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The kinematics of human tool use

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The Kinematics of Human Tool Use

Ruth A. Dickson, BSc, MSc

This thesis is submitted in partial fulfilment of the requirement for the degree of Doctor of Philosophy, completed in the school of Psychology, Bangor University.

Declarations

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Abstract

The aim of this thesis was to use kinematic analysis to further our understanding of tool use. We wanted to investigate whether there were similarities in how people picked up objects with their hand and with a tool, and whether these remained when we manipulated the ratio and motor equivalence of the tool. This allowed us to investigate the concepts of end-effector control and internal tool models. Participants compensated for the ratio of the red 1.4:1 tool to the same extent when only cued with tool colour as when having all of the information. This shows that information about the tool must have been stored in memory, supporting the idea of internal tool models. Participants produced qualitatively similar movements with our tools and the hand, showing no difference in the peak velocity and altering peak end-effector aperture based on tool ratio. Further to this, participants displayed similar adaptive mechanisms in response to visual uncertainty with the hand, the blue 1:1 tool and the red tool, but not with the yellow 0.7:1 tool however. Throughout the thesis participants also compensated less for the ratio of this tool than the red one. Whilst attempting to investigate the imperfect compensation seen with both tools we understood this issue more. Participants overestimated object size with the yellow tool and performed more poorly at a size discrimination task as well. This pointed towards a biased internal tool model, tending towards the aperture of the hand. This accounted for the asymmetric compensation seen between the red and yellow tools. We concluded that the imperfect compensation for tool ratio was caused by noise in the internal tool models and that the yellow tool model was then biased as well, further reducing compensation. Our findings support the idea that the precision with which we can use a tool could be modulated by prior experience with that transformation. We also believe that the degree of motor equivalence of the tool contributes to precision of use, with tools that are not directly equivalent taking longer to develop a robust internal model for. However, even tools without direct motor equivalence display some of the hallmarks of reaching and grasping with the hand, suggesting that grasping movements could be encoded in end-effector units.

Chapter 1: General Introduction

1.1. A brief introduction to human tool use

Human tool use is arguably an amazing ability. It has been referred to as both "one of our most remarkable skills" (Cardinali et al., 2012) and "a complex and fascinating ability" (Massen & Rieger, 2012) in the literature. Human beings began using basic stone tools millions of years ago (Panger, Brooks, Richmond & Wood, 2002) and in the present day most people use a wide variety of tools to help them achieve tasks that would otherwise be much harder or even impossible to complete. Whilst we are by no means the only species to use tools, it can certainly be argued that we are the most adept at it. Anything from a pair of tongs, to a piece of sports equipment, to a musical instrument or even a car could be considered a tool. These are all vastly different pieces of equipment that differ in complexity, form and function. Yet we as humans are able to become experts in using all of them.

The basic issue that we have to solve to be able to use a tool is a transformational one. Tools alter the relationship between the hand and the world. This leads to a 'control problem' where movement at the hand relates to an altered movement at the end-effector (the tip of the tool). To be able to use a tool in the fluid manner that we do, we must be able to account for this transformation successfully, but how we do this is not really known.

1.2 What is a tool?

For the purpose of this thesis, a tool is something that results in the movement of an end-effector in the world, which is spatially separate from the hand. This definition works for our purposes, however it is actually very difficult to come up with a definition of a tool that holds true for every situation. Whilst human tool use has long been studied it has been highlighted in the past that this is where a lot of research falls down – they fail to adequately define what a tool actually is. Osiurak, Jarry and Le Gall (2010) looked at the definitions put forward by some of the prominent authors of tool use literature and discovered three recurring features that can be used to answer the question, "What is a tool?".

I. Tools are discrete, unattached environmental objects.

II. Tools amplify the user's sensorimotor capabilities.

III. Tools are restricted to what is manipulated by the user.

However, applying these definitions to real life situations shows that defining tools and tool use is not as simple as it first seems, and opens up the issue of what tools are actually "true tools" (St Amant & Horton, 2008). For example, a clamp can be used to hold a piece of wood to a table while sawing through it, could it be argued that the clamp is a tool? The user is not manipulating the clamp and it is not discrete from the environment so according to Osiurak et al.'s (2010) definitions the clamp would not be classed as a "true tool". Instead it could be classified as a "borderline tool" (Osiurak et al., 2010) or a "proto-tool" (Seed & Byrne, 2010). Osiurak et al. (2010) discuss the third recurring feature further. Using the documented case of Egyptian vultures smashing eggs onto the ground to break them (van Lawick-Goodall, 1970, as cited in Osiurak et al., 2010), they point out that here it is the egg that is being manipulated by the user, so does the egg become the tool? They instead put forward the idea that maybe a tool is something that is used to alter the physical properties of something else, but also point out that that violates one of their basic principles, set out above (Osiurak, et al., 2010). So even with what initially seems to be a basic set of rules it can still be difficult to determine what is and is not a tool. It is obvious that a concrete, operationalised definition of a tool is actually hard to come by and a definition may never be entirely unambiguous. This is why for our purposes in this thesis when we refer to a tool we mean an instrument where a movement at the hand results in the movement of a spatially separate end-effector in the world.

Whilst tools may be difficult to define, they can be more easily divided up into different classifications. For example, tools can either improve upon a capability that the user already has (using a mechanical arm to reach something too far away from us, or using pliers to increase our grip force) or they can give the user an entirely new capability (using a pair of scissors to cut something—a task that cannot be achieved with the hand alone). Another classification is that tools can be described with reference to two different types of transformation: kinematic and dynamic (Massen & Rieger, 2012). Tools classed as having a kinematic transformation are ones where the body's *movements* are transformed into the tool's movements. For example, the movement of your hand when you use a pair of tongs is transformed into the movement of the tongs' tips. A dynamic transformation is where the *force* that the actor exerts onto the tool is transformed into the force that the tool exerts on an object or the environment. For example, when you use a pair of pliers the force that you exert onto the pliers' handles transforms into a higher force onto the object you are holding. Again, this is not a clear-cut definition though as there are arguably tools that fall into both of these categories. For example, a pair of tongs can have both a kinematic and dynamic transformation.

Another way of categorising tools is by using the concept of motor equivalence. This is where a tool performs a movement that is motorically equivalent to what can be achieved with the hand (Arbib, Bonaiuto, Jacobs & Frey, 2009). To use the example of a pair of tongs again, they open and close in a manner that mimics the precision grip of the finger and thumb, and thus have motor equivalence. Using a bread knife however to slice a loaf of bread uses a very different movement to taking the bread and tearing it in two with your hands, and therefore a bread knife does not have motor equivalence.

Motor equivalence is not a binary concept however. There are some tools that have some level of motor equivalence but do not directly mimic the movement of the hand. For example, a pair of test tube holders open and close in the same manner as the finger and thumb. However, they do this in the opposite direction to how the finger and thumb move. These arguably do not have the same level of motor equivalence as a standard pair of tongs, however they certainly are more motorically equivalent to the hand than a bread knife. This is a concept that we hope to investigate further during this thesis.

1.3 Reaching and grasping an object with the hand

The process of grasping an object is complex. It involves the co-ordination of lots of different joints in the arm and hand, which must move not only linearly but also rotationally during the grasp (Smeets & Brenner, 1999). Moreover, the timing of the finger movements needs to be co-ordinated with the movement of the limb as the grasp unfolds to ensure that the hand is in the correct configuration as it contacts the object (Goodale & Servos 1996; Jeannerod 1988). Despite this, grasping with the hand has been shown to be a precise movement. When people grasp an object, they scale the opening of their finger and thumb with the size of the object (Jeannerod, 1981; 1984; 1997; Smeets & Brenner, 1999, Wing, Turton & Fraser, 1986) and they scale the speed of their movement with the distance of the object (Jeannerod, 1984; 1988).

Because of the complexity of the movement it can be difficult to study grasping as a whole, as there are many different aspects involved. This has led to the approach of analysing separate indices within the movement that are more easily comparable. By identifying these indices from within the grasp, the movement can be reduced down to a handful of numerical values that are much easier to comprehend, measure and compare than an entire grasping movement would be. One of the first people to study grasping in this way was Jeannerod (1981) who suggested that there were two separate visuomotor channels that are utilised in a reaching and grasping movement; one to control the transport of the hand and the other to control the formation of grip size. This was suggested because it easily mapped onto what we observe when we watch reaching and grasping movements and also because research on monkeys has suggested that these separate pathways may exist in the brain (Jeannerod, 1999; Jeannerod, Arbib, Rizzolatti & Sakata, 1995). This theory divided the whole grasping movement into two more easily studied parts – the reach and the grasp. For a long time, this separation was accepted (Arbib, 1981; Jeannerod, 1981; 1999), however more recently other theories have been suggested (Smeets & Brenner, 1999). It has been demonstrated that the timing of the movement of the finger during a grasp co-ordinates with the movement of the arm, suggesting that the reach and grasp components of the movement may not be separable after all (Goodale & Servos, 1996).

Wing and colleagues also carried out experiments to show that it is not the wrist that is transported during a movement but instead it is the thumb (Haggard & Wing, 1997; Wing & Fraser, 1983; Wing et al., 1986). They suggest that because the variability of the wrist remains constant throughout the movement whereas that of the thumb reduces as the object is approached, that it must be the motion of the thumb that is being planned for during the movement (Haggard & Wing, 1997). Smeets and Brenner (1999) also suggest that rather than the reach and the grasp being two separate entities, the movement is instead simply the pointing of both the finger and thumb towards the appropriate surfaces of an object. They build on the work about the variability of the movement of the thumb during a grasp (Wing & Fraser, 1983; Wing et al., 1986) and suggest that a similar change in variability is also seen with the finger (Paulignan, Frak, Toni & Jeannerod, 1997; Smeets & Brenner, 1999). Therefore, they suggest that perhaps it is both the finger and thumb that are being transported during a movement.

1.4 Reaching and grasping an object with a tool

As complex as grasping an object with the hand is, the process is complicated further when a tool is used. As discussed previously, using a tool creates a transformational problem. What the user does with their hand, does not necessarily directly relate to what happens to the tool's tip/s, and even if the movement at the tip is the same, then there is still a spatial offset to adjust for that is not present when grasping with the hand.

This thesis will focus on the end-effector aspect of this issue. How is it that we can successfully pick up an object with a tool when the end-effector (the tool's tips) moves in a different manner to the hand? In the current literature on tool use there are multiple bodies of work that can give potential solutions to the end-effector problem; some of these will be discussed below.

1.4.1 Tool use and the body schema

As discussed, tool use involves altering the normal relationship between the hand and the world. This means that even the use of a very simple tool adds an arguably quite complex addition to the arm of the user. Despite this, we are able to use tools to perform precise tasks. How are we able to have such fine control over an object that is not part of our body?

To answer this question, one concept that has been put forward is that we use tools in a way that is akin to them being an extension of our own bodies (Head & Holmes, 1911). This theory relates to the concept of a 'body schema' - the idea that we have an internal schematic representation of our own bodies. This means that we use the information that we know about our own arm/hand and apply this to a tool. Hypothetically, this could be anything from modelling position in space to using information about the angles and movements of our own joints and applying these to a tool. The modern concept of the body schema was coined by Head and Holmes (1911). They state, “Anything which participates in the conscious movement of our bodies is added to the model of ourselves and becomes part of those schemata: a woman’s power of localization may extend to the feather in her hat” (Head & Holmes, 1911, p188). This illustrates the concept nicely, anything that we pick up and consciously move we begin to model as a part of own body, using the information we know about how our joints and muscles move and applying this to the external object.

This is an important concept when it comes to the topic of tool use. To be able to take what you know about your own body and how it works and apply this information to a discrete object would enable to you manipulate this object in a similar manner. When we program our own movements, it is thought that we use a forward model (Wolpert & Flanagan, 2001); making predictions about how a movement will play out and adjusting in the form of online corrections as the movement occurs. To be able to use this ability and apply it to a tool could account for why people are able to pick up a tool they have never seen before and use it in a precise manner.

Colloquial observations can help to support the idea of the body schema. Most people will have experienced the feeling that a tool was ‘part of them’. Take the example of driving your car through a narrow tunnel and suddenly feeling compelled to tuck your arms into your body to make yourself fit through—is this an example of incorporating a tool (your car) into your body schema? There is also the idea that when someone is very adept at using a tool—for example a professional tennis player—they feel like the tool (their racket) is an extension of their own arm. They do not think about where their hand needs to be in order to hit the ball but are instead thinking about the end of the racket, but this alone is not proof that they are using knowledge about their arm to do this.

More concretely than this, there has been a lot of research carried out on tool use and the body schema. Cardinali et al. (2009a) compared grasps made before and after tool use. They found that in the reaching phase of the movement that movement times were shorter, peak velocity and peak deceleration occurred earlier and that peak velocity and deceleration were higher before tool use than they were after. This means that after using a tool, participants reached lower peak speeds, later on in the movement and took longer to complete the movement than they had before using the tool. They found no changes in the grasping phase of the movement however. They argue that this demonstrates that the tool was incorporated into the body schema due to the fact that differences are suggestive of grasping using a longer arm. They also asked participants to point to the location of a vibrotactile stimulation on their arm and then reach an object using the tool and point to the stimulation again. They found that after tool use people estimated that stimulation on the fingertips and elbows was further away than they had prior to tool use, suggesting that they perceived their arm length to be longer after using a tool. The work by Cardinali et al. (2009a) supports the idea that there is an extension or stretching of bodily representations in the brain rather than just a change in focus from the hand to the tip of the tool. Arbib et al. (2009) disagree with this concept, however, and instead suggest that because different tools would extend the body schema in different ways (depending on the end-effector of the tool) it is likely that “a tool extends the hand’s functionality rather than replacing the hand” (Arbib et al., 2009, p 442). This means that while the function of the hand can be used to understand the tool, the tool never replaces the hand and we are always aware of the hand's location. Extension of our concept of the hand may make sense when using a simple tool like a stick, but this falls apart when more complex tools are used. Arbib et al. (2009) therefore suggest that rather than the brain's concept of the hand itself being 'stretched' to incorporate the tool, instead a more complex process would be needed when tools do not have motor equivalence.

Bongers (2010) replicated part of Cardinali et al.'s (2009a) experiment with a large pair of tongs and suggested that the changes in grasping with the hand after tool use are unlikely to be due to an updating of the body schema. He found during tool use that there was a plateau at the peak of the grasp and suggested that this could indicate a decoupling of the opening and closing of the hand during tool use. This means that the opening and closing of a tool are two separately programmed movements, independent of one another. Bongers (2010) therefore suggests that the after-effects seen in the Cardinali et al. (2009a) experiment may simply have been a generalized slowing caused by the learning of the tool and nothing to do with changes in mapping state or the body schema.

Cardinali et al. (2012) built upon their previous work further by getting participants to make grasping movements with the hand before and after using a tool again, but this time they either used the tool to grasp an object, or they used it to match the tool-tip opening to the size of an object (therefore not actually using the tool). When looking at the size-matching task they found no change in the peak velocities and decelerations reached pre and post tool use, they did however find a reduction in their amplitudes. Compared to the grasping task where they replicated their old findings, peak velocities and decelerations occurred later in the movement post tool use. They argue that this demonstrates that the nature of the task will affect whether or not a tool is incorporated into the body schema.

Witt, Proffitt and Epstein (2005) ran an experiment that demonstrated that participants only incorporate a tool into their body schema when they actually use it and that passively holding a tool is not enough to effect a change. They showed that when judging the distance of an object (either verbally or through a matching task), that distance was underestimated after using a tool. They then used the same matching task but participants only held the tool and did not reach with it, here the distance effects disappeared. They argue that this shows that passively holding a tool is not enough to prompt incorporation of the tool into the body schema. There are other experiments that support this concept. Brown, Doole, and Malfait (2011) used hand proximity effects to test this idea. This is the concept that the brain has bimodal visual-tactile neurons that respond when information is presented near to the hand. It has been shown that people respond faster to objects that are placed close to their hands and it is thought that this could be due to the recruitment of these bimodal neurons. Brown et al. (2011) investigated whether this hand proximity effect could be induced when objects appeared close to the tip of a tool that the participant was holding. In the experiment participants were assigned to either an active training group, a passive training group or a control group. The active training group were required to point the tip of the tool at targets during their training, the passive group held the tool but it was guided to targets by the experimenter and the control group simply sat holding the tool for 15 minutes. All participants then completed six pointing trials to look at how well they could use the tool and then took part in a visual detection task that was modified from the Posner cueing task: half of the blocks they did this task holding the tip of the tool near the screen (within 5cm) and half they held it 30cm away. They found that the active group were able to use the tool the best out of all the participants as they had the fastest movement times and a low number of pointing errors. The passive group had the same amount of pointing errors, however they had slower movement times suggesting that they were not as skilled with the tool as the active group were. On the visual detection task participants in the active group showed a significant effect for tool proximity, moving faster when the tool was near the screen, they also showed a faster reaction time than the other two groups. This suggests that Brown et al. (2011) were able to observe 'tool proximity effects' and therefore these bimodal visual-tactile neurons that could be responsible for the hand proximity effect may be recruited during tool use as well. Their research also supports the literature that active movement is necessary for a tool to be incorporated into the body schema, it seems therefore that some motor experience with a tool may be necessary for incorporation to occur. They suggest that studies that have found that passive holding is enough for changes in processing to occur may have found their results as the tools they used were very simple or already familiar to the participant allowing their motor-skill history to enable incorporation. So, it may be that when using a novel tool that motor experience plays an important role in spatial adaptation and incorporation into the body schema.

