarty ME, Clifton RK, Ashmead DH, Lee P, Goubet N (2001) How infants use vision for grasping objects. Child Dev 72:973-987

McGuire LM, Sabes PN (2009) Sensory transformations and the use of multiple reference frames for reach planning. Nat Neurosci 12:1056-1061

Melvin KG, Doan J, Pellis SM, Brown L, Whishaw IQ, Suchowersky O (2005) Pallidal deep brain stimulation and L-dopa do not improve qualitative aspects of skilled reaching in Parkinson's disease. Behav Brain Res 160:188-194

Merzenich MM and Jenkins (1993) Reorganization of cortical representations of the hand following alterations of skin inputs induced by nerve injury, skin island transfers, and experience. J Hand Ther 6:89-104

Messier J and Kalaska JF (2000) Covariation of primate dorsal premotor cell activity with direction and amplitude during a memorized-delay reaching task. 84:152-65

Metz GA, Whishaw IQ (2000) Skilled reaching an action pattern: stability in rat (Rattus norvegicus) grasping movements as a function of changing pellet size. Behav Brain Res 116, 111-122

Michel F, Henaff MA (2004) Seeing without the occipito-parietal cortex: Simulatagnosia as a shrinkage of the attnetional visual field. Behav Neurol 15:3-13

Milliken GW, Ward JP, Erickson CJ (1991) Independent digit control in foraging by the aye-aye (Daubentonia-madagascariensis). Folia Primatologica 56:219-224

Milner AD, Goodale MA (1995) The visual brain in action. Oxford: Oxford Press

Milner AD, Goodale MA (2006) The visual brain in action (2nd ed.). Oxford: Oxford Press

Milner AD, Goodale MA (2008) Two visual systems re-viewed. Neuropsychologia 46:774-785

Mishkin M, Ungerleider LG (1982) Contribution of striate inputs to the visuospatial functions of parieto-proccipital cortex in monkeys. Behavioural Brain Research, 6:57-77

Mitz AR, Wise SP (1987) The somatotopic organization of the supplementary motor area: intracortical microstimulation mapping. 7:1010-1021

Monaco S, Kroliczak G, Quinlan DJ, Fattori P, Galletti C, Goodale MA, Culham, JC (2010) Contribution of visual and proprioceptive information to the precision of reaching movements. Exp Brain Res 202:15-32

Mon-Williams M, McIntosh RD (2000) A test between two hypotheses and a possible third way for the control of prehension. Exp Brain Res 134:268-27

Morrongiello BA, Rocca PT (1989) Visual feedback and anticipatory hand orientation during infants' reaching. Percept Motor Skill 69:787-802

Mountcastle VB, Lynch JC, Georgopoulos A, Sakata H, Acuna C (1975) Posterior parietal association cortex of the monkey: Command functions for operations within extrapersonal space. J Neurophys 38:871-908

Murata A, Fadiga L, Fogassi L, Gallese V, Raos V, Rizzolatti G (1997) Object representation in the ventral premotor cortex (area F5) of the monkey. J Neurophysiol 78:2226-2230

Murata A, Gallese V, Luppino G, Kaseda M, Sakata H (2000) Selectivity for the shape, size, and orientation of objects for grasping in neurons of monkey parietal area AIP. J Neurophysiol 83:2580-2601

Murray EA, Coulter JD (1981) Organization of corticospinal neurons in the monkey. J Comp Neurol 195:339-365

Neafsey EJ, Bold EL, Haas G, Hurley-Gius KM, Quirk G, Sievert CF, Terreberry RR (1986) The organization of the rat motor cortex: a microstimulation mapping study. Brain Res 396, 77-96

Napier JR (1956) The prehensile movements of the human hand. J Bone Joint Surg Am 38-B:902-913

Napier JR (1980) Hands. Princeton, New Jersey: Princeton University Press

Newell KM, Scully DM, McDonald PV, Baillargeon R (1989) Task constraints and infant grip configurations. Dev Psychobiol 22:817-31