As suggested above, there have been studies that have found that passive holding is enough to induce changes in the body schema however. Carlson, Alvarez, Wu and Verstraten (2010) argue that objects that are simply being held can be integrated into the body schema. They investigated this using the afterimage paradigm. This involves sitting the participant in a totally darkened room and flashing a bright light to create an afterimage of the scene. Once this afterimage is created, if a body part included in the image is moved then this part of the image will fade whilst the rest remains (Davies, as cited in Carlson et al., 2010; Gregory, Wallace & Cambell, as cited in Carlson et al., 2010). This effect is said to be driven by a conflict in the proprioceptive information about the location of the limb and the visual information about limb location provided by the afterimage, causing the visual image to change. They used this paradigm to assess whether other items have been incorporated into the body schema by seeing if moving them also causes the image to fade or whether it remains intact. They demonstrated that a ball faded from the after-image when it was held in the hand and dropped, however it did not fade when it was held in a mechanical arm that was attached to the table and dropped. They argue that this shows that the ball has been incorporated into the body schema, despite there being no task associated with this. This is contradictory to the research mentioned previously. This is a relatively indirect measure of the body schema however, that relies on subjective reporting so this could be the reason why. It is, however, worth considering, to demonstrate that it is not necessarily clear cut when a tool does or does not get incorporated into the body schema.

There is enough research in the area that there seems to be some weight to the idea that tools could be incorporated into the body schema, but up to this point we are yet to discuss *how* this might occur. As discussed previously, Cardinali et al.'s (2009a) experiment suggests this could be achieved by stretching the concept of our hand to include the tool. This was however refuted by Arbib et al. (2009) who argued that this does not make sense when more complicated tools are being used. Povinelli, Reaux and Frey (2010) also suggest that it seems implausible that we stretch our perception of our body to include the tool, but instead we keep separate representations of the tool and the hand at all times. They state that there are tasks, such a cooking, where it would be too dangerous to perform the task with the hand alone. It would therefore not make sense to stretch the concept of the arm/hand to include the tool, as we still need to be aware of the position of our hand during the task. They demonstrated this by getting chimpanzees to decide whether to perform a task with their hand or a tool when there was a potential hazard present. When there was obviously no hazard present then all chimpanzees preferred to use their hands to reach some food from a box. However, when the box was closed (and therefore potentially contained a hazard) 50% of the chimps opted to use the tool to open the box and kept their hands away from it. They also favoured the tool when the box was open and obviously contained a hazard. The other 50% of chimps however preferred to use their hand throughout the task, even when the box was open and a hazard was clearly present. The authors argue this may show that the hazard was not perceived as dangerous by these chimps, as even when the hazard was clear and obvious they still chose to use their hand regardless. They argue that the behaviour displayed by the 50% of chimps who opted to use a tool under potentially dangerous situations show that they are aware of both their hand and the tool during tool use.

Overall, research does suggest that it is possible that we could use the information that we know about our own bodies and how they move and apply this to the tools that we use. Whether we truly embody the tool as an extension or replacement of our arm is debatable. But considering that it is accepted that we make predictions about the way our limbs will move as we carry out an action (and correct our movement online, based on this prediction (Wolpert & Flanagan, 2001)), it is not an incredible leap that we could take this knowledge and apply it to a tool that works in a similar manner to the hand.

1.4.2 Control of the end-effector

A concept that is similar to the body schema is the idea that we work to control the end-effector during a movement, whatever that happens to be. When reaching and grasping with the hand this would be the finger and thumb, but when reaching a grasping with a tool it would be the tool's tips. This is slightly different to the concept of the body schema because here rather than embodying the whole tool, people are instead controlling its tips in a way akin to the hand. This is a slight but important distinction, rather than incorporation of a tool the brain instead uses end-effector units to encode an action and moves the hand accordingly when the end-effector is the tip of a tool.

One experiment that looked at this is that by Umiltà et al. (2008). Using single-cell recording of 113 motor neurons in area F5 (the area involved in grasping in primates) they demonstrated that motor neurons that fired when opening the hand to grasp also fired when grasping with a tool. This in itself is not surprising as the hand is still involved in the movement when using a tool. However, in this experiment they taught monkeys to use both a normal and reverse pair of pliers to grasp pieces of food. Using these tools to grasp the food uses opposite hand actions (opening the hand to open the pliers in the normal case and closing the hand to open the pliers in the reverse one). They found that the neurons in F5 that fired when opening the normal pliers also fired when opening the reverse ones. The fact that the neurons in F5 fired when both tools were being opened shows that it is not dependant on the opening of the hand and instead these neurons seem to be coding for the end-effectors of the tool.

Gentilucci, Roy and Stefanini (2004) carried out an experiment with a similar purpose on human beings. They wanted to know whether the kinematics of a grasping movement are controlled independently of the end-effector being used. Kinematics are the features of a movement, meaning that they wanted to know whether grasping movements were comparable across different end-effectors and therefore whether they all shared a common motor representation. To investigate this, they compared grasps using the hand and a tool that had two mechanical fingers. This tool operated in a similar manner to the reverse tool in the experiment by Umiltà et al. (2008), participants had to squeeze the tools handle to open its tips. Therefore, if the kinematics of grasping with the hand were similar to those when grasping with a tool then it could also suggest that the movement is being planned in end-effector units, not in hand ones. When comparing the kinematics of the hand and the tool they found that participants produced larger peak end-effector apertures with the tool but took less time to reach these apertures when compared to the hand. They argue that this is likely due to the participants being inexperienced with the tool as demonstrated by the fact that this effect is more marked for smaller object sizes – when task demands are therefore higher, and that this difference lessens with each block of the experiment. They found no difference however between the peak velocities reached in the two conditions and reach the conclusion that grasp representations are encoded independently of the end-effector used. They also found the same plateau during tool use that is later seen in the experiment by Bongers (2010), suggesting that this could be a common feature of grasping with a tool.

A third experiment that has investigated this concept is by Itaguci and Fukuzawa (2014) who aimed to investigate the underlying mechanisms of hand and tool grasp control. Like Gentilucci et al. (2004) they also assumed that there was an underlying single-principle that governs grasping regardless of the end-effector being used. They got participants to grasp objects with their index finger and thumb, middle finger and thumb, chopsticks and a "scissor-like tool". They chose these conditions so that they had a familiar and unfamiliar hand grasp and tool grasp as they hypothesised that the smoothness of the aperture control would be determined by prior experience with the effector. They found no difference in the scaling of peak end-effector aperture with object size or the timing of its onset across the conditions. They also found no difference in the movement times. However, they did identify the plateau found by both Gentilucci et al. (2004) and Bongers (2010), and found that its duration was modulated by familiarity. The scissor tool had the longest plateau, followed by the unfamiliar middle finger hand grasp and the chopstick condition (which had no difference between them) with the index finger hand grasp having the shortest plateau. They say that this is evidence that grasping is effector-independent but modulated by familiarity of the effector.

This is a possible alternate explanation to the body schema, it could be that when we use a tool to grasp an object that we attempt to control the tips of the tool in the same manner that we would the finger and thumb. Grasping would therefore be planned in terms of world movement or end-effector units, this could be achieved by planning in broad terms initially before adjusting this for the effector being used.

1.4.3 Tool use and peripersonal space

There is also a wealth of research about tool use and its effect on peripersonal space that can help us to understand how people are able to use tools. Peripersonal space is defined as the space immediately surrounding a person that they can reach without having to move (Rizzolatti, Fadiga, Fogassi, & Gallese, 1997). There is an issue in the literature that often there is a lot of overlap between peripersonal space and the body schema (Berlucchi & Aglioti, 2010; Cardinali, Brozzoli & Farnè, 2009b; Critchley, 1979, as cited in Berlucchi & Aglioti, 2010; de Vignemont, 2010; Maravita, Spence, & Driver, 2003; Poeck & Orgass, 1971; Vallar & Rode, 2009). The definitions of body schema and peripersonal space need to be universally defined and fully operationalized for them to be more useful as concepts as currently there are disagreements about the meanings of the terms in the literature (de Vignemont, 2010). They are so poorly defined that in some instances researchers have instead come up with a new term to describe the whole field based on some past research – corporeal awareness (Berlucchi & Aglioti, 2010). However, this does not really solve the problem, because if they really are separate entities then they should be able to be defined properly and used appropriately. Cardinali, et al. (2009b) attempted to fully operationalize the definitions and assess whether they are in fact two separate concepts or just simply two different names for the same thing. They found that there were indeed many similarities between the two and that often in the literature people ascribe an extension of peripersonal space to the fact that a tool has been incorporated into the body schema. However, Cardinali et al. (2009b) state that other experiments would need to be carried out to ensure that there is certainly no dissociation between the two before they could be considered to be two sides of the same coin.

Literature in this area makes the assumption that there is a distinction between 'near' (peripersonal) and 'far' (extrapersonal) space in the brain. This is primarily based on a double dissociation that has been demonstrated between near space and far; patients have been shown on many occasions to display impairment in only one of these regions and not the other suggesting that they are controlled by separate systems (Brain, 1941, as cited in Longo & Lourenco, 2006; Cowey, Small, & Ellis, 1994; Vuilleumier, Valenza, Mayer, Reverdin, & Landis, 1998). It must however be considered that this boundary is something that cannot really be concretely tested and instead must be studied through various measures that are thought to be a proxy for where this boundary is. An example of such an experiment is that by Berti & Frassinetti (2000) who tested a patient who showed neglect during a line bisection task in near but not far space when using a laser pointer. However, if the far-space bisection task was performed using a stick the neglect returned and was as severe as her near-space neglect. The authors argue that this shows that the patient remapped far-space as near when using a tool; extending peripersonal space.

Contrary to this, Pegna, Petit and Caldara-Schnetzer (2001) tested a patient whose responses suggest that these effects may be to do with the task performed and not the representation of space *per se*. Their patient showed no unilateral spatial neglect when using a laser pointer to bisect lines that were either near to them or far away. However, when using a pencil to bisect near lines and a pencil on a stick to bisect far lines neglect was present suggesting that the neglect was contingent on the action required to perform the task rather than the distance. Berti and Frassinetti's (2000) finding has, however, also been replicated in healthy controls. Longo and Lourenco (2006) showed that when using a laser pointer there was a leftward bias on a line bisection task for near space which changed into a rightward bias for far space. When a stick was used to do the bisection task, however, a leftward shift was always present. An interesting thing to note about this finding is that the shift between leftward and rightward bias was gradual. As the line was moved farther away the rightward bias increased systematically and the same for the leftward bias as the line was moved closer. This suggests that 'far' and 'near' space may not be as easy to operationalize as some studies have previously suggested, and may instead be labels that sit at two ends of a continuum.

Iriki, Tanaka and Iwamura (1996) used single-cell recordings from two macaque monkeys to look at the effect of tool use on visual receptive fields (vRFs) located in the intraparietal sulcus. These 59 cells were chosen because this region is linked to processing of both somatosensory information and spatial vision. They got the monkeys to reach for food pellets either with their hand or with a tool when they were out of reach. They measured the firing rate of these neurons before, during and after this task to look at the effect of using a tool on the vRFs. Before tool use the cells only fired when the food was in the region close to the monkey's hand. During tool use 17 of the 59 cells fired when the food was in proximity to the tool. This firing occurred when the hand was much further away from the food than in the hand grasping trials. This arguably demonstrates an elongation of the vRF to include the tool not just the hand. Finally, measurements taken 3 minutes after tool use showed similar vRFs to the pre-tool use measurements. This shows that when macaque monkeys used a rake to retrieve food that was out of reach, that their visual receptive fields extended to include the rake and the area now accessible to them because of it. This suggests that using a tool can alter the way that we code for the space near to us. Caution must be taken before applying these results directly to humans however, as it is currently uncertain whether these areas of the monkey brain are comparable to those in humans (Maravita & Iriki, 2004).

Obviously single-cell recording is not ethically possible with human subjects however, so other more indirect methods must be employed to probe the concept of peripersonal space in humans. Some patients who have suffered right-brain damage fail to report tactile stimulation on their left hand when it is presented concurrently with a visual stimulus presented on the right hand – this is known as cross-modal extinction. Farnè and Làdavas (2000) showed that after using a rake to reach distant objects, cross-modal extinction in stroke patients was worse than when patients had not used a tool when the visual stimulus was presented far from the hand. They suggested that this shows that the peripersonal space around the hand had been extended by using a tool, akin to the extension of vRF in the experiment by Iriki et al. (1996). Another study by Farnè, Iriki and Làdavas (2005a) used the same cross-modal extinction paradigm and showed that “a relatively prolonged, but passive experience” (Farnè et al., 2005a, p414) holding a tool was not enough to cause this apparent extension of peripersonal space. This is similar to what a lot of the body schema research has also found about extension of the body schema when passively holding a tool (Brown et al., 2011; Witt et al., 2005).

Farnè, Bonifazi and Làdavas (2005b) used tools of different lengths in another experiment and suggest that peripersonal space may in fact be extended less when using a short rake than it is when using a longer one. This is because cross-modal extinction in far-space was less severe after using a shorter tool than it was when using a longer one, possibly suggesting that extension of near space was less when using the shorter tool. Using the same cross-modal extinction paradigm Farnè et al. (2005a) found that when the effector of the tool was not at the end of the tool peripersonal space does not extend to include the entire tool. They compared the level of cross-modal extinction after using a 30cm tool, a 60cm tool and a 'hybrid' 60cm tool where the effector is 30cm from the handle. Cross-modal extinction was comparable between the 'hybrid' tool and the 30cm tool, but not the 60cm tool, suggesting that the possible extension of peripersonal space during tool use only goes as far as the effector of the tool and does not necessarily expand to include the whole thing.

Using a very similar paradigm Bonifazi, Farnè, Rinaldesi and Làdavas (2007) found that there was no change in the accuracy of reporting tactile stimulation of the hand before and after tool use when the visual stimulation was presented near the hand. However, when the visual stimulation was presented at the mid-point of the tool or at the tip they found a drop in accuracy after tool use. They suggested that this shows that tool use *extends* peripersonal space to include the length of the tool rather than just *shifting* the focus from the handle to the tool tip. This is because the extinction only occurs when the visual stimulation is presented at the equivalent distance of the end-effector that has just been used – either the tool tips or the finger and thumb. This is contrary to what has been suggested in some of the body schema research, which instead suggests that there is always a representation of the hand present during tool use (Arbib et al., 2009; Povinelli et al., 2010)

Also, contrary to the body schema literature, it has been demonstrated by both Holmes, Calvert and Spence (2007) and Osiurak, Margado and Palluel-Germain (2012) that the intention to use a tool could be enough to alter the neural representation of peripersonal space. Holmes et al., (2007) showed that preparing to use a tool enhanced visual-tactile interactions near to the tool, they say that this is likely due to visual information around the tool becoming relevant when preparing to use a tool. Osiurak et al., (2012) demonstrated that getting participants to hold a long baton whilst estimating the distance of an object led to them underestimating the distance compared to holding nothing. Both of these experiments suggest that peripersonal space could be altered before a tool is actually used, possibly due to the intention of its use in the near future. Could it be that holding a tool is enough to alter your perception of the space around you when the intention to use that tool is clear, however it is not enough to induce changes in the body schema itself?

Whilst this literature does not really answer the question of how it is that we can precisely use tools, it does certainly seem to suggest that tool use may change our perception of the world around us. Whilst this does not explain human expertise at using tools, it does suggest that we do have a fundamental understanding of tools and how they work, to the extent that our brains respond appropriately by extending our receptive fields during tool use, and this in itself could contribute to our expertise.

1.4.4 Internal tool models and mapping states

Whilst the vast majority of tool use literature has arguably focused on body schemas and peripersonal space, the focus of this thesis is about another possible explanation of our ability to use tools - whether models of tools exist inside the brain and how these could theoretically work. One possible way that body schemas could be utilised in practice is by the brain developing internal models of tools based on our experience with our own limbs and what we know about a tool's geometry. This could involve storing a set of information about a tool (or class of tool) that demonstrates how movement at the hand translates to movement at the end-effector of the tool. This mapping between hand movement and end-effector movement would then allow the user to control the tool based on a model of the hand. As discussed earlier, our normal movements involve utilising a forward model that is based on prediction and then corrected online (Wolpert & Flanagan, 2001). It is therefore possible that the same mechanism is utilised when grasping with a tool and these models are used to make predictions about the movement. There is a surprisingly small amount of research available about internal tool models and changes in mapping states. Imamizu, et al. (2000) asked participants to track a moving target across a screen using a mouse. During baseline testing a normal mouse was used, but during test sessions a novel mouse was used where the cursor was rotated 120^{o} around the centre of the screen, meaning the participant was using an unfamiliar tool. They scanned participants with an MRI machine while they performed the task with the normal mouse to get a baseline measurement of the task. They then scanned them again when they performed the task with the novel mouse to look for any differences in brain activity between the two tasks. They found that the posterior superior fissure was more active during test sessions than baseline ones. They compared the error rates when using the two mice throughout the experiment and found that in the final three blocks there were no differences, suggesting that participants had learnt to use the novel mouse. Even in these blocks there was still more activity in the posterior superior fissure. This is an area of the cerebellum, which has been shown in the past to be primarily responsible for motor control. Imamizu et al. (2000) argue that this area likely reflects the newly acquired internal tool model. They suggest that in this experiment the internal tool model is likely to represent the change in the relationship between moving the mouse and the movement of the cursor on the screen. They suggested that the model for the normal mouse must be located elsewhere in the brain as they saw no activity around the posterior superior fissure when the normal mouse was used. This would suggest that basic tool models may be stored in one area of the brain and then alterations to these models could be stored elsewhere. Finally, they discuss some previous research carried out on the brains of monkeys (Sasaki et al., 1977, as cited in Imamizu et al., 2000) that suggests that the posterior superior fissure receives inputs from the premotor cortex and the parietal association cortex, which could therefore make it a suitable area to represent models of tools. Interestingly they also state that internal models for motor movements are located in the evolutionarily older parts of our cerebellums (Shidara, Kawano, Gomi & Kawato, 1993, as cited in Imamizu et al., 2000; Gomi et al., 1998, as cited in Imamizu et al., 2000; Kobyashi et al., 1998, as cited in Imamizu et al., 2000), whereas models for tools and other objects appear to be located in much newer parts of our brains. This suggests that the ability to store information about tools could be a more newly developed skill compared to information about our own motor skills. It does need to be considered however that this experiment only uses a mouse which may not be a tool in the strictest sense. Also, what has changed between their normal and novel conditions is arguably an abstract mapping, not the tool per se. However due to the limited amount of literature available on the topic of internal tool models this is still a relevant finding.