Newell KM, Scully DM, McDonald PV, Baillargeon R (1993) Body scale and infant grip configurations. Dev Psychobiol 26:195-205

Olivier E, Edgley SA, Armand J, Lemon RN (1997) An electrophysiological study of the postnatal development of the corticospinal system in the macaque monkey. J Neurosci 17, 267-76

Opitz D, Gegenfurtner KR, Bulthoff HH (1996) A comparison of grasping real and virtual objects. Perception 25:92-93

Padberg J, Franca JG, Cooke DF, Soares JG, Rosa MG, Fiorani M Jr, Gattass R, Krubitzer L (2007) Parallel evolution of cortical areas involved in skilled hand use. J Neurosci 27:10106-10115

Padberg J and Krubitzer L (2006) Thalamocortical connections of anterior and posterior parietal cortical areas in New World titi monkeys. J Comp Neurol 497:416-435

Pare M, Smith AM, Rice FL (2002) Distribution and terminal arborizations of cutaneous mechanoreceptors in the glabrous finger pads of the monkey. J Comp Neurol 445:347-59

Parma V, Roverato R, Ghirardello D, Bulgheroni M, Tirindelli R, Castiello U (2011a) When flavor guides motor control: an effector independence study. Exp Brain Res 212:339-346

Parma V, Ghirardello D, Tirindelli R, Castiello U (2011b) Grasping a fruit. Hands do what flavour says. Appetite 56:249-254

Passarelli L, Rosa MG, Gamberini M, Bakola S, Burman KJ, Fattori P, Galletti C (2011) Cortical connections of area V6Av in the macaque: a visual-input node to the eye/hand coordination system. J Neurosci 31:5145-5157

Patla AE, Vickers JN (2003) How far ahead do we look when required to step on specific locations in the travel path during locomotion? Exp Brain Res 148, 133-138

Paulignan Y, Jeannerod M, MacKenzie C, Marteniuk R (1990a) Selective perturbation of visual input during prehension movements. 2. The effects of changing object size. Exp Brain Res 87:407-420

Paulignan Y, MacKenzie C, Marteniuk R, Jeannerod M (1990b) Selective perturbation of visual input during prehension movements. 1. The effects of changing object position. Exp Brain Res 83:502-512

Perenin MT, Vighetto A (1988) Optic ataxia: a specific disruption in visuomotor mechanisms. I. Different aspects of the deficit in reaching for objects. 111:643-674

Petrides M, Pandya DN (1984) Projections to the frontal cortex from the posterior parietal region in the rhesus monkey. J Comp Neurol 228:105-116

Perris E, Clifton R (1988) Reaching in the dark towards sound as a measure of auditory localization in infants. Infant Behav Dev 11:473-492

Pettersson L-G, Alstermark B, Blagovechtchenski E, Isa T, Sasaki S (2007) Skilled digit movements in feline and primate – recovery after selective spinal cord lesions. Acta Physiol 189:141-154

Pettypiece CE, Culham JC, Goodale MA (2009) Differential effects of delay upon visually and haptically guided grasping and perceptual judgements. Exp Brain Res 195:473-479

Pettypiece CE, Goodale MA, Culham JC (2010) Integration of haptic and visual size cues in perception and action revealed through cross-modal conflict. Exp Brain Res 201:863-873

Phillips JR, Johansson RS, Johnson KO (1992) Responses of human mechanoreceptive afferents to embossed dot arrays scanned across fingerpad skin. J Neurosci, 12:827-39

Pons TP, Kaas JH (1986) Connections of area 2 of somatosensory cortex with the anterior pulvinar and subdivisions of the ventroposterior complex in macaque monkeys. J Comp Neurol 240:16-36

Prevosto V, Graf W, Ugolini G (2009) Posterior parietal areas MIP and LIPv receive eye position and velocity inputs via ascending preposito-thalamo-cortical pathways. Eur J Neurosci 30:1151-1161