We use such a large array of tools in our daily lives though that it raises the question of how we could possibly store models of every tool that we use. Imamizu, Kuroda, Miyauchi, Yoshioka and Kawato (2003) suggest that the cerebellum does contain multiple internal models, but that there are areas within the cerebellum that similar tools share. Again, their subjects tracked a moving target using a computer mouse (one normal mouse and two novel mice: one that altered the speed of the cursor and another that altered the rotation as in the previous experiment (Imamizu et al., 2000)). They found that the three different mice caused activity in three distinct locations. The authors suggested that this shows that models of different tools are stored individually in the brain. However, there was some overlap of the areas with those related to other similar tools. This could mean that there are areas of the brain that may respond to the common features of similar tools and then individual areas that take account of small differences between the tools. It is an interesting concept, we could have basic models of broad tool categories, for example pairs of tongs, and then store further information about specific details separately as we use different types of these tools.

1.5 Limitations of past research

A lot ofprevious tool use research has used very simple tools such as sticks and rakes. These tools are excellent at answering questions about tools that extend the reach, but we use tools for many more functions than that in daily life. Using these types of tools in research can show little about the changes in mapping state that occur during tool use and can tell you nothing about the more complex tool transformations that we also use. Arbib et al. (2009) state that during tool use we must remap the correspondence between visual and haptic signals that we receive. They go on to point out that whilst this remapping and embodying of tools may be a sensible theory when applied to simple tools like sticks and pliers, it becomes more complicated when more complex tools are being used. This is related to the concept of motor equivalence, discussed earlier. Is it useful to an individual to embody a mechanical digger when its end-effector movements have little correspondence to those of the hand? Tool embodiment begins to make less sense as a concept when applied to tools that give us a new ability rather than extending an existing capability. If embodiment involves the brain understanding the input/output mapping of a tool then this can continue to usefully apply to tools that do not have direct motoric equivalence. However, if embodying a tool involves representing the mechanical structure of the device it begins to make less sense with tools that do not relate at all to the movement of the hand.

Another limitation with a lot of the previous research is that, on the whole, experiments only use one tool and compare that to the hand. This makes it difficult to draw many conclusions from these experiments as you can only see the distinct effect of the hand compared to the tool, and not how this effect might be modulated as the tool itself changes.

A final limitation is that most experiments measure the after-effects of tool use. This means that participants use a tool and after this the experimenter analyses the difference in their behaviour compared to before tool use. This is an adequate methodology to simply demonstrate that a tool has been incorporated into the schema or that it has affected a person's movements in some way. However, to investigate these effects further it would be beneficial to see how movements themselves differ when using a tool compared to the hand, and also how they differ when the tool is altered slightly. For example, the experiment discussed previously by Cardinali et al. (2009a) found differences of 1-2cm in a stimuli localisation task after tool use, suggesting that they felt that their arm was longer. This effect was found after using a 40cm tool, so would it be expected that the effects would be 40cm in size if this was assessed during tool use? This is one of the issues of relying on after-effects because it is difficult to make quantitative predictions about the size of the effect that should be expected.

Each of these limitations has led us to our approach in this thesis.

1.6 Our direction

For the reasons outlined above, we want to avoid having to measure the after-effects of tool use and instead measure effects that occur during tool use. This will allow us to make quantitative predictions about the effects that we should see during tool use, rather than simply having the binary outcome of seeing a change or not. The use of kinematic analyses allows for an online assessment of tool use. Kinematic analysis is the recording and measurement of movements. From these movements, key indices can be identified and these points can be compared across experimental conditions. By measuring the movements that individuals make when they reach and grasp with a tool, both general tool use and hopefully possible tool mapping states can be studied online rather than having to rely on after-effect measures. By carrying out an experiment in this manner, tool use could then be studied as it happens and therefore quantitative predictions could be made about how movements should change during tool use (for more information about the indices that are relevant to this thesis see section 2.6).

As discussed previously, it is thought that the reason that grasping with the hand is so effective is that it relies on prediction (Wolpert & Flanagan, 2001); the idea of predicting what will happen to the hand for a given motor command and correcting movements online as the grasp is performed. The idea is that the brain knows what will happen to the hand when it uses a certain motor program. This is known as a forward model, the mechanism that allows the brain to know where the hand will end up in a movement. This predicted end position can then be compared to current body position so movement corrections can be made online. Any differences between the current position and the predicted position are an error and can be used to improve the model. When this idea is applied to tools it is slightly more complicated as a tool changes the mapping between the hand and the world. Somehow, the brain can adjust for this new relationship (possibly through incorporation into the body schema, adaptation to the tool or an understanding of the tool mapping) and use the effectors of the tool in a precise and controlled way.

Along with the work mentioned previously by Cardinali et al. (2009a) and Bongers (2010) that showed that grasping with a tool is slower than grasping with the hand, three previous experiments have looked more in depth at the kinematics of tool use. Gentilucci et al. (2004) we have discussed previously in reference to encoding movements in end-effector units. They used kinematic analyses to compare different reaching and grasping components when picking up an object with the hand or a tool. An issue with the experiment ran by Gentilucci et al. (2004) is that the tool used was a pair of tongs that needed a large amount of force to open them. This could therefore be the cause of the larger peak end-effector apertures seen with the tool in this experiment as the tool was not easy to control in a fine manner. We have also discussed Itaguchi and Fukuzawa (2014) in detail in refence to encoding in end-effector units. They found that the precision of aperture control is modulated by past experience with the tool. Zheng and Mackenzie (2007) also used kinematic analysis to compare the hand to a tool. They got participants to lift a small dowel off a base with their hand or a 1:1 pair of tongs. This means that this tool was different to the one used by Gentilucci et al. (2004) as it opened as the hand opened rather than being a reverse tool. The experiment by Zheng and Mackenzie (2007) found longer overall movement times when using the tool than the hand, slower peak velocity and a larger peak end-effector aperture as well. This could therefore suggest that in this case the hand and the tool tips are not being encoded in the same manner as there are marked differences between the two movements. A limitation of this experiment however is that the tool consisted of a pair of kitchen tongs where the handles and tool tips had been cut off. This tool was then taped onto the thumb and forefinger. The authors state that this is not a naturalistic tool and therefore limits the conclusions that can be drawn from their findings. This is because the effects that they have found could have been due to task difficulty, getting used to some an un-naturalistic type of tool. It could be that if the experiment was replicated with a more typical pair of tongs that the findings between the tool and the hand would be more comparable.

These experiments contributed heavily to the direction we took in this thesis. By only comparing movements with one type of tool to those of the hand, limited conclusions can be drawn from the experiments. It seems unlikely that there will be global tool effects that apply to every type of tool as so many different types of tool exist. However, there may well be effects that are specific to different classes of tool or different manipulations. By using more than one tool in our experiments, we hope to be able to probe this idea further. This will hopefully allow us to investigate the concept of programming a movement in end-effector units, as we will be able to see the differences between different types of tools and not just between a tool and the hand.

We also wanted to be able to investigate the idea of mappings states in this thesis. We felt that by using pairs of tongs in our research (like Zheng and Mackenzie (2007) and Gentilucci et al. (2004) did in their experiments), instead of a reach-extending tool like many previous experiments, we should be able to probe the idea of mapping states more easily than past research has been able to. As previously discussed, using tongs creates a change in the mapping between the fingers and the end-effectors of the tool, yet tongs are easily used by human beings on a daily basis. Again, by using *multiple* pairs of tongs we hope to be able to investigate further, to what extent people can adapt to this change in mapping state. By altering the ratio of a pair of tongs (how far the tool's tips open n relation to the opening of the tool handles) we can make quantitative predictions about how people's grasping behaviour should change. Zheng and Mackenzie (2009) have carried out a study in the past that looked at the effect of changing the tool ratio on a reaching and grasping movement. They asked participants to match the size of an object on a screen by opening their finger and thumb or the tips of a 1:1 tool (where the tool tips and the finger and thumb are open the same amount) or a 1:2 tool (there the tool tips are open twice as wide as the finger and thumb) to the right separation. They found that participants underestimated the size of an object when using the tools compared to the hand. However, they found no effect of ratio change, with the two tools offering similar results to one another. We want to build upon this research. Our method of using kinematic analysis allows us to investigate the effect of altering tool ratio whilst making a grasp with the tool, rather than using a matching task. A matching task only looks at the end point of the movement, it is possible that there will be effects of ratio change during the movement itself, and our paradigm will therefore enable us to look at more of the movement than Zheng and Mackenzie's (2009) study.

We designed a set of three tongs with three different ratios between the opening of the tool tips and the opening of the fingers and thumb, 0.7:1, 1:1 and 1.4:1. When using the 0.7:1 tool, when the hand is open 10cm the tool tips would be open 7cm, whereas the tips of the 1.4:1 tool would be open 14cm. We chose the ratios of our three tools very carefully. By including a 1:1 tool in our experiments we hoped to create a tool that worked similarly to the hand, preserving the ratio between the thumb and finger and the end-effectors of the tool. By doing this we can compare the kinematics when using the 1:1 tool to those produced when grasping with the hand, showing what effects are present when we use a pair of tongs that are as simple of possible. By looking at the grasp profiles of the 1:1 tool and the hand we can see whether the tool tips on this tool are used in a similar manner to the finger and thumb, or whether there are differences in grasping behaviour.

We then included two other tools that act in opposite manners to one another. The 0.7:1 tool opens less than the hand and the 1.4:1 tool opens more. We used this balanced design because if the brain is modelling the tool tips in the same manner as the finger and thumb then these two tools should also have similar grasp profiles. If we make the assumption that the brain is trying to control the tips of the tool in the same manner regardless of the tool being used then we can use this to assess how effectively participants are using the tool. By comparing the kinematics of the 1:1 tool to those produced with our other two tools we can investigate how altering the ratio of the tool changes the kinematics of the movements. Are participants able to control the tips of our 0.7:1 tool and 1.4:1 tool in the same way as the 1:1 tool or not? If the brain is either programming the movement in end-effector units or it accurately models the tool as if it were the hand and is able to understand the different tool mapping states then ratio change should have little effect on tool kinematics and we would find similar results across our three different tools. By altering the ratio of the tools that are used during the experiment we can look at how precisely the brain is able to account for tool geometry during a grasping movement. By having these known tool ratios, we can make quantitative predictions about what the end-effector apertures produced when grasping with the tools should be. By having these two different comparisons available to us we hope to be able to further probe the differences in kinematics between the hand and tools and see if there are any situations where tool kinematics are similar to that of the hand, or if people will always move slower and produce larger plateaued peak grip apertures when using a tool.

We can look at the performance with the 1:1 tool and use this as a baseline or control condition to see what performance looks like with a basic pair of tongs. We can then make predictions about what the grasp should look like when using the other two tool ratios. Because of this we can therefore judge the extent to which the tool geometry is accounted for based on what peak end-effector apertures are produced during the movement with the other two tools.

Chapter 2: General Methods

2.1 Reaching and grasping with the hand

There have been many studies carried out in the past that focus on the kinematic properties of reaching and grasping objects using the hand (Smeets & Brenner, 1999). Through these studies it has been shown that the properties of an object affect how it is grasped. For example, a variation in the size of an object would result in different peak grip apertures being formed, with larger objects causing participants to open their fingers wider (Jeannerod, 1981; 1984; 1997; Smeets & Brenner, 1999, Wing et al., 1986). If a participant is uncertain about the object that they are grasping this can also lead to larger peak grip apertures being formed Keefe, Hibbard & Watt, 2011; Schlicht & Schrater, 2007; Sivak & Mackenzie, 1990; Wing, Turton & Fraser, 1986). Because of these object driven modulations in kinematics an approach has been developed where movements are studied by measuring these different indices. The fact that indices like peak grip aperture and peak velocity vary in this way means that they can be used as measures in experiments to see how different manipulations affect a grasp. By studying how widely participants grasp or how quickly they move you can attempt to investigate underlying differences in the movements. However, it is important to remember that these kinematic indices are just emergent properties of what we are really trying to measure – the reaching and grasping movement.

Despite a lot of research being carried out on reaching and grasping with the hand, little information is known about reaching and grasping using tools. As discussed previously, there have been very few experiments that have measured the kinematics of reaching and grasping with tools (Bongers, 2010; Cardinali et al., 2009a; Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Wing, Turton & Fraser, 1986; Zheng & Mackenzie, 2007).

2.2 Our tools

The experiments in this thesis were designed to investigate whether grasp control takes account of different relationships between hand opening and tool opening. To examine this, we created custom tong-type tools, with different ratios between handle opening and tool-tip opening. We built our own tools as it enabled us to have complete control over their properties (if we had used a pair of store-bought tongs we would not have had as finer control over how the tool worked and for the experiments that we wanted to carry out it was important that we used tools with precise ratios). A tool's ratio is a number that represents how wide the tool tips will open for a certain hand opening. If a tool had a ratio of 1:1 then if the handles were open 1cm the tips would also be open 1cm, whereas if a tool had a 2:1 ratio then a hand opening of 1cm would correspond to a tool tip opening of 2cm. In our experiments, we used a 1:1 tool, a 0.7:1 tool and a 1.4:1 tool, allowing us to investigate the effects of different tool ratios on kinematic movements. The ratio of tool-tip opening to hand opening (which we refer to throughout this thesis as tool gain) was varied for these tools by placing the pivot in different positions. They required little force to open as we wanted to avoid strange movements solely because participants struggled to open the tools. We chose to use tongs firstly because they allowed us to make the ratio manipulations and secondly because they have motor equivalence with the hand (meaning that the tips of the tools move in a similar way to the hand during a grasping movement). Both of these factors can help us to explore the concept of tool models and coding movements in end-effector units further, as discussed earlier. The tools are shown in Figures 2.1 and 2.2.

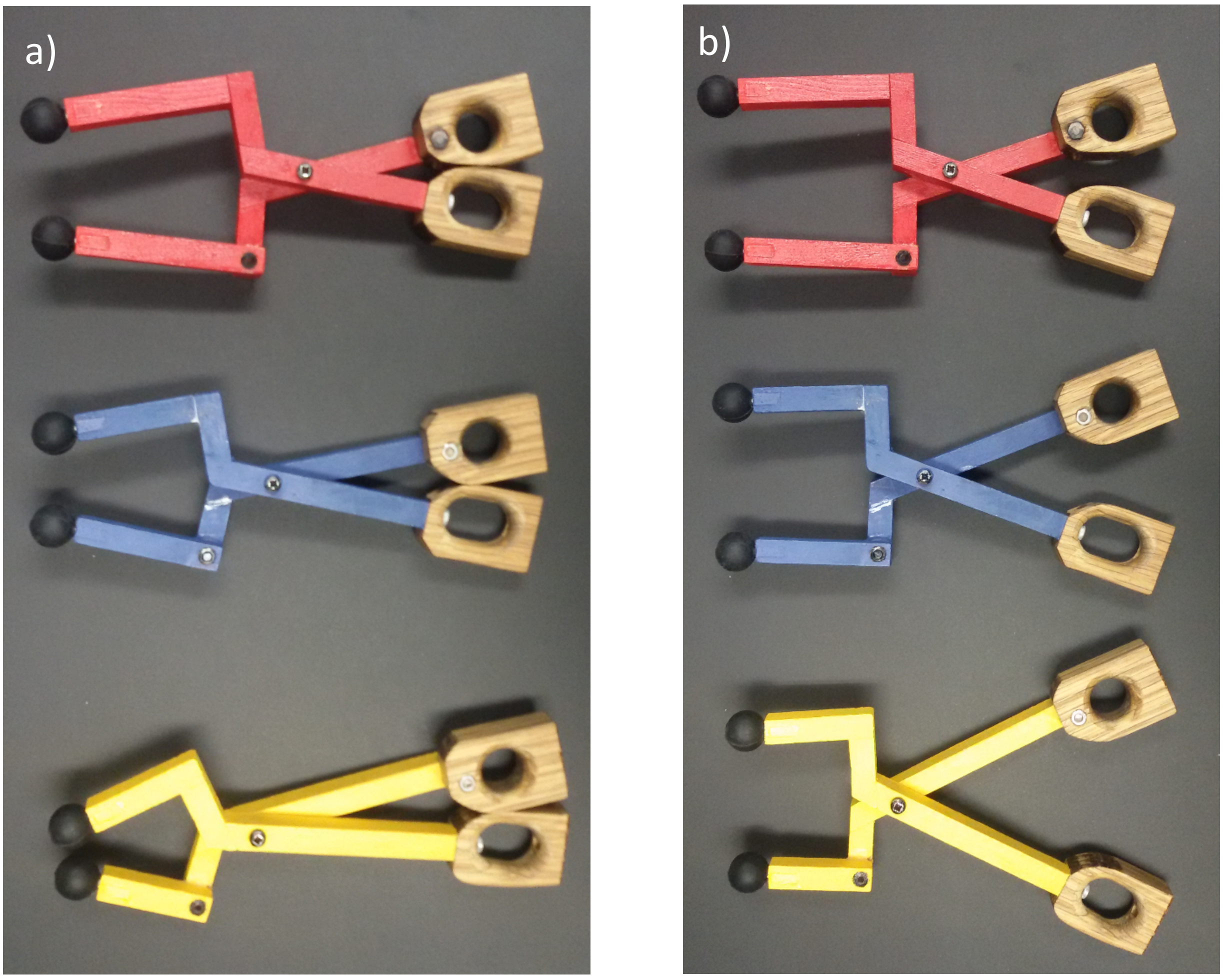


Figure 2.1. The three tools in (a) closed positions and (b) all with the same tool opening (end-effector aperture) – note the difference in the openings of the handles (hand aperture).