Prevosto V, Graf W, Ugolini G (2010) Cerebellar inputs to intraparietal cortex areas LIP and MIP: functional frameworks for adaptive control of eye movements, reaching, and arm/eye/head movement coordination. Cereb Cortex 20:214-228

Prevosto V, Graf W, Ugolini G (2011) Proprioceptive pathways to posterior parietal areas MIP and LIPv from the dorsal column nuclei and the postcentral somatosensory cortex. Eur J Neurosci 33:444-460

Proske U, Gandevia SC (2012) The proprioceptive senses: Their roles in signaling body shape, body position and movement, and muscle force. Physiol Rev 92:1651-1697

Qi HX, Preuss TM, Kaas JH (2008) Somatosensory Areas of the Cerebral Cortex: Architectonic Characteristics and Modular Organization. In: JH Kaas, EP Gardner (Eds.) *The Senses: A Comprehensive Reference, Vol 6 Somatosensation*, pp. 143-169, Oxford: Elsevier

Qi HX, Kaas JH (2004) Myelin stains reveal an anatomical framework for the representation of the digits in somatosensory area 3b of macaque monkeys. J Comp Neurol 477:172-87

Raos V, Franchi G, Gallese B, Fogassi L (2003) Somatotopic organization of the lateral part of area F2 (dorsal premotor cortex) of the macaque monkey. J Neurophysiol 89:1503-1518

Raos V, Umilta MA, Gallese V, Fogassi L (2004) Functional properties of grasping-related neurons in the dorsal premotor area F2 of the macaque monkey. J Neurophysiol 92:1990-2002

Raos V, Umilta MA, Murata A, Fogassi L, Gallese V (2006) Functional properties of grasping-related neurons in the ventral premotor area F5 of the macaque monkey. J Neurophysiol 95:709-729

Rausell E, Jones EG (1991) Chemically distinct compartments of the thalamic VPM nucleus in monkeys relay principal and spinal trigeminal pathways to different layers of the somatosensory cortex. J Neurosci 1991 11:226-37

Reed CL, Klatzky RL, Halgren E (2005) What vs. where in touch: an fMRI study. NeuroImage 25:718-726

Reghem E, Tia B, Bels V, Pouydebat E (2011) Food Prehension and Manipulation in *Microcebus murinus* (Prosimii, Cheirogaleidae). Folia Primatologica 82:177–188

Reichenbach A, Thielscher A, Peer A, Bulthoff HH, Bresciani JP (2014) A key region in the human parietal cortex for processing proprioceptive hand feedback during reaching movements. Neuroimage 84:615-625

Rice NJ, Tunik E, Grafton ST (2006) The anterior intraparietal sulcus mediates grasp execution, independent of requirement to update: new insights from transcranial magnetic stimulation. J Neurosci 26:8176-8182

Rizzolatti G, Carmada R, Fogassi L, Gentilucci M, Luppino G, Matelli M (1988) Functional organization of inferior area 6 in the macaque monkey. 2. Area F5 and the control of distal movements. Exp Brain Res 71:491-507

Rizzolatti G, Cattaneo L, Fabbri-Destro M, Rozzi S (2014) Cortical mechanisms underlying the organization of goal-directed actions and mirror-neuron based action understanding. Physiol Rev 94:655-706.

Rizzolatti G, Luppino G (2001) The cortical motor system. Neuron 31:889-901

Rizzolatti G, Luppino G, Matelli M (1998) The organization of the cortical motor system: new concepts. Electroencephalogr Clin Neurophysiol 106:283-296

Rizzolatti G, Matelli M (2003) Two different streams form the dorsal visual system: anatomy and functions. Exp Brain Res 153:146-157

Robin DJ, Berthier NE, Clifton RK (1996) Infants' predictive reaching for moving objects in the dark. Dev Psych 32:824-835

Robinson TE (1978) Electrical stimulation of the brain stem in freely moving rats: I. Effects on behavior. Physiol Behav 21:223-31

Roland PE (1987) Somatsensory detection of microgeometry, macrogeometry and kinesthesia after localized lesions of the cerebral hemispheres in man. Brain Res 434:43-94

Rondot P, de Recondo J, Dumas JL (1977) Visuomotor ataxia. Brain 100, 355-376

Rönnqvist L, Hofsten von C (1994) Neonatal finger and arm movements as determined by a social and an object context. Early Dev Parenting 3:81-94

Rozzi S, Calzavara R, Belmalih A, Borra E, Gregoriou GG, Matelli M, Luppino G (2006) Cortical connections of the inferior parietal cortical convexity of the macaque monkey. Cereb Cortex 16:1389-1417

Rozzi S, Ferrari PF, Bonini L, Rizzolatti G, Fogassi L (2008) Functional organization of inferior parietal lobule convexity in the macaque monkey: electrophysiological characterization of motor, sensory and mirror responses and their correlation with cytoarchitectonic areas. Eur J Neurosci 28:1569-1588

Sabes PN (2011) Sensory integration for reaching: models of optimality in the context of behavior and the underlying neural circuits. Prog Brain Res 191:195-209

Sacrey LA, Alaverdashvili M, Whishaw IQ (2009) Similar hand shaping in reaching-for-food (skilled reaching) in rats and humans provides evidence of homology in release, collection, and manipulation movements. Behav Brain Res 204:153-161

Sacrey LA, Karl JM, Whishaw IQ (2012a) Development of visual and somatosensory attention of the reach-to-eat movement in human infants aged 6 to 12. Exp Brain Res 223:121-136

Sacrey, L-A.R, Karl JM, Whishaw IQ (2012b) Development of rotational movements, hand shaping, and accuracy in advance and withdrawal for the reach-to-eat movement in human infants aged 6-12 months. Infant Behav Dev 35:543–560

Sacrey LA, Whishaw IQ (2010) Development of collection precedes targeted reaching: resting shapes of the hands and digits in 1-6-month-old human infants. Behav Brain Res 214:125-129

Sacrey LA, Whishaw IQ (2011) Subsystems of sensory attention for skilled reaching: Vision for transport and pre-shaping and somatosensation for grasping, withdrawal, and release. Behav Brain Res 231:356-365

Safstrom D, Edin BB (2004) Task requirements influence sensory integration during grasping in humans. Learn Mem 11:356-363

Safstrom D, Edin BB (2008) Prediction of object contact during grasping. Exp Brain Res 190:265-277

Sainburg RL, Poizner H, Ghez C (1993) Loss of proprioception produces deficits in interjoint coordination. J Neurophysiol 70:2136-47

Sakata H, Taira M, Kusunoki M, Murata A, Tanka Y (1997) The TINS Lecture. The parietal association cortex in depth perception and visual control of hand action. Trends Neurosci 20:350-357

Sakata H, Taira M, Kusunoki M, Murata A, Tanaka Y, Tsutsui K (1998) Neural coding of 3D features of objects for hand action in the parietal cortex of the monkey. Philos Trans R Soc Lond B Biol Sci 353:1363-1373

Sartori L, Staulino E, Castiello U (2011) How objects are grasped: the interplay between affordances and end-goals. PLoS One, 6:e25203

Sathian K, Lacey S (2007) Journeying beyond classical somatosensory cortex. Can J Exp Psych 61:254-264

Sathian K, Lacey S, Stilla R, Gibson GO, Deshpande G, Hu X, LaConte S, Glielmi C (2011) Dual pathways for haptic and visual perception of spatial and texture information. NeuroImage 57:462-475

Saling M, Mescheriakov S, Molokanova E, Stelmach GE, Berger M (1996) Grip reorganization during wrist transport: the influence of an altered aperture. Exp Brain Res 108:493-500

Schieber MH, Santello M (2004) Hand function: peripheral and central constraints on performance. J Appl Physiol 96:2293-300

Schlesinger M, Parisi D (2001) Multimodal control of reaching – simulating the role of tactile feedback. IEEE Trans Evol Comput 5:122-128