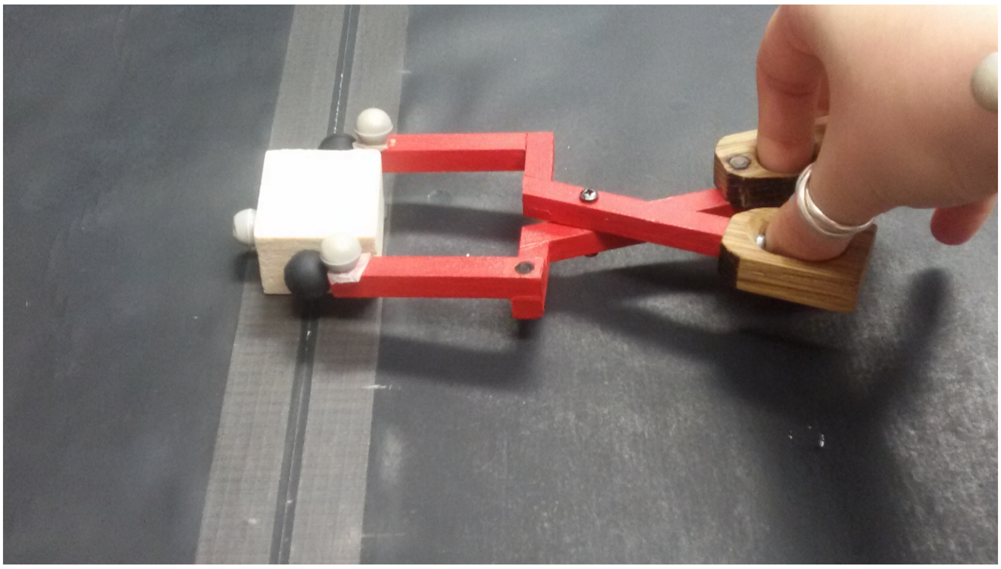


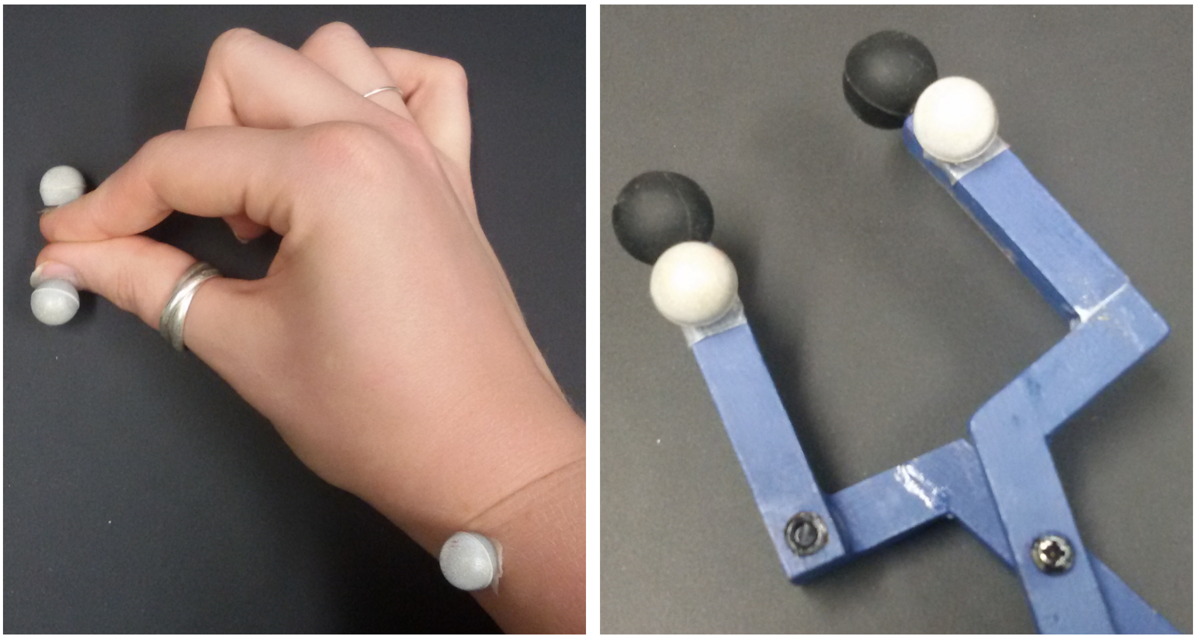
Figure 2.2. A participant using the red 1.4:1 tool to grasp an object.

We included a tool with a 1:1 ratio because it acted as a control condition, allowing us to isolate the effect of using a tong-type tool *per se*, compared to just grasping with the hand. The other two ratios were chosen as we could then assess the effect of tool gain by comparing performance with these tools to that of the 1:1 tool whilst keeping the overall tool gain balanced throughout the experiments. This meant that throughout the experiments that used these three tools the ‘average tool ratio’ was 1:1. This was important because if the tool’s ratio did have an effect on the movement we wanted to make sure this was balanced throughout the experiments. The tools were all made from wood that was painted so that they would be easy to tell apart. The handles were also wood but were created separately and then screwed on to each arm of the tool. Two 15 mm black rubber balls were attached to the tips of each tool. These were used as the rubber helped participants to grip the objects that they were interacting with and the spherical shape created good contact however the object was grasped. All the tools were the same length with each tool arm measuring 150 mm from the centre of the rubber ball to the centre of the handle. Each tool had a pivot that joined the two arms of the tool together and allowed them to be easily opened and closed. The main difference in the design of the three tools was in their ratios (where the pivot was placed), however the length of the tool prongs and their colours also differed. The 1:1 tool’s pivot was half way down the tool and this tool was painted blue. The 0.7:1 tool’s pivot was closer to the tool tips than it was to the handles and this tool was painted yellow. Finally, the 1.4:1 tool’s pivot was closer to the handle than the tool tips and it was painted red. We painted the tools different colours to make them more easily identifiable by participants. This meant that participants could be told easily at the beginning of each trial which tool they should be using and stopped the potential for errors where the wrong tool could be used on a given trial.

2.3 Movement recording

Participants' movements were recorded using three Proreflex MCU240 motion capture cameras (Qualysis AB, Sweden; Figure 2.3). The cameras were wall-mounted and flooded the room with infrared light, the light then reflects off retroreflective markers (see Figures 2.4 and 2.5) in straight lines. This allows the tracking and recording of the position of retroreflective markers.

Figure 2.3. The three Proreflex cameras (Qualysis, Sweden) on our wall-mount.



Figures 2.4 and 2.5. Retroreflective markers attached to the hand and the 1:1 tool.

The recording of the retroreflective marker positions is possible because the Proreflex system is initially calibrated by moving a calibration wand with two fixed retroreflective markers at each end over another set of markers that form a known set of co-ordinates (see Figures 2.6 and 2.7) allowing for the later reconstruction of marker positions.

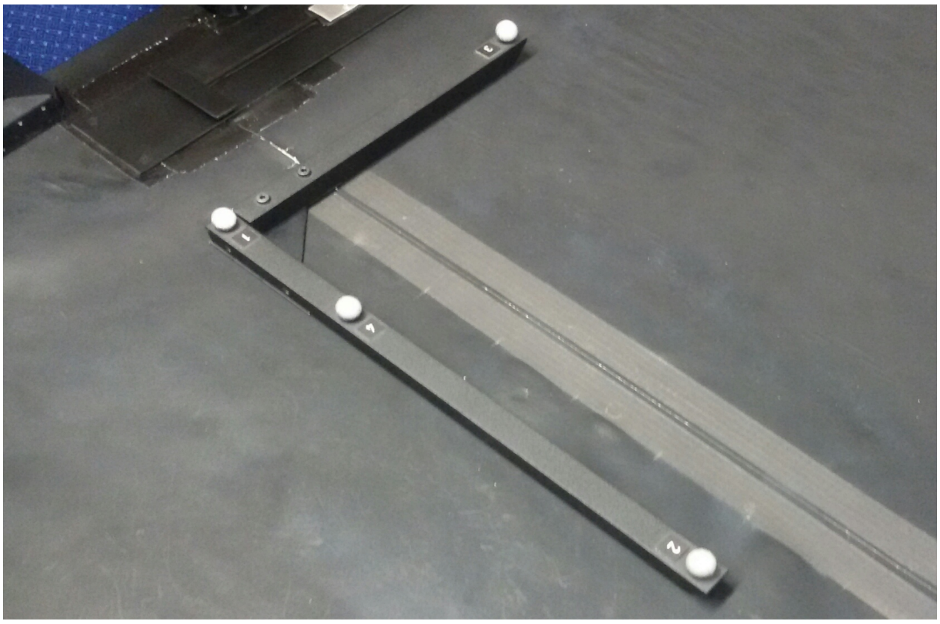


Figure 2.6. These four markers serve as predetermined co-ordinates that enable the Proreflex MCU240 cameras (Qualysis AB, Sweden) to be calibrated.

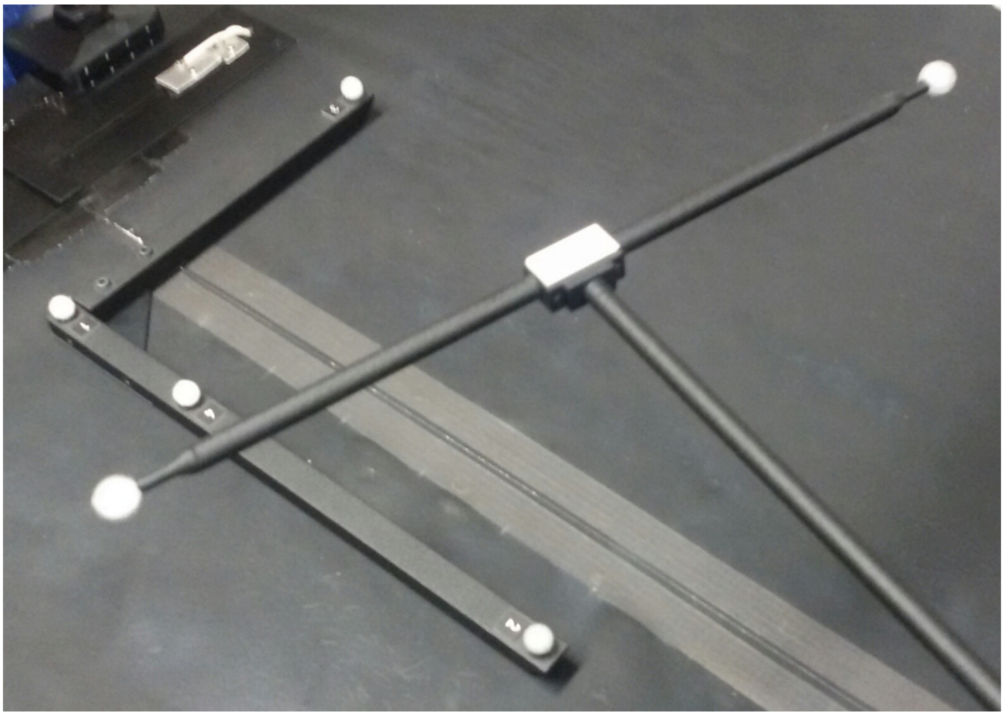


Figure 2.7: The calibration wand being passed over the calibration markers.

For grasping movements using the hand we attached retroreflective markers to the centre of the thumb nail and index finger nail of the participant's right hand. For grasping movements using the tools, retroreflective markers were attached to the tips of each of the tools. These markers allowed us to record the peak end-effector aperture produced with both the hand and the tools during our experiments by measuring the distance between the two markers and adjusting the offset to calculate the opening of the finger and thumb or the tool tips. We also attached a marker to the wrist of the participant, over the radius bone (to allow for similar placement across sessions and participants) and this marker was used to measure the velocity of the hand, as it is more stable than the finger and thumb or tool tips during a grasp (see Figures 2.4 and 2.5).

These recorded trajectories could then be tracked, played back and edited using Qualysis Track Manager (Version 1.10.282, Qualysis, Sweden). This software allowed for the retroreflective markers to be labelled and any issues with the trial to be rectified. For example, if a marker had become occluded during some frames of the trial it would initially be registered as two separate markers. The software could be used to relabel them as the same marker and if the gap was smaller than 10 frames it could be filled to avoid missing values. The software was then used to output a TSV text file that listed the x, y and z co-ordinates of each marker for every frame of the movement on that trial.

These text files were then analysed using custom-written Matlab code that first creates a smoothed trajectory using a low-pass filter (Butterworth filter, 12 Hz cut-off) and then allows for kinematic attributes (such as peak end-effector aperture or peak velocity) to be identified and recorded.

2.4 Apparatus

In all of the experiments it was important to be able to control when the participant was able to see the experimental area. This was because we wanted to be able to place the objects on the table without the participant seeing their size or location before they made the grasp. In the earlier experiments, a piece of liquid crystal film was used to control the participant's field of view (see Figure 2.8). This film is referred to as a privacy screen throughout the thesis. The screen measured 150 mm x 75 m and was opaque until an electrical current was applied, when it would turn transparent. This gave us control over when the participant could and could not see the experimental area.

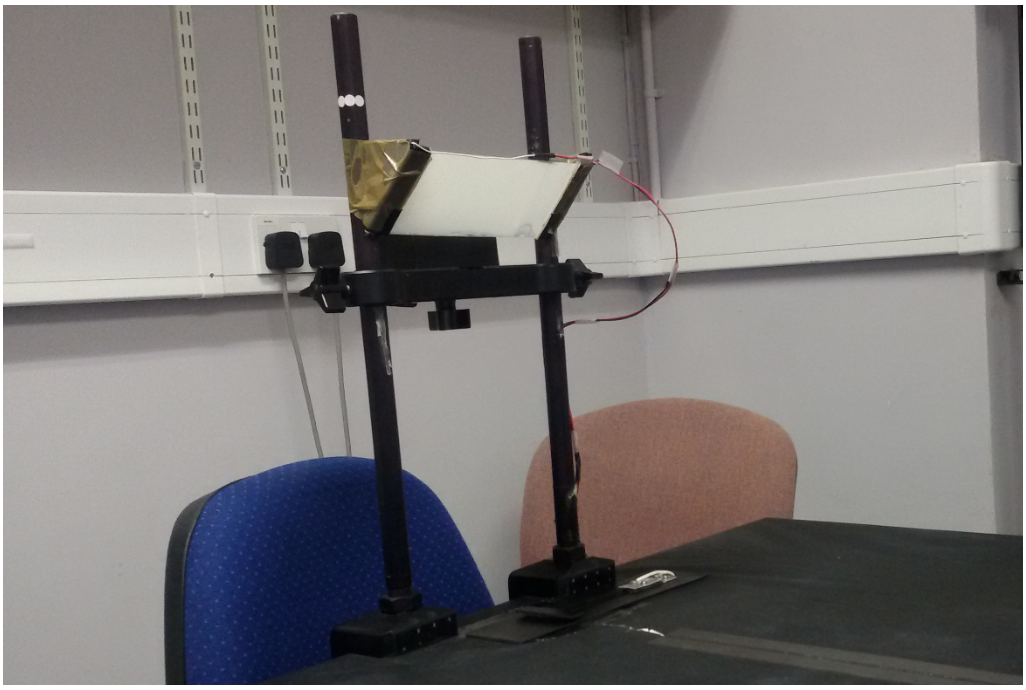


Figure 2.8. The privacy screen attached to the chin rest.

However, later in the thesis a pair of liquid-crystal shutter-glasses (PLATO Vision Occlusion Spectacles, Translucent Technologies Inc., Canada) were used either in conjunction with or as a replacement for the privacy screen (see Figure 2.9). These glasses were used in later experiments as they fully occluded the participant's view, whereas the privacy screen only obscured part of it and relied on the participant staying in the right location. The shutter glasses also closed much faster than the privacy screen giving us even finer control over the participant's vision. It is stated in each experimental methods section which method of vision control was used for each experiment.