Schmidt RA and Lee TD (2011) Motor control and learning: A behavioral emphasis 5 th edtion. Champaign Il: Human Kinetics

Schum N, Jovanovic B, Schwarzer G (2011) Ten- and twelve-month-olds' visual anticipation of orientation and size during grasping. J Exp Child Psychol 109:218-231

Schwark HD, Tennison CF, Ilyinsky OB, Fuchs JL (1999) Inhibitory influences on receptive field size in the dorsal column nuclei. Exp Brain Res 126:439-442

Scott SH, Sergio LE, Kalaska JF (1997) Reaching movements with similar hand paths but different arm orientations. II. Activity of individual cells in dorsal premotor cortex and parietal area 5. J Neurophysiol 78:2413-2426

Shallice T, Venable N, Rumiati RI (2005) Dissociable distal and proximal motor components: Evidence from perseverative errors in three apraxic patients. Cogn Neuropsychol 22:625-39

Shipp S, Blanton M, Zeki S (1998) A visuo-somatomotor pathway through superior parietal cortex in the macaque monkey: cortical connections of areas V6 and V6A. Eur J Neurosci 10:3171-3193

Siddiqui A (1995) Object size as a determinant of grasping in infancy. J Genet Psychol 156:345-358

Sivak B, MacKenzie CL (1990) Integration of visual information and motor output in reaching and grasping: the contributions of peripheral and central vision. Neuropsychologia 28:1095-1116

Smeets JB, Brenner E (1999) A new view on grasping. Motor Control 3:237-271

Snyder LH, Batista AP, Andersen RA (1997) Coding of intention in the posterior parietal cortex. Nature 386:167-170

Stelmach GE, Castiello U, Jeannerod M (1994) Orienting the finger opposition space during prehension movements. J Mot Behav 26:178-186

Stepniewska I, Cerkevich CM, Fang PC, Kaas JH (2009) Organization of the posterior parietal cortex in galagos: II. Ipsilateral cortical connections of physiologically identified zones within anterior sensorimotor region. J Comp Neurol 517:783-807

Stepniewska I, Fang PC, Kaas JS (2005) Microstimulation reveals specialized subregions for different complex movements in posterior parietal cortex of prosimian galagos. Proc Natl Acad Sci U.S.A. 102:4878-4883

Stepniewska I, Fang PC, Kaas JH (2009a) Organization of posterior parietal cortex in galagos: I. Functional zones identified by microstimulation. J Comp Neurol 517:765-782

Stepniewska I, Cerkevich CM, Fang PC, Kaas JH (2009b) Organization of posterior parietal cortex in galagos: II. Ipsilateral cortical connections of physiologically identified zones within anterior sensorimotor region. J Comp Neurol 517:783-807

Stilla R, Sathian K (2008) Selevtive visuo-haptic processing of shape and texture. Human Brain Mapping 29:1123-1138

Sustaita D, Pouydebat E, Manzano A, Abdala V, Hertel F, Herrel A (2013) Getting a grip on tetrapod grasping: form, function, and evolution. Biol Rev Camb Philos Soc 88:380-405

Tanne-Gariepy J, Rouiller EM, Boussaoud D (2002) Parietal inputs to dorsal versus ventral premotor areas in the macaque monkey: evidence for largely segregated visuomotor pathways. Exp Brain Res 145:91-103

Taira M, Mine S, Georgopoulos AP, Murata A, Sakata H (1990) Parietal cortex neurons of the monkey related to the visual guidance of hand movement. Exp Brain Res 83:29-36

Taoka M, Tanaka M, Hihara S, Ojima H, Iriki A (2013) Neural response to movement of the hand and mouth in the secondary somatosensory cortex of Japanese monkeys during a simple feeding task. Somatosens Mot Res 30:140-152

Thelen E, Corbetta D, Kamm K, Spencer JP, Schneider K, Zernicke RF (1993) The transition to reaching: Mapping intention and intrinsic dynamics. Child Dev 64:1058-1098