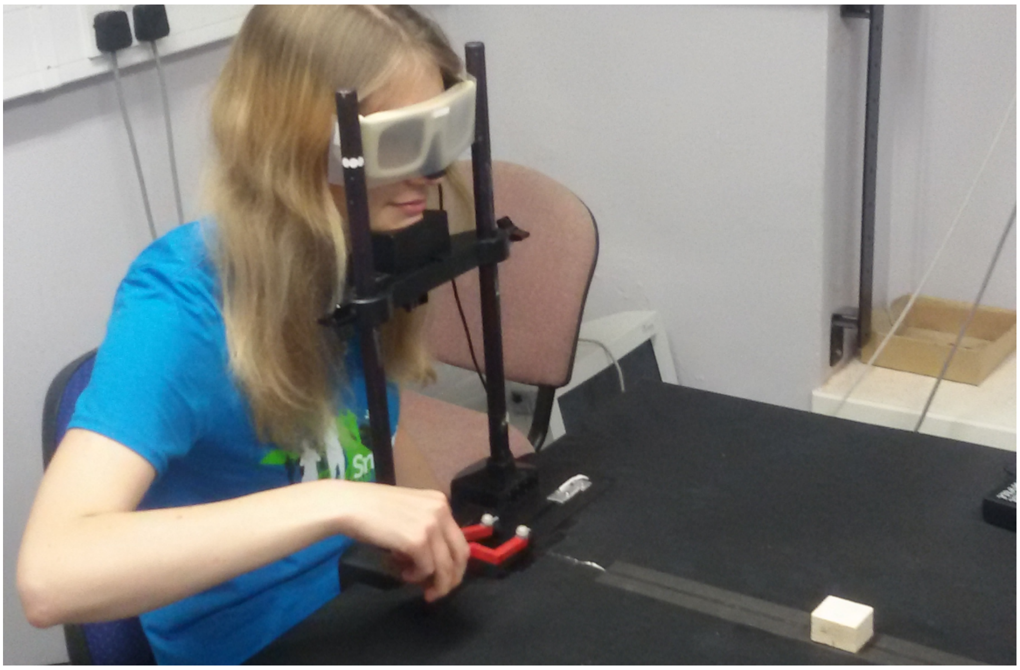


Figure 2.9. A participant in the liquid-crystal shutter-glasses (PLATO Vision Occlusion Spectacles, Translucent Technologies Inc, Canada)

Two computers were used in the set-up of most of the experiments. One to record the information from the cameras and another to run the experimental code. This second computer did many things including monitoring the object strip to see when an object had been lifted, recording trial information and timings and triggering the cameras to start recording at the start of each trial.

It was important during all of the experiments that we knew exactly when the participant started moving to pick up the object. Firstly, this was because this start time was used to calculate how quickly the participant lifted the object (this will be explained in more detail later in this chapter). Secondly, it was important because we wanted participants to make natural movements and therefore we did not want them to sit and think about the movement a lot before they grasped the object. By having a quantifiable start time we could identify trials where the participants took too long to move off at the start of the movement and void these trials. So that we could accurately record the start of the movement a start button was custom-built as we found that standard start buttons required a large amount of force to keep depressed and it was thought that this would be both difficult and tiring for the participant to do whilst using a tool over long periods. For this reason, we designed a start button that could be depressed using very little pressure, so that participants could interact with it easily whilst using our tools. It consisted of a plastic rectangle measuring 15 mm x 60 mm affixed to the top of a 100 mm strip of carbon fibre, this strip was on top of a second 100 mm carbon fibre strip, separated at one end using a small piece of plastic (see Figures 2.10 and 2.11).

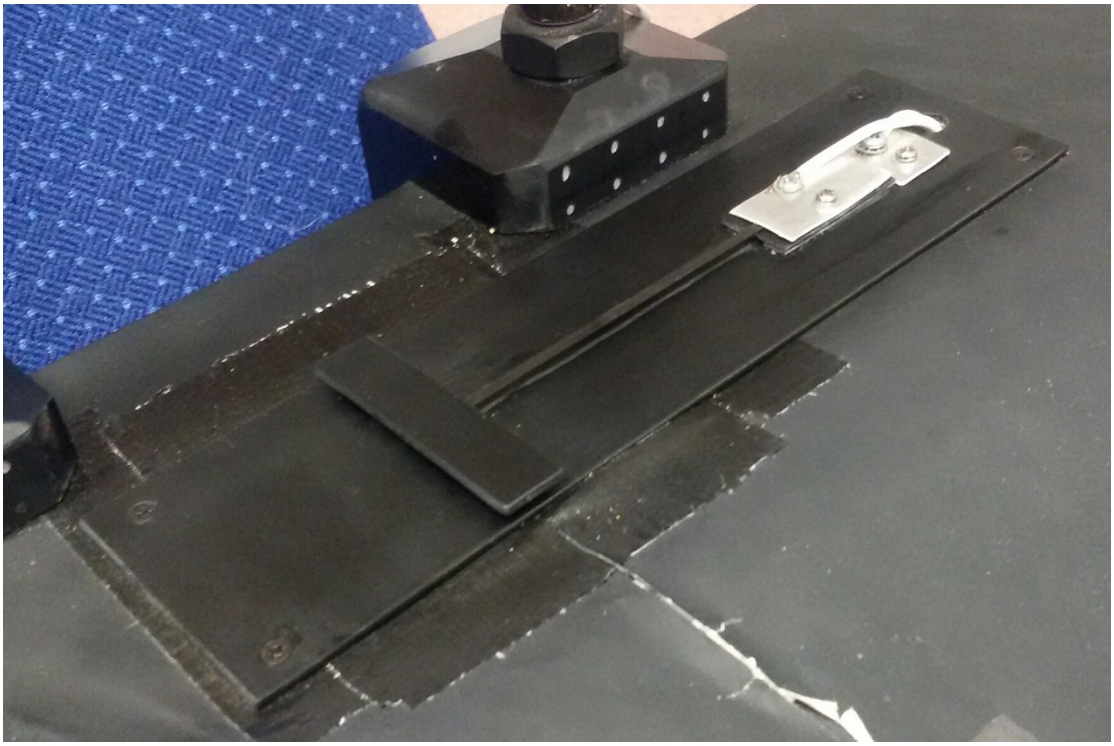


Figure 2.10. The start button used during our experiments.

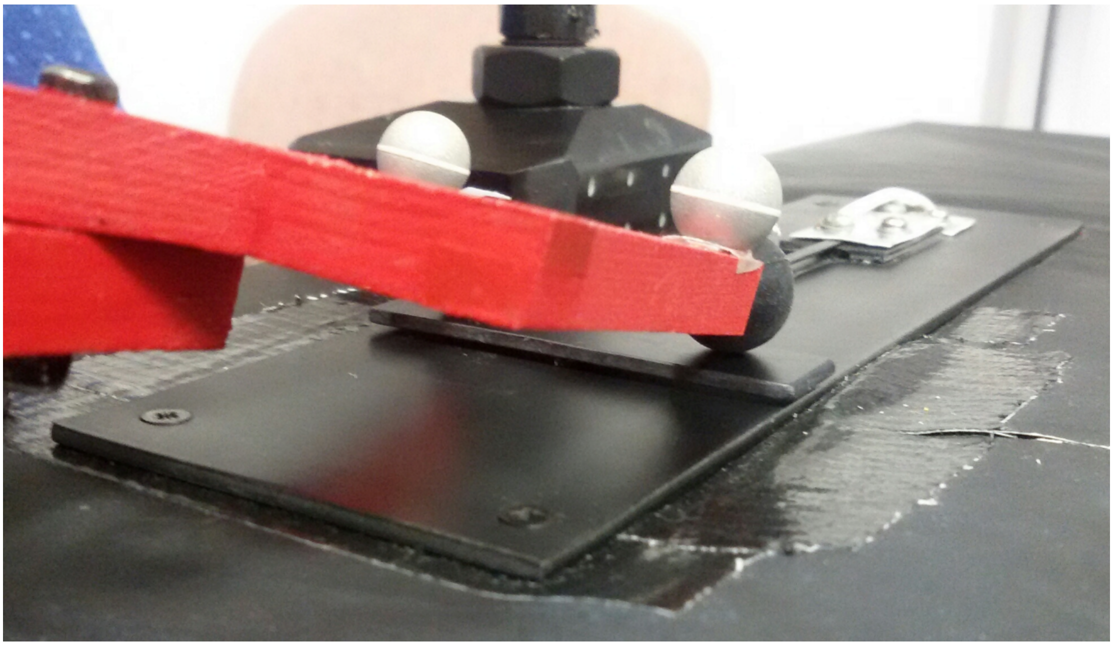


Figure 2.11. The start button being depressed using the 1.4:1 tool.

When the participant pressed on the plastic rectangle the two carbon fibre strips contacted each other and formed a circuit. The experimental computer monitored this circuit so that we could ensure that participants were in the correct starting position. The breaking of this circuit could also be used to trigger things in the experiments.

As said previously, we also needed a way to measure exactly when the participant had lifted the object. This allowed us to investigate whether any of our manipulations affected the time taken to lift the object up and meant that we could use this as an end point of the movement. To allow us to measure the time taken to lift up the object we used a system where the object closed a circuit on the table. This meant that when the participant picked up the object the circuit would be broken and a time could be recorded in the data file. The circuit consisted of two 18 mm x 500 m strips of conductive fabric, placed 5 mm apart, running down the midline of the table that were wired to create an incomplete circuit. The objects also had conductive fabric on the bottom allowing the circuit to be closed when they were placed on the table (see Figures 2.12 and 2.13).

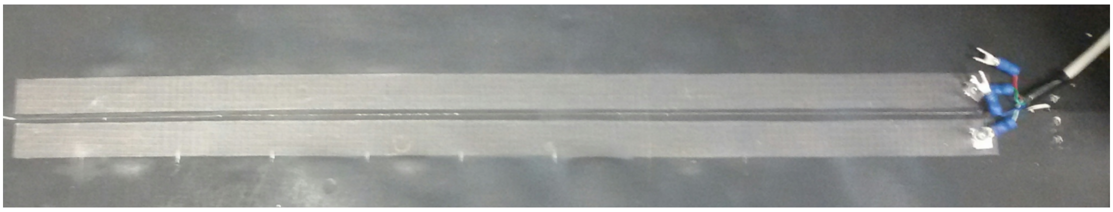


Figure 2.12. The conductive strips used during the experiments to allow a precise measurement of object contact.

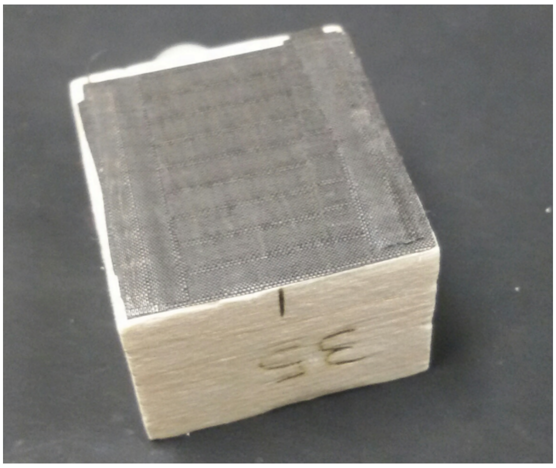


Figure 2.13. An object with conductive fabric stuck to the bottom allowing the circuit on the table to be closed when the object is placed down.

The objects grasped by participants were small wooden blocks made out of balsa wood. The exact dimensions of these blocks varied in each experiment so specific dimensions will be given in the relevant chapters (see Figure 2.14 for an example object set). We used balsa wood because it is a very lightweight material, which made it easy for participants to lift up the objects when using the tools. The concern was that if heavier objects were used then they would be hard to interact with using the tools and this may result in unnatural movements.

Figure 2.14. An example of the objects used throughout the thesis

2.5 General points

Fully informed consent was always collected from participants at the start of each experiment. All experiments were conducted in accordance with the Declaration of Helsinki and approved by the ethics board at Bangor University. Participants were compensated at the end of each session at a rate of £6 an hour, and fully debriefed at the end of the final session.

When looking into significant main effects further we will use planned comparisons throughout the thesis. These will compare performance with the blue 1:1 tool to the hand, the yellow 0.7:1 tool and the red 1.4:1 tool. This will allow us to compare the hand to the tool that is most similar to it – the 1:1 tool preserves the ratio between the hand and the world. It will also allow us to compare performance with the two gain changing tools to that of the 1:1 tool to assess the effect of altering the ratio of a tool. These are theoretically driven comparisons as these are the areas where we expect to see meaningful differences and therefore other comparisons will not be made.

2.6 Indices of interest

The main method of analysis in this thesis is the comparison of various kinematic indices across the different conditions in each experiment. Each of the indices used in this thesis is explained in more detail in its own section below. Figures 2.15 and 2.16 illustrate most of the kinematic indices used in an attempt to add clarity. Figure 2.15

illustrates the indices related to grasping the object (i.e. peak end-effector aperture). Figure 2.16 illustrates the indices related to reaching towards it (i.e. peak velocity).

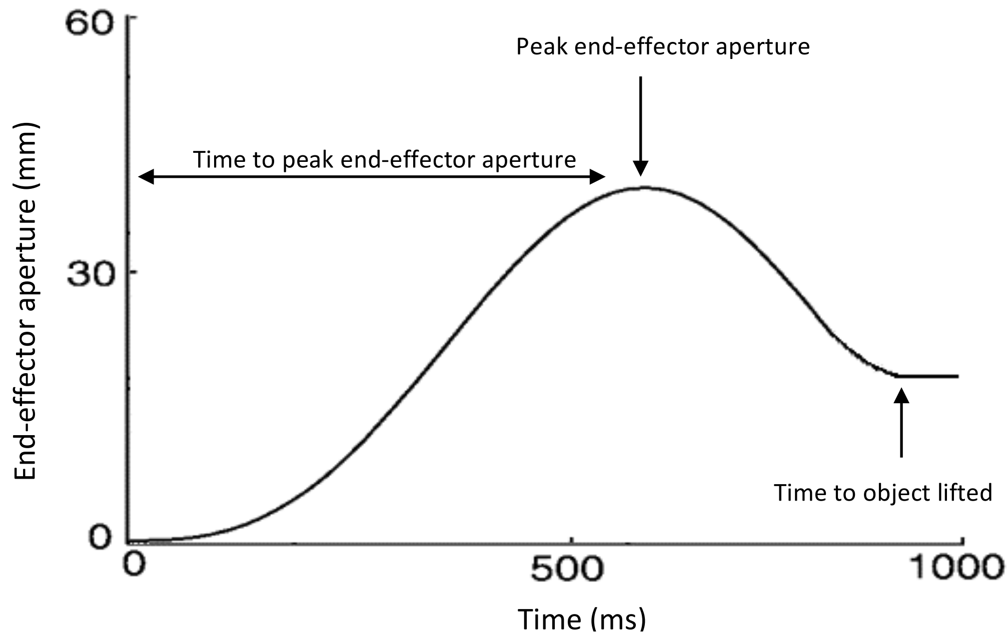


Figure 2.15. A plot showing the kinematic indices relating to tool/hand opening.

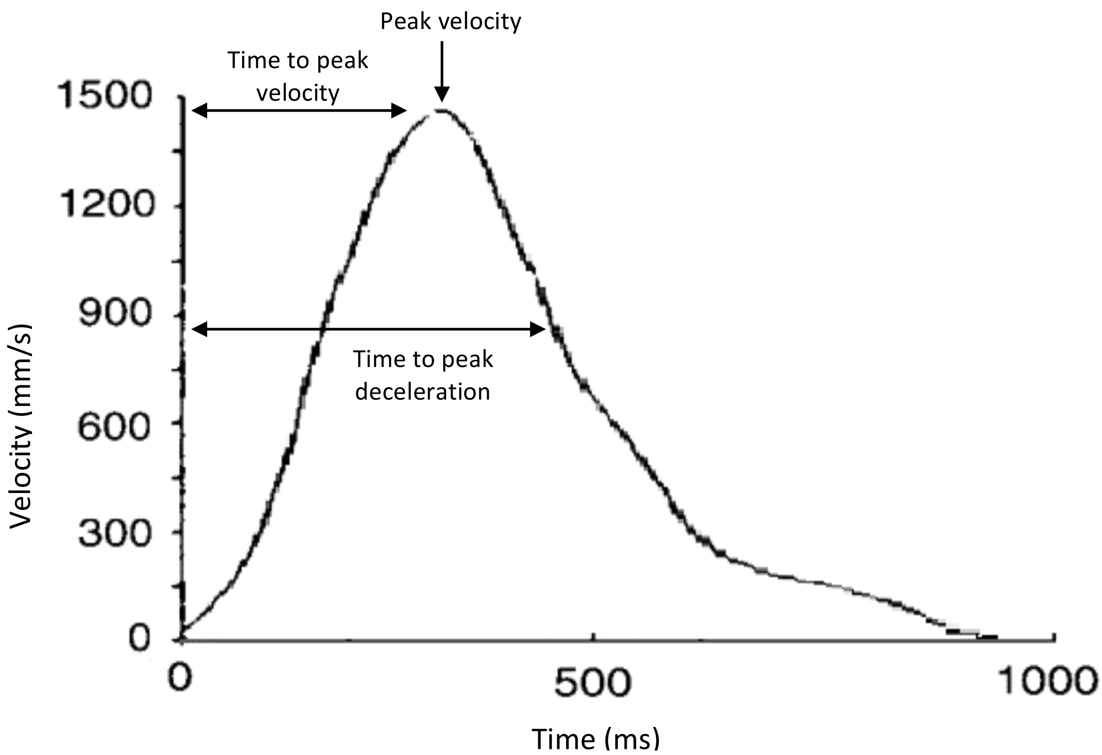


Figure 2.16. A plot showing the kinematic indices relating to movement speed.