Thelen E, Corbetta D, Spencer JP (1996) Development of reaching during the first year: role of movement speed. J Exp Psychol Human 22:1059-1076

Thelen E, Spencer JP (1998) Postural control during reaching in young infants: a dynamic systems approach. Neurosci Biobehav Rev 22:507-514

Thomas BL, Karl, JM, Whishaw IQ (In prep) The tactile origins of grasping in human infants: Refinement of functional grip configurations through self-touching

Timman D, Stelmach GE, Bloedel JR (1996) Grasping component alterations and limb transport. Exp Brain Res 108:486-492

Tsu E, Ellman SJ, Berman AJ (1966) Deafferentation in monkeys: effect on conditioned grasp response. Science 151:593-594

Tremblay F, Ageranioti-Belanger SA, Chapman CE (1996) Cortical mechanisms underlying tactile discrimination in the monkey. I. Role of primary somatosensory cortex in passive texture discrimination. J Neurophysiol 76:3382-403

Trillenberg P, Sprenger A, Petersen D, Kompf D, Heide W, Helmchen C (2007) Functional dissociation of saccade and hand reaching control with bilateral lesions of the medial wall of the intraparietal sulcus: implications for optic ataxia. Neuroimage 36 Suppl 2:T69-T76

Trulsson M and Johansson RS (2002) Orofacial mechanoreceptors in humans: encoding characteristics and responses during natural orofacial behaviours. Behav Brain Res 135:27-33

Tunik E, Frey SH, Grafton ST (2005) Virtual lesions of the anterior intraparietal area disrupt goal-dependent on-line adjustments of grasp. Nat Neuroscie 8:505-11

Twitchell TE (1965). The automatic grasping responses of infants. Neuropsychologia 3, 247-259

Twitchell TE (1970) Reflex mechanisms and the development of prehension. In: *Mechanisms of motor skill development*, K Connolly (Ed.) New York: Academic Press

Valenza N, Ptak R, Zimine I, Badan M, Lazeyras F, Schnider A (2001) Dissociated active and passive tactile shape recognition: a case study of pure tactile apraxia. 124:2287-2298

Valyear KF, Chapman CS, Gallivan JP, Mark RS, Culham JC (2011) To use or to move: goal-set modulates priming when grasping real tools. Exp Brain Res 212:125-142

Van Boven RW, Johnson KO (1994) The limit of tactile spatial resolution in humans: grating orientation discrimination at the lip, tongue, and finger. Neurology 44:2361-2366

Van Der Fits IB, Hadders-Algra M (1998) The development of postural response patterns during reaching in healthy infants. Neurosci Biobehav Rev 22:521-526

Vega-Bermudez F and Johnson KO (1999) SA1 and RA receptive fields, response variability, and population responses mapped with a probe array. J Neurophysiol 81:2701-10

Vesia M and Crawford JD (2012) Specialization of reach function in human posterior parietal cortex. Exp Brain Res 221:1-18

Wallace PS, Whishaw IQ (2003). Independent digit movements and precision grip patterns in 1–5-month-old human infants: hand-babbling, including vacuous then self-directed hand and digit movements, precedes targeted reaching. Neuropsychologia 4:1912–1918

Wang JJ, Wai YY, Weng YH, Ng KK, Huang YZ, Ying LL, Liu HL, Wang CH (2009) Functional MRI in the assessment of cortical activation during gait-related imaginary tasks. Journal of Neurotransmission, 116:1087-1092

Wang X, Wall JT (2006) Cortical influences on rapid brainstem plasticity. Brain Res 1095:73-84

Watt SJ, Bradshaw MF, Rushton SK (2000) Field of view affects reaching, not grasping. Exp Brain Res 135:411-416

Wentworth N, Benson JB, Haith MM (2000) The development of infants' reaches for stationary and moving objects. Child Dev 71:576-601

Whishaw IQ (2003) Did a change in sensory control of skilled movements stimulate the evolution of the primate frontal cortex? Behav Brain Res 146:31-41