2.6.1 Peak end-effector aperture

One part of a movement that is canonically studied in kinematic research is that of peak grip aperture. This is defined as the widest separation of the finger and thumb prior to picking up an object. In our experiments, we instead refer to this as *peak end-effector aperture* to encompass both hand grasping and tool grasping. Whenever we use this term, we are therefore talking about both the distance between the tips of the tool or the finger and thumb. Whereas when the term peak hand aperture is used we are talking about the opening of the hand, both when using a tool and when not. Obviously when grasping with the hand both peak end-effector aperture and peak hand aperture will be the same, as the finger and thumb are the apertures, however the distinction is needed to be able to compare the hand to the tools. So by labelling this point in the movement as peak end-effector aperture it can refer to either the separation of the finger and thumb or the separation of the two tool tips allowing us to see if the opening of the tool tips scales in a similar way to that of the finger and thumb in typical grasping experiments.

In past experiments using studying reaching and grasping with the hand peak grip aperture has been shown to scale linearly with object size (Jeannerod, 1981; 1984; 1997; Smeets & Brenner, 1999; Wing et al., 1986), meaning that the larger the object is, the larger the peak grip aperture will also be. Of course, to some extent this is common sense, a larger object will require a larger grip aperture to be able to pick it up successfully. However, when grasping an object, the peak grip aperture is usually larger than the object itself, people typically open their hand wider than the object and then close the finger and thumb around it at the end of the movement. This means that the peak grip aperture would not necessarily need to increase linearly as object size does to successfully grasp an object.

However, it has been shown that under normal conditions peak grip aperture does increase with object size in a uniform manner with a slope of about 0.8 usually observed (Smeets & Brenner, 1999). This slope can be affected by changing the properties of the object being grasped. For example, a steeper slope is observed when the object being grasped is a block rather than a cylindrical shape (Verheij, Brenner & Smeets, 2012).

Peak grip aperture has also been shown to increase as visual uncertainty about an object increases (Keefe, Hibbard & Watt, 2011; Schlicht & Schrater, 2007; Sivak & MacKenzie, 1990; Wing et al., 1986); suggesting that the brain builds in a margin-for-error when there is uncertainty present, reducing the chance of an error occurring. Because peak grip aperture can be modulated in this manner it is arguably an informative measure of various aspects of task performance. For example, it could be used to probe how certain a participant was about the grasp they were making, and could possibly show how much the participant understands about the grasp they are making. If peak grip aperture does not scale with object size in a certain situation it could be argued that the visuo-motor system is incorrectly estimating the necessary movement. We were interested in seeing if peak end-effector aperture showed any of these modulations when tools were used to grasp an object. For example, when using a tool to pick up objects do we still scale our peak end-effector aperture as object size increases?

In our experiments, the peak end-effector aperture is expressed in millimetres and was calculated using our custom written Matlab code. The code worked out the 3D distance between the finger and thumb markers or tool tip markers in each frame of the movement and then plotted these on a graph. The code then highlighted the most likely point for the peak end-effector aperture on the graph by finding the first peak of the movement. It was then possible to quickly look through the trials and visually inspect the peak end-effector apertures and alter any that the code had not identified correctly. Once this had been done then the values were printed into the data file. These were then adjusted to account for the offset between the location of the markers and the actual tool tips or finger and thumb pads. This was done by taking readings with the tools and the hand using known apertures by taking recordings when an object with a known size was being held. This was done for numerous sizes and a formula was calculated that adjusted the recorded opening to the actual opening of the tool and the hand.

The time taken to reach the peak end-effector aperture is another interesting index. When it has been measured when grasping with the hand in the past this is a measure that scales reliably with object distance, with peak grip aperture occurring later when the object is farther away from the participant. In our analyses, this index was calculated by measuring how much time had passed in seconds from the moment that the start button was lifted until the peak end-effector aperture had been formed.

2.6.2 Peak velocity

Peak velocity is the maximum velocity that was reached during the course of the movement, allowing analysis of the maximum speed of the movement. Past research has shown that it scales reliably with object distance (Jeannerod, 1984; 1988) and that peak velocity decreases when uncertainty is introduced, for example when visual feedback during the reach is removed (Loftus, Servos, Goodale, Mendarozqueta & Mon-Williams, 2004; Melmoth & Grant, 2006). A plausible reason for this could be that the system is compensating for uncertainty by slowing the movement down, giving the participant more time to act appropriately and utilise online visual feedback.

In our experiments, peak velocity was recorded from a retroreflective marker placed over the radius bone on the wrist. It was calculated using our custom-written

Matlab code by measuring the velocity of the wrist marker and identifying the first peak. As with peak end-effector aperture the code produced graphs of velocity for each trial and identified the most likely point that peak velocity occurred, so again the experimenter was able to manually check that the correct value had been selected on each trial.

Again, the time taken to reach the peak velocity is another interesting index. This is an attribute that scales reliably with object distance, with time to peak velocity occurring later when an object is farther away from the participant. It is an attribute that is related to peak velocity, in the fact that usually when peak velocities are higher the time to peak velocity is also higher. In our analyses, this was recorded in seconds and was calculated by seeing how long after the start button was lifted peak velocity occurred.

2.6.3 Time to peak deceleration

This is the time taken to reach the point in the movement where maximum deceleration occurred. Again, it is an attribute that is linked to peak velocity in the fact that if peak velocity occurs later on in the movement then so will peak deceleration. In our analyses, this was recorded in seconds and was calculated by seeing how long after the start button was released peak deceleration occurred. Peak deceleration was also calculated using our custom-written Matlab code, the deceleration for each frame was plotted on a graph and the code identified the most likely peak. The experimenter was able to then manually check that the correct peak had been selected before the data was printed to the file.

2.6.4 Overall movement time

This is the amount of time that passed between the start of the movement and picking up the object. In our experiments, this was the amount of time that passed between the start button being released and the object losing contact with the strip on the table.

2.6.5 Time in the slow phase

This is the amount of time spent from the point of peak velocity to when the participant lifted the object. It is the final approach of the reach when the hand (or tool) is closing in on the object. Time in the slow phase can be extended under conditions of uncertainty, for example when grasping without vision (Churchill, Hopkins, Rönnqvist & Vogt, 2000) or when grasping monocularly (Servos & Goodale, 1994). By spending more time in the slow phase participants allow themselves a greater amount of control at the end of the movement.

Different kinematics indices were used in each of our experiments because not all of the indices were relevant for every experiment. It is detailed in each results section which indices were used in that experiment.

2.7 Caution in interpreting kinematic indices

As mentioned before, the main index of interest throughout this thesis will be that of peak end-effector aperture. This is because one of our main manipulations is to vary tool ratio and assess what effect these changes have on grasp aperture control. However, caution must be taken when interpreting these results. Studying changes in kinematic indices is a way of attempting to measure underlying differences between movements. However, these indices are just emergent properties of these differences. We can attempt to characterise the movement as a whole using these different indices, but it is important to remember that and not assign more meaning to findings than is actually there. For example, finding differences in three different kinematic indices does not make the finding more substantial than if you found differences in only two. It is important to always try to use the differences in the indices to think about the movement as a whole.

As discussed previously, peak end-effector aperture may increase when the task is more demanding but it may also increase when participants are uncertain about the situation as well. It also the case that when someone is uncertain they can slow their movement down when making the grasp, particularly at the end of the movement as they approach the object (measured using the time in the slow phase). This could mean that peak end-effector aperture does not change at all and instead peak velocity reduces as a sort of 'trade-off' to allow a constant peak end-effector aperture. Equally if a participant moves faster on some given trials than others this could lead to them also producing a larger peak end-effector aperture. Because of these things it is important to be cautious when attributing cause to the changes seen in these indices. It is not possible to reverse engineer the brain's estimate of object size or tool ratio because the effects in our kinematic indices could be caused by many different things. This can be helped by looking at multiple indices (particularly using the peak end-effector apertures and peak velocities in tandem) to ensure that a picture of the full movement is available rather than just making judgements based on a single index. However, even when utilising many different indices there is no way to be certain about the cause of changes in the movements. It is also the case that when using these indices you are reducing a complex movement down to a handful of numbers. This again is a risky practice because you are only looking at very select points of the movement and discarding the rest where differences could lie. This can be addressed by looking at average grasp profiles. These are profiles that are constructed to show each index across the course of the whole movement. For example, you could have an average profile for velocity and another for end-effector aperture and these would show how these indices varied throughout the entire movement, not just at the one peak. These can be created by averaging individual grasp profiles together from each trial and plotting the data on a graph to give each participant's individual performance. Participant's averages can then also be averaged together to give a global average performance with each tool.

Chapter 3: A kinematic analysis of tool use

3.1 Experiment 1: Kinematics of grasping with tools

We use tools every day of our lives to help us to complete tasks that would be very difficult or often impossible without them. However, despite our daily reliance on tools and all the information that is known about reaching and grasping with the hand, little is known about the kinematics of grasping with a tool. A tool alters the relationship between the hand and the 'end-effector'. Usually when grasping the end-effector is the finger and thumb. However, when using a tool, it is the tool tips that now need to be controlled. Some tools have what is referred to as "motor equivalence", meaning that the hand movements required to move the tool tips are qualitatively similar to movements made if you were using the hand alone to complete the task (Arbib et al., 2009). For example, grasping with simple tongs requires opening and closing of the hand aperture in a similar manner to grasping directly with the hand. Quantitatively there are likely to be differences in the required movements, however. When you use a tool to grasp an object the brain must solve a transformation problem. For different types of tool, the brain will have to understand different transformations to be able to control the tool tips precisely and accurately. Some experiments have started to look at this topic (Bongers, 2010; Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Zheng & Mackenzie; 2007), but it has not been studied in anywhere near as much detail as normal reaching and grasping has. This chapter aims to look in more detail at the kinematics of reaching and grasping with a tool, whilst investigating how alterations in tool geometry can affect kinematics.

3.1.1 A common motor representation of grasp

Gentilucci et al. (2004) investigated the idea that the kinematics of grasping movements may be planned and controlled in terms of the movements of end-effectors in the world, as opposed to being controlled in terms of specific joint angles. The potential advantage of such a mechanism is that it allows movements to be planned and controlled in simpler units, that are independent of the specific motor output required to produce them (which would be different with different tools, for instance). They point out that previous models have posited two phases of a grasp (Arbib, 1990; Arbib et al., 1985). The first involves the planning of pre-shaping parameters based on visual information about the object, and is therefore in terms of the required movement of end-effector in the world. The second involves the implementation of these parameters for a specific effector. That is, what motor commands are needed to produce the desired movement in the world. Gentilucci et al. (2004) attempted to determine whether these two processes were separate. They reasoned that if they were separate, the initial phase of the grasp would be to plan pre-shaping parameters that were the same, whether grasping with the hand or with a tool. If this were the case then regardless of the tool that was being used these parameters would be the same. They called this having a "common motor representation of grasp" (Gentilucci et al., 2004, p497). If, however, the two processes were jointly performed then they suggest that we may have different motor representations that we utilise when using different effectors. That is, the 'pre-shaping' part of the grasp would be dependent on the effector being used and would therefore differ when using the hand compared to when using a tool.

To assess these possibilities, they compared grasping movements made with the hand to those made with a tool. To allow them to separate their two hypotheses they chose a tool where the participant had to close their hand to open the tool, opposite to how they would grasp an object with their hand. This meant that the finger and thumb in the hand grasping condition, and the arms of the tool in the tool grasping condition, moved in the same manner – a pinch grip. However, the hand itself had to move in the opposite direction in each condition to achieve this. Participants picked up objects with both their hand and the tool and the authors compared the kinematics of the two different effectors to see if there were any similarities between the two types of grasp. The rationale of the study was that if there was a common motor representation of grasp then similarities should be seen between the kinematics of the grasps made with the hand and those made with the tool, particularly those related to the visual properties of the object.

It was found that with both the tool and the hand participants produced larger peak end-effector apertures as the object's size increased, in line with previous research on reaching and grasping with the hand (Jeannerod, 1981; 1984; 1997; Smeets & Brenner, 1999, Wing et al., 1986). This would be in line with participants having an internal model of the tool that functions in a similar manner to the hand's predictive model. When comparing the actual apertures produced with the hand and the tool however, they found that participants opened the tips of the tool significantly wider than they opened the finger and thumb when grasping the same objects. They also found that when using the tool to grasp an object, participants produced a grasp that had a distinct plateau after the peak end-effector aperture was reached, something that is not typically seen when reaching and grasping with the hand. This does not necessarily discredit the concept of internal tool models or planning the movement in end-effector units. This could still be the case, however larger apertures may be seen with the tool because the brain is working from a model that is biased or noisy, therefore building in margin-for-error in the peak end-effector apertures produced with the tool. When using the tool participants also reached their peak end-effector aperture quicker than they did with the hand, and took longer to close the tool around the object than they did the finger and thumb. This was particularly true when grasping smaller objects. This effect could arguably be caused by the type of tool that Gentilucci et al.

(2004) used in their experiment. The tool was spring-loaded, requiring more force to open than to close. It also required increasingly large forces to open as the tool opening widened. For example, to achieve a separation of 3 cm between the tool tips ~6 Newtons (N) of force had to be applied to the handles, whereas to open the tips 7 cm required ~10 N. This complex 'mapping' means participants might have had less fine control when using the tool than they did when using the hand, and increased uncertainty about how motor commands related to end-effector movements in the world. It is not implausible that participants learnt that a large amount of force was needed to open this tool and therefore squeezed quite hard at the start of every trial, regardless of object size, this would lead to them rapidly reaching their peak end-effector aperture.

There was no difference in the peak velocity reached with the tool or the hand during the movements. However, participants did spend more time in the final slow movement phase, as the end-effector approached the object (time in the slow phase), for smaller objects than large ones. This is sensible, smaller objects will require a finer amount of precision to grasp. By slowing down in the final precise phase of the movement, participants are allowing themselves to use visual feedback to help grasp the object. This effect was more obvious during tool use than it was with the hand and overall movement times were longer. Again, these findings make sense in terms of adjusting for a flawed model, by slowing down the movement visual feedback can be utilised to adjust the model accordingly.

Gentilucci et al. (2004) suggest that because the kinematic parameters related to the calculation of intrinsic properties of an object did not vary that this supports the concept of a common motor representation of grasp. However, the kinematic parameters in Gentilucci et al.'s (2004) experiment were not identical across tool and hand. Significantly larger peak effector apertures were produced when using the tool than when using the hand. Gentilucci et al. (2004) stated that there was a common motor representation of grasp if parameters that were related to intrinsic object properties were the same across effector. It could be argued that formation of peak end-effector aperture is something that is affected by the object's intrinsic properties (its size). However, one factor that could account for increased peak effector apertures was the spring-loaded tool. This complex mapping meant participants had less fine control when using the tool than they did when using the hand, and arguably increased uncertainty about how motor commands related to end-effector movements in the world. A sensible method to cope with uncertainty during grasping is to build in a margin-for-error by forming larger peak end-effector apertures, reducing the chance of colliding with the object (Keefe, Hibbard & Watt, 2011; Schlicht & Schrater, 2007). This could therefore account for the larger peak end-effector apertures that were produced with the tool than the hand. Because the experiment only compared the movements of one tool and the hand it is hard to draw conclusions about which one of these explanations is correct. It could be that uncertainty about the how the tool worked led to larger peak end-effector apertures despite a common motor representation of grasp. However, it could also be that the movements were different because the manner in which the brain controls a tool is inherently different to how it uses the hand.

Gentilucci et al. (2004) did not set out specifically to measure the kinematics of tool use, but instead used a tool as an experimental manipulation to address another question. Nonetheless, their results do suggest that there are similarities between grasping with the hand and grasping with a tool. Their findings suggest that using a tool affects the peak effector apertures produced during the movement but does not affect the peak velocity. Participants did however spend a lot longer in the slow phase when they used a tool. This could be interpreted as them finding it more difficult to perform precise movements with the tool than they did with their hand. When this is the case slowing down towards the end of the movement is a sensible strategy as it gives more time for online corrections to be executed and allows the use of visual feedback to adjust the predictive model online.

3.1.2 Programming movements in end-effector units

Another way of thinking about Gentilucci et al.'s (2004) common motor representation of grasp is to say that movements are being programmed in end-effector units. This means that initially the movement is planned in general units that would apply to any tool and then later in the movement the specifics of the tool would be applied. A study that looks at this concept is that by Umiltà et al. (2008). They measured the firing rate of neurons in the ventral premotor cortex of monkey brains while grasping with normal and reverse pliers. The end-effector (either finger and thumb, or tool tips) did the same thing in each trial: open and then close around the object. However, the hand had to perform opposite movements for the two tools. They found that the some of the neurons that fired when the normal tool (and therefore the hand) opened also fired when the reverse tool opened (meaning that the hand was closing). This suggests that these neurons were not coding for movement of the hand, but were instead coding for the movement of the end-effector. This is the case because these neurons fired for opposite movements of the hand but the same movements of the tool tips.

At some point during a successful reaching and grasping movement the muscles must be instructed to move in the correct manner. The question is, when do the transformations required occur? The experiment by Umiltà et al. (2008) suggests this is at a surprisingly 'late' stage in the process of preparing motor output, meaning that grasping may well be planned in terms of world movement or end-effector units. This is consistent with Gentilucci et al.'s (2004) view and suggests that programming could be done in broad terms initially before being applied to the effector being used.

3.1.3 Measuring tool use using kinematics

A study that has attempted to directly assess the kinematics of reaching and grasping with a tool is that by Zheng and Mackenzie (2007). Their participants reached for and lifted a dowel that was on either a wide or narrow stand, with either their dominant or non-dominant hand, and with or without a pair of tongs. By using these manipulations, they could probe the differences between grasping with the hand and a tool more deeply. Changing the size of the stand that the dowel was picked up from explored differences in the ability to make precise movements. Grasping with the non-dominant hand is harder than using the dominant one, allowing the authors to explore how task difficulty affected kinematics. It can be looked at whether similar strategies were adopted for the non-dominant hand and the tool.

Their tool was made by removing the tips and handles from a pair of kitchen tongs and taping the cut-down tongs to the thumb and finger of the participants. Once the tongs had been cut down, the hinge was in the middle giving the tool a 1:1 ratio between hand opening and tool-tip opening.

They found that overall, the reaching and grasping movements took longer with the tool than they did with the hand, and participants spent more time in the slow phase which replicates what Gentilucci et al. (2004) found in their experiment. Unlike Gentilucci et al. (2004), Zheng and Mackenzie (2007) also found that participants reached lower peak velocities when grasping with the tool than they did with their hand. The width of the object's stand had no effect when grasping with the hand. When using the tool, however, movements were slower when grasping objects on the narrow stand. There is arguably going to be more noise in the control of the tool than with the hand. The tool adds extra transformations and having to account for the relationship between hand posture and position of the tool tips adds an extra layer of uncertainty. Moreover, the mechanical properties of any tool that extends the reach of the arm means that spatial variability in hand posture is amplified at the tool tip (consider trying to open your front door with your key attached to the end of a long stick). A sensible way to cope with this complex and possibly flawed internal model of the tool would be to slow down to allow for incorporation of visual feedback – something that would not necessarily be needed when grasping with the hand. This is supported by the fact that movements were even slower with the tool when grasping from the narrow base, because this requires a finer degree of control.

Participants opened the tool tips wider than they did their finger and thumb when grasping the same sized objects, supporting what Gentilucci et al. (2004) found in their experiment. Zheng and Mackenzie (2007) do raise the point that the fact that the tool was taped to the finger and thumb of the participant is not particularly naturalistic and that this may limit the applicability of their results to other tools, so further research with more typical tools would be beneficial to see if the same results are found. This is important to consider when attempting to generalise between specific findings and other types of tools, or tool use more generally.

Another experiment that looked at the kinematics of tool use was that by Itaguchi and Fukuzawa (2014) they used familiar and unfamiliar tools and hand grasping patterns to see if the precision of a grasp is affected by familiarity of the end-effector. They found that participants scaled their peak end-effector aperture in all four of their conditions and found no significant difference in the movement times either. They did however identify the same plateau that Gentilucci et al. (2004) saw in their tool grasping profiles. In this experiment, it was present in all conditions but modulated by familiarity of the effector, being largest for the unfamiliar tool and smallest for the dominant hand grasp. This is supportive of the idea of internal tool models and planning movements in end-effector units. The brain appears to be trying to produce the same movement regardless of the effector used. With more familiar effectors participants can grasp the object in a more fluid motion, however the less familiar they are with the effector that they are using, the more disjointed the opening and closing of the effector becomes. This is indicative of participants giving themselves more time to visually confirm that they will successfully grasp the object before closing the end-effectors, whilst still producing the same qualitative movement overall.

A final experiment that has measured the kinematics of grasping with a tool was run by Bongers (2010). Bongers (2010) measured the kinematics of grasping with the hand and a 1:1 tool and found, like Gentilucci et al. (2004) and Zheng and Mackenzie (2009) that participants opened the tips of the tool wider than they did their hand when grasping the same object. Movement times for tool use were also longer than with the hand, like previous experiments. Finally, he also found the same plateau after the peak effector aperture during tool use that was seen in the experiments by Gentilucci et al. (2004) and Itaguchi and Fukuzawa (2014). Bongers (2010) suggests that this plateau shows that opening and closing the hand is decoupled when using a tool. The hand opens, stays in an open position and then closes, these being two separate processes rather than a smooth opening and closing of the hand usually seen in grasping. This plateau was not seen in hand trials after tool use suggesting that it is specific to using the tool and does not carry on to trials immediately after tool use. These findings also fit with the concept of an end-effector control strategy with adjustments to cope with uncertain tool models.

Whilst there are differences in what these four studies found there is evidence that using a tool often led to larger peak effector apertures and often to slower and longer movements as well. The fact that this was not found in every experiment is explainable – different tools are going to have different effects on the grasping profile. As Itaguchi and Fukuzawa (2014) demonstrated, familiarity of a tool modulates the precision with which a person can use it, and this can go some way to explaining the differences seen in these past experiments. When thinking about this research in terms of internal tool models and end-effector control a lot of these findings make sense. Normal reaching and grasping movements rely on a predictive model that uses online feedback to make corrections. When an internal model of a tool is utilised, it is plausible that this same feedforward and feedback system is being recruited. However, if the brain's model is noisy or inaccurate, then one of two things could happen; it could either make mistakes such as producing an incorrect end-effector aperture or it could behave in a strategic manner as it knows the model is flawed. In this case we might see an overall slowing of the movement to allow online visual feedback to have more of an effect, or wider peak end-effector apertures could be produced to avoid collisions as the brain knows that both the proprioceptive feedback and the feedforward model itself are noisy or biased.

3.1.4 Comparing grasps with the hand and grasps with tools

One feature of most of the above studies (excluding Itaguchi and Fukuzawa (2014)) is that they explored how the brain uses tools by directly comparing grasps made with and without tools. Using similarities and differences in kinematics to infer whether the underlying control processes were similar. This is problematic because in almost all cases tools necessarily have specific features that make it likely that kinematic parameters will differ quantitatively from hand grasps, whether they share common control processes or not. For example, as described earlier, Gentilucci et al.'s (2004) tool contained springs, Zheng and Mackenzie's (2007) tool was taped to the hand/ and Bongers' (2010) tool was 40cm long arguably adding an increase in motor noise. These features are likely to have their own independent effects on movement kinematics, which are not specifically investigated by the experiment. In experiment-design terms, there are likely to be many uncontrolled variables that change between hand grasping and tool grasping, making it difficult to interpret the effects of the main manipulation unambiguously. Itaguchi and Fukuzawa (2014) did use two different tools in their experiment however they were two very different tools – one was a pair of chopsticks and the other was similar to a pair of scissors. Again, this makes it difficult to use their findings to explicitly look at the underlying tool models as it is hard to know how the differences between the two tools will affect the movement kinematics.

Therefore, we took a slightly different approach, to address this problem. Rather than using a single tool, we used a range of tools of the same global 'class'. All our tools were pairs of tongs, but each one had a different geometry. That is, we varied the geometrical relationships between hand opening and tool-tip opening (see section 2.2 for more information). This still allowed us to compare grasping with and without a tool, as in previous work. Specifically, we could compare hand grasping to grasping with our 1:1 tool, which preserved the relationship between hand opening and the end-effector. More importantly, we could also compare movements made with different-geometry tools (1.4:1 and 0.7:1) to the 1:1 tool which all required different hand movements to produce the same end-effector movement. This way, we examine the visuo-motor system's response to different tool geometries, quantitatively, while holding all the other uncontrolled factors (awkwardness of operation, grip of contact surfaces etc.) largely constant. Thus, kinematic differences across different tool geometries cannot be attributed to having used a tool *per se*. By altering tool gain we could make quantifiable predictions about performance with the three tools. If the visuo-motor system attempted to produce the same movement with the end-effectors as previous research has suggested might be the case (Gentilucci et al., 2004; Umiltà et al., 2008), then we should be able to identify this using our paradigm. We can look at the kinematics of participants grasping differently sized objects placed at different locations with the hand and the three tools. We can then compare these kinematics to see if they support the idea of a common representation of grasping/controlling movements in terms of the end-effector or not.

3.1.5 Predictions

3.1.5.1 For the hand and the 1:1 tool

Predictions for hand compared to the 1:1 tool are unclear based on past experiments. If the brain is planning movements in end-effector units and successfully executes this movement then we would see no differences in the kinematics of the hand and the 1:1 tool. However, even this tool has very different mechanical properties to the hand (and switches the movement of the thumb and finger in relation to the end-effectors). Therefore, even if the movement is planned in end-effector units we may see similar effects as previous research, such as increased peak end-effector aperture and time in the slow phase (Bongers, 2010; Gentilucci et al., 2004; Zheng & Mackenzie, 2007) and a decrease in peak velocity (Zheng & Mackenzie, 2007).

We will also look at some other indices including the time that it takes for participants to reach the peak end-effector aperture and peak velocity as well as the time it takes to pick the object up and how much time participants spent in the slow phase. Looking at all these different indices will allow us to see where the differences are in grasping with the hand and with a tool.

3.1.5.2 For the different tool geometries

If movements are planned in end-effector units and the brain attempts to control the tool tips in the same manner as the finger and thumb (Botvinick & Cohen, 1998; Cardinali, et al., 2012; Gentilucci et al., 2004; Roy & Farne, 2009a; Umiltà et al., 2008), then when grasping a given object, the end-effector aperture profiles of the three tools should be the same (altering hand aperture to compensate for tool ratio). The opposite finding to this would be that people are not controlling movements in terms of end-effector units and instead make the same *hand* movements regardless of the tool that they are using. These cases form two extremes that we refer to in this thesis as 'perfect' and 'zero' compensation for the changes in tool geometry. Based on past research what is possibly more likely is that internal models of the tools are biased or unreliable and therefore an alternative is that we see performance in between these two extreme cases. If the brain programs movements in end-effector units but uses an incorrect tool model, or it makes consistent adjustments as it knows that the models are flawed or biased, then this could lead to data in between the two extremes. Here we would see some compensation for tool ratio, but it would be incomplete and tend back towards that of the known model of the hand. To measure this throughout the thesis we will use a compensation factor (described in more detail in section 3.3.3), that quantitively measures how well participants have compensated for the ratio of the tool.

We may also see that peak velocities differ across the three tools. The 1:1 tool preserves the movement of the hand in the world. Therefore, it may be more intuitive to use and have a more accurate tool model allowing participants to reach faster speeds. When grasping with the 0.7:1 or 1.4:1 tool participants have an extra transformation to take account of, altering the movement of the hand in the world. Therefore, it would not be unexpected to see slower peak velocities with the red and yellow tools, because online visual feedback may be needed when using these tools to adjust the predicted movement.

Finally. we wanted to examine whether the plateau after the peak end-effector aperture that was seen in previous experiments when using a tool (Bongers, 2010; Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014) was also present with our three tools, to gain more of an idea of whether this is an effect of using a tong-type tool to grasp an object.

3.2 Methods

3.2.1 Participants

Twelve right-handed participants were recruited through opportunity sampling (eight female, four male). All participants had normal or corrected-to-normal vision, and no known motor impairments that would affect their ability to make a normal grasp.

3.2.2 Stimuli and Apparatus

The privacy screen, start button, object strip, tools, retroreflective markers and cameras are the same as those described in section 2.4.

An adjustable chin rest was affixed at the centre of the table edge; this ensured that both the start button and any experimental objects would be in line with the participant's midline. The height of the chair and the height of the chin rest could both be adjusted so that the participant's eyes lined up with a pre-marked position that ensured that they could not see over the top of the privacy screen (see Figure 3.1 for a picture of how the experimental area looked during this experiment).

Figure 3.1. Experimental setup. The privacy screen, start button and object strip are visible in the picture (see section 2.4 for further explanation of these items).

The target objects in this study were seven balsa wood blocks that ranged in size from 20-50 mm in 5 mm increments. Balsa wood was used to create light objects so that they were easy to pick up with our tools. This is because the tools have a smaller point of contact than the finger and thumb making it harder to lift an object up. By making the objects as light as possible, the contact point was enough to be able to easily lift the objects with the tools. During statistical analysis only 6 of the objects were used. This is because the red 1.4:1 tool could not be used to pick up the 20 mm object so we removed this object from statistical analysis. It was included in the experiment though to try to increase task demands. The objects were placed either 150 mm, 300 mm or 450 mm away from the participant, along the body midline.

A 'calibration object' was created so that participants would have the opportunity to use the tool at the beginning of each trial before they were required to perform the trial itself (see Figure 3.2 and 3.3). This enabled participants to interact with the tool before they were required to use it on an actual trial, giving them the best possible chance to use the tool in an accurate manner. The calibration object consisted of two wooden blocks that were attached at one end with a screw to create a pivot and separated at the other end using a small spring. This allowed us to record when the participant grasped the object as the two wooden blocks would close together forming a circuit and successful contact was recorded. After a second of holding the object the participant was prompted to return to the start button for the start of the actual grasp. This ensured that the participant had successfully interacted with the calibration object on each trial.

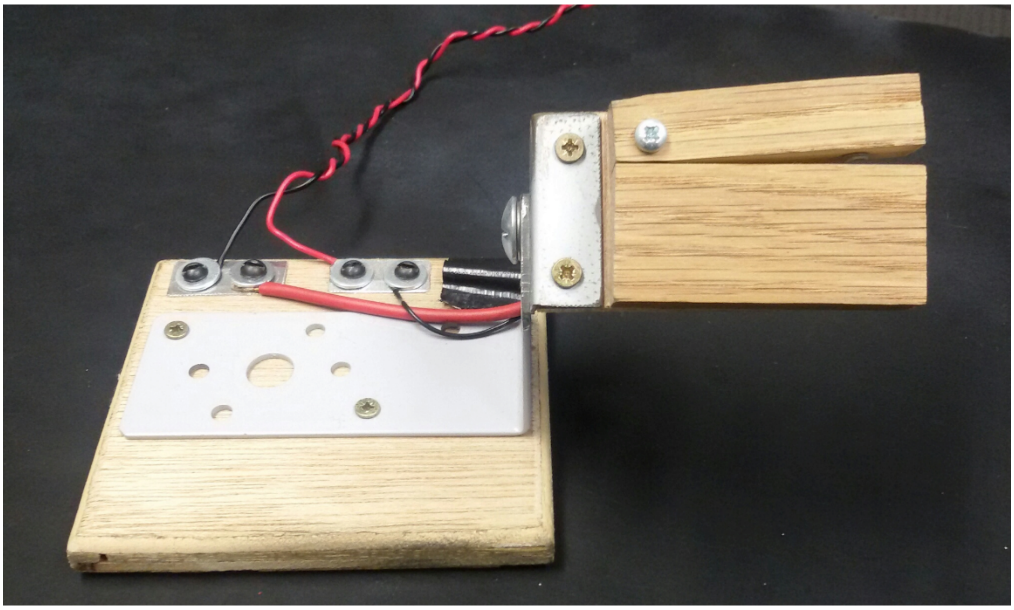


Figure 3.2. The calibration object in its open position.

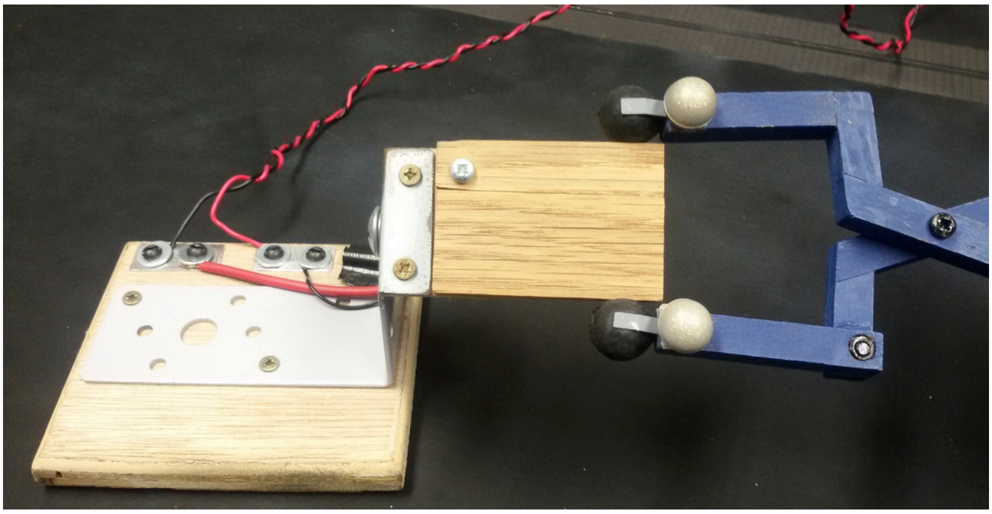


Figure 3.3. The calibration object being grasped with the 1:1 tool.

3.2.3 Procedure

The chair and chinrest were adjusted to suit the participant and to ensure that they were in the correct position. A retroreflective marker was attached to their right wrist over the pisiform bone. In the hand session markers were also attached to the centre of the forefinger nail and thumbnail. For the three tool sessions markers were attached to the tools, directly onto the wooden arms directly above the black rubber balls on the tips (see Figure 3.3 for an example).

For the hand session, the participant was instructed to hold their thumb and forefinger together in a closed position and depress the start button. At this point the privacy screen turned opaque to prevent the participant from seeing the experimental area. The experimenter placed an object on the table and pressed the space bar to initiate a trial; this switched the privacy screen to transparent allowing the participant to see the object on the table. One second later, a beep signalled the participant to pick up the object, before placing it to the right-hand side of the experimental area and returning to the start button. Participants were instructed to grasp the object quickly but accurately, and as naturally as possible, without taking time to think about what they were doing. To control the visual information about object properties, and the time available to plan the movement, trials were considered void if the start button was lifted before the beep sounded, or >600 ms after it. This was to prevent different strategies being employed in different conditions of the experiment, such as spending more time planning the movement in tool conditions compared to the hand one. Void trials were added onto the end of the experiment to ensure that all trials were completed.

For the tool sessions, the procedure was mostly identical to the hand grasps, with the following exceptions. At the start of each trial the participant was first told which tool to pick up (blue, red or yellow). The calibration object was then placed on the table and they were instructed to grasp it with the tool until the privacy screen turned opaque. They were then told to depress the start button with the tool tips in a closed position, from which point the trial was the same as with the hand.