Whishaw IQ, Coles BLK (1996) Varieties of paw and digit movement during spontaneous food handling in rats: Posture, bimanual coordination, preferences, and the effect of forelimb cortex lesions. Behav Brain Res, 77;135-148

Whishaw IQ, Dringenberg HC, Pellis SM (1992a) Spontaneous forelimb grasping in free feeding by rats: motor cortex aids limb and digit positiong. Behav Brain Res 48:113-125

Whishaw IQ, Pellis SM (1990) The structure of skilled forelimb reaching in the rat: a proximally driven movement with a single distal rotary component. Behav Brain Res 41:49-59

Whishaw IQ, Pellis SM, Gorny BP (1992b) Skilled reaching in rats and humans: evidence for parallel development or homology. Behav Brain Res 47:59-70

Whishaw IQ, Sacrey LA, Travis SG, Gholamrezaei G, Karl JM (2010a) The functional origins of speech-related hand gestures. Behav Brain Res 214:206-215

Whishaw IQ, Sarna JR, Pellis SM (1998) Evidence for rodent-common and species-typical limb and digit use in eating, derived from a comparative analysis of ten rodent species. Behav Brain Res 96:79-91

Whishaw IQ, Suchowersky O, Davis L, Sarna J, Metz G, Pellis SM (2002) Impairment of pronation, supination, and body coordination in reach-to-grasp tasks in human Parkinson's disease (PD) reveals homology to deficits in animal models. Behav Brain Res 133:165-176

Whishaw IQ, Tomie JA (1989) Olfaction directs skilled forelimb reaching in the rat. Behav Brain Res 32:11-21

Whishaw IQ, Travis SG, Koppe SW, Sacrey LA, Gholamrezaei G, Gorny B (2010b) Hand shaping in the rat: conserved release and collection vs. flexible manipulation in overground walking, ladder rung walking, cylinder exploration, and skilled reaching. Behav Brain Res 206:21-31

White LB, Castle P, Held R (1964). Observations on the development of visually-directed reaching. Child Dev 35:349-364

Whitlock JR (2014) Navigating actions through the rodent parietal cortex. Front Hum Neurosci 8: doi: 10.3389/fnhum.2014.00293

Wilber AA, Clark BJ, Forster TC, Tatsuno M, McNaughton BL (2014) Interaction of egocentric and world-centered reference frames in the rat posterior parietal cortex. J Neurosci 34:5431-5446

Wilkson EJ, Sherk HA (2005) The use of visual information for planning accurate steps in a cluttered environment. Behav Brain Res 164:270-274

Wimmers RH, Savelsbergh GJP, Beek PJ, Hopkins B (1998). Evidence for a phase transition in the early development of prehension. Dev Psychobiol 32:235–248

Wing AM, Turton A, Fraser C (1986) Grasp size and accuracy in approach in reaching. J Mot Behav 18:245-260

Wise SP, Donoghue JP (1986) Motor cortex of rodents. In: Sensory-Motor Areas and Aspects of Cortical Connectivity: Cereral Cortex EJ Jones, A Peters (Eds.), pp 243-265, New York: Plenum

Witherington, D.C. (2005) The development of prospective grasping control between 5 and 7 months: a longitudinal study. Infancy 7:143-161.

Wong YJ, Whishaw IQ (2004) Precision grasps of children and young and old adults: individual differences in digit contact strategy, purchase pattern, and digit posture. Behav Brain Res 154:113-123

Woodworth RS (1899) The accuracy of voluntary movement. Psychol Rev 3:1-119

Wu H, Williams J, Nathans J (2012) Morphologic diversity of cutaneous sensory afferents revealed by genetically directed sparse labeling. Elife 1:e00181

Yokochi H, Tanaka M, Kumashiro M, Iriki A (2003) Inferior parietal somatosensory neurons coding face-hand coordination in Japanese macaques. Somatosens Mot Res 20:115-125

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