The experiment was carried out over four separate sessions, each consisting of one single block of 126 trials. During the first experimental session participants picked up the objects using their right hand and during the other three sessions they used the tools. Hand and tool trials could not be interleaved in the same block because in the hand grasping trials the retroreflective markers needed to be attached to the thumb and forefinger, and the participant could not put their fingers into the handles of the tool with these markers attached. It was therefore decided that these trials should be completed in a separate, initial block. Allowing us to avoid having to repeatedly remove the markers meaning that they stayed in the same position throughout the hand block.

The hand grasping session consisted of each of the seven objects being placed at each of the three distances, six times. The order of these trials was randomised for each participant. The three tool grasping sessions also consisted of each of the seven objects at being placed at each of the three distances. In each tool session, every size/distance combination was repeated twice for each of the three tools. Again, trial order was randomised for each participant, with the three different tools also being randomly interleaved. This meant that after all three tool-sessions had been completed six repetitions of each trial type (object size x distance combinations) had been performed with each tool. The red 1.4:1 tool was not used to grasp the 25mm object because the tool tips could not close enough to grasp this object. To ensure that each of the tools was still used equally the larger six objects were grasped more times with the red tool.

Experimental sessions were not allowed to occur more than a day apart, with participants encouraged to complete all four sessions on consecutive days. This constraint was aimed at ensuring that as far as practically possible there would be carry-over of any learning of the tools' properties to future sessions.

Participants were paid for their participation at the end of each session and were debriefed when all four of their sessions had been completed. Participants could withdraw from the experiment at any time if they wanted to, but no participants did.

3.3 Results

3.3.1 Peak velocity

Figure 3.4a plots the average peak velocity reached in this experiment (a) as a function of object distance, collapsed across size and (b) as a function of object size, collapsed across distance for the hand and the three tools. It shows that in all conditions, including with all three tools, participants reached a higher peak velocity when objects were placed farther away from them. This is in line with the stereotypical pattern observed when grasping with the hand (Jeannerod, 1984; 1988).

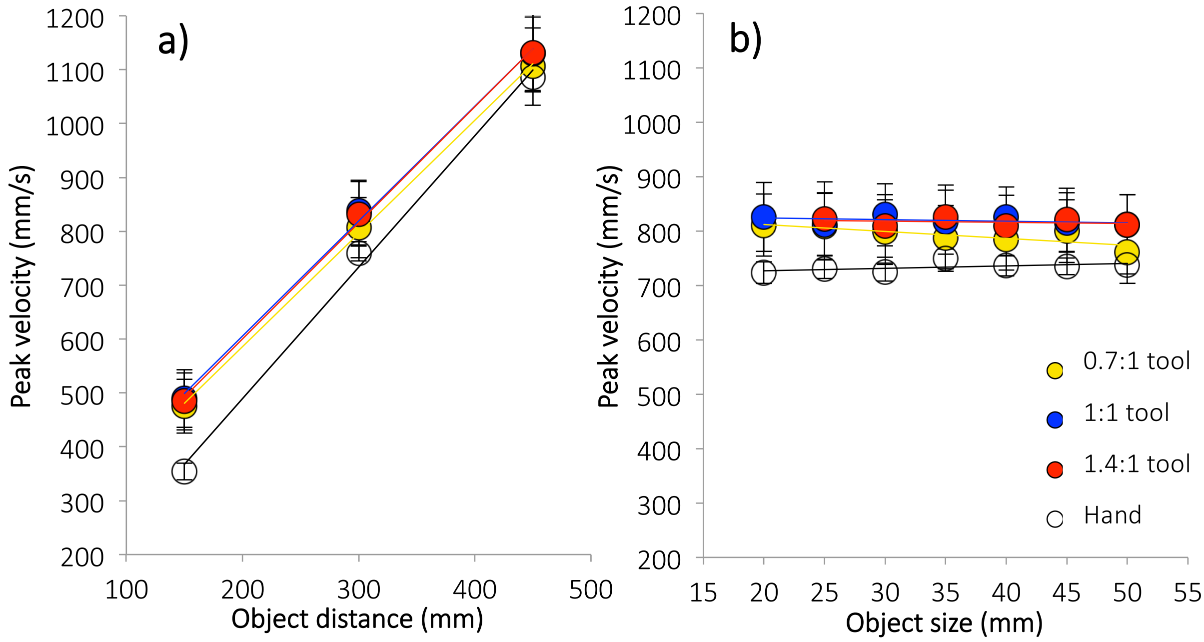


Figure 3.4. Peak velocity data. (a) As a function of object distance, collapsed across size. (b) The same data as a function of object size, collapsed across distance. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=12.

A 4 x 6 x 3 (grasp type (grasp type includes the hand and the three tools) x object size x object distance) repeated measures ANOVA revealed a main effect of object distance on peak velocity ($F(1.13,12.43) = 359.49$, $p<.001$). Mauchly's test indicated that there was a violation of the assumption of sphericity for grasp type, object size and object distance so a Greenhouse-Geisser correction was applied. This is the case in many of the ANOVAs throughout the thesis and will only be highlighted briefly in each instance in the future. Planned contrasts show that significantly higher peak velocities were reached for objects placed at 300mm than those placed at 150mm ($F(1,11)=435.52$, Greenhouse Geisser corrected, $p<.001$) and also at 450mm compared to 300mm ($F(1,11)=332.91$, Greenhouse Geisser corrected, $p<.001$).

Figure 3.4b plots the same data but shows it at each object size collapsed over distance. Here it can be seen that participants moved slightly faster when using the tools than they did when using their hand. However the ANOVA showed no main effect of grasp type on peak velocity ($F(1.23,13.50)=1.90$, Greenhouse Geisser corrected, $p=.190$). This is in line with Gentilucci et al.'s (2004) findings, but different to Zheng & Mackenzie (2007), who found that participants moved more slowly when using a tool. The fact that we saw no difference in the peak velocities reached with the tools and the hand does suggest a similar control strategy could be being employed. It also showed that object size did not have a significant effect on peak velocity ($F(1.48,16.30)=1.35$, Greenhouse Geisser corrected, $p=.280$).

Figure 3.4b shows that the peak velocities produced with the three tools do seem to differ qualitatively for larger objects, with participants moving slower with the yellow tool when grasping larger objects (although not significantly so). This is understandable as the 50 mm object was at the upper limit for some participant's hand opening when using the yellow tool; this was taken into account in future experiments.

3.3.2 Time to peak velocity

Figure 3.5 plots the time taken to reach peak velocity (a) as a function of object distance, collapsed across size and (b) as a function of object size, collapsed across distance for the hand and the three tools. Figure 3.5a shows that the time taken to reach peak velocity increased with object distance. This is a logical finding because more ground needs to be covered in order to pick up the object, and therefore this will take longer. This is therefore the expected pattern for time to peak velocity when grasping with the hand. It is interesting to see, however that when grasping with a tool stereotypical results are still found.

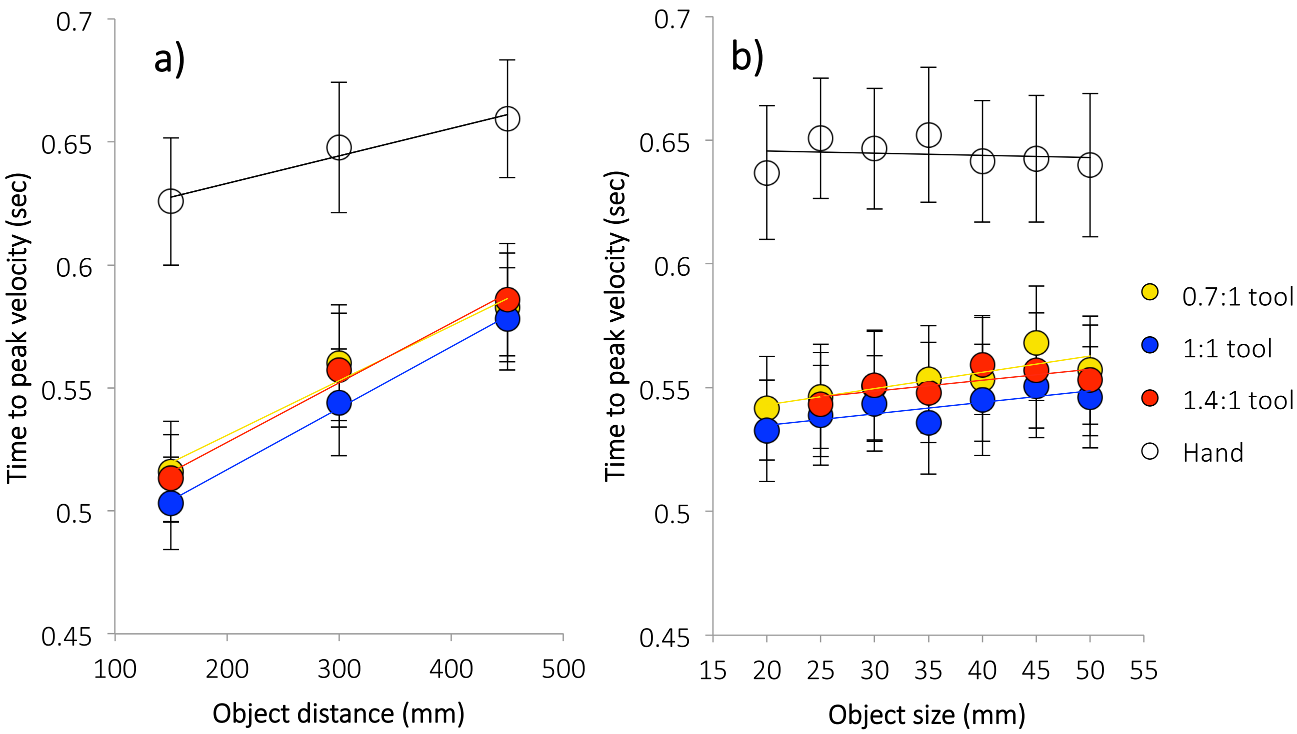


Figure 3.5. Data showing the time taken to reach peak velocity in seconds. (a) Average time to peak velocity as a function of object distance, collapsed across size. (b) The same data as a function of object size, collapsed across distance. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=12.

A 4 x 6 x 3 (grasp type x object size x object distance) repeated measures ANOVA revealed a main effect of grasp type ($F(1.03,11.32)=15.61$, Greenhouse Geisser corrected, p=.002). When looking at planned contrasts it can be seen that participants took significantly longer to reach their peak velocity when grasping with the hand compared to the blue tool (F(1,11)=19.10, p=.001).

There was also a main effect of object distance (F(1.13,12.37)=58.84, Greenhouse Geisser corrected, p<.001). Participants took significantly longer to reach peak velocity when grasping an object placed at 300mm than one placed at 150 mm (F(1,11)=42.76, p<.001), the same was true for objects at 450 mm compared to those at 300 mm (F(1,11)=73.01, p<.001). However, there was no main effect of object size (F(5,55)=0.54, p=.743).

Because there was no significant difference in the peak velocity reached for the hand and the three tools it can be said that participants did not slow down when grasping with a tool to utilise visual feedback. Participants did however reach their peak velocity significantly earlier when using the tools than they did with the hand.

Due to the limited difference seen in the peak velocities any differences seen in peak end-effector apertures will be easier to interpret as any differences seen there do not need to be interpreted alongside a difference in peak velocity.

3.3.3 Scaling of peak end-effector aperture

Smeets and Brenner (1999) have shown that in reaching and grasping experiments with the hand a scaling function of 0.8 is expected. Table 1 plots the scaling functions in this experiment. It shows that we have achieved the expected scaling function with the hand. Data for the hand was collected in a single block and therefore it is presented as such. Table 1 also shows that the scaling functions of the tools increase throughout the experiment. By block 3 participants demonstrated similar scaling with the blue 1:1 tool and the hand. Showing that participants are using this tool in a way that is similar to the hand, which could suggest a common motor representation being utilised here.

Table 3.1. A table showing the scaling functions in each block for the hand and each of the three tools.

Hand/Tool	Block 1	Block 2	Block 3
Hand		0.74	
0.7:1 Yellow Tool	0.54	0.57	0.59
1:1 Blue Tool	0.69	0.73	0.77
1.4:1 Red Tool	0.81	0.96	0.98

There are however, different scaling functions produced with the other two tools. The yellow 0.7:1 tool has a scaling function of 0.59 by the final block of the experiment which is a lower slope than the hand and the blue 1:1 tool. This suggests that participants are not altering their end-effector aperture as much when using this tool when presented with different object sizes. The opposite effect is demonstrated with the red 1.4:1 tool however, where a scaling function of 0.98 is seen in the final block. This suggests that participants are altering their end-effector aperture more based on object size with this tool compared to the 1:1 tool or the hand. These findings do not necessarily contradict the concept of end-effector programming however. The fact that the effects are in the opposite direction to one another is consistent with participants attempting to control the end-effectors in the same manner but having internal tool models that are biased towards the hand, leading to an under-opening of the yellow tool and an over-opening of the red one.

3.3.4 Peak end-effector aperture

Figure 3.6 plots (a) peak end-effector apertures and (b) peak hand apertures produced when grasping each object with the tools and the hand. It can be seen by looking at Figure 3.6a that individuals increased their peak end-effector aperture as the object size increased with the hand and the three tools (as suggested by the scaling data presented above). It also shows that the yellow and red tools' end-effectors were neither being controlled in exactly the same manner as the blue tool nor were the same hand apertures being produced regardless of tool used.

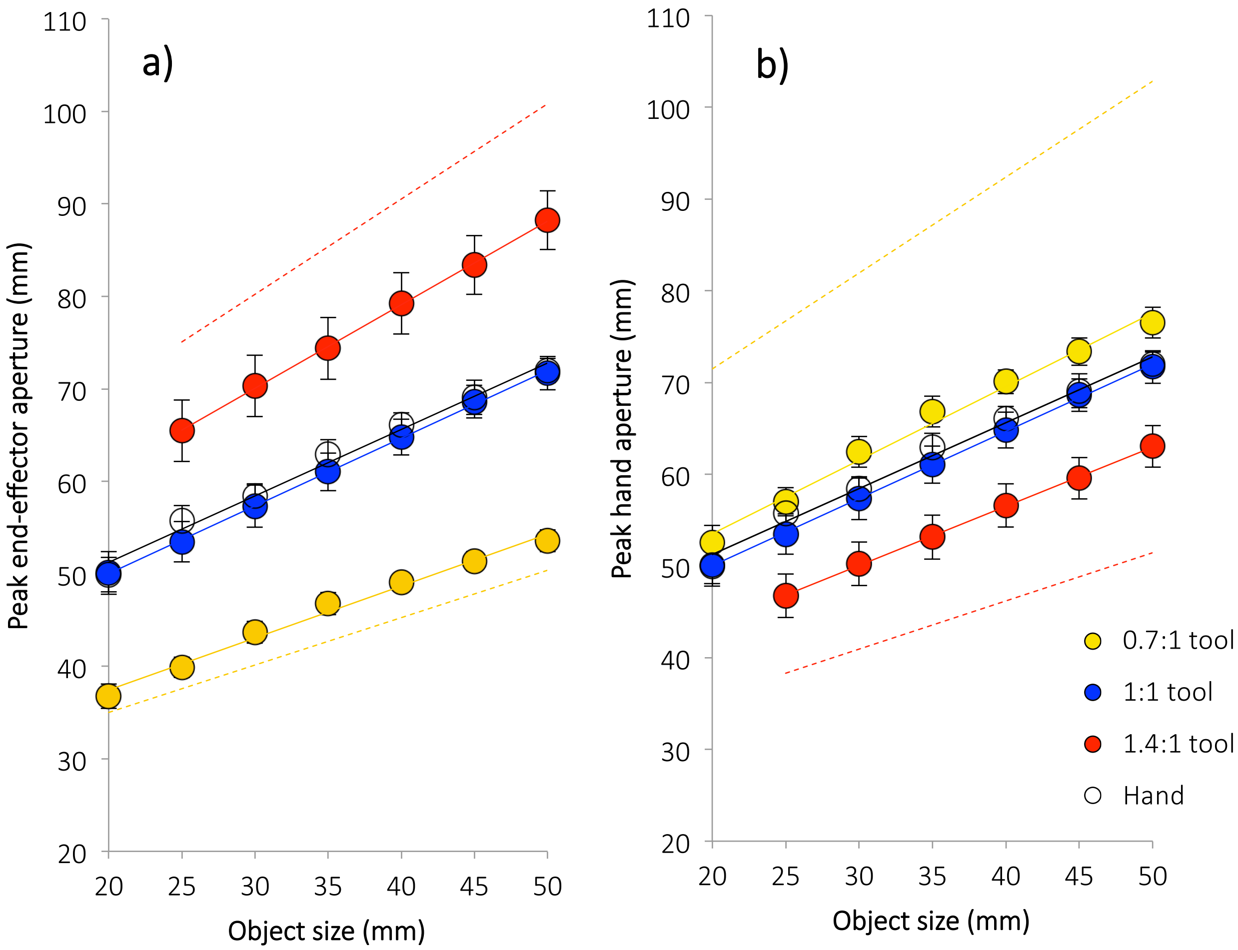


Figure 3.6. Aperture data, as a function of object size, collapsed across distance. (a) In end-effector units. The dashed lines show the predictions for the 0.7:1 (yellow) and 1.4:1 (red) tools if there was no compensation for the effect of tool geometry. See main text for how this was calculated. (b) The same data plotted in hand aperture units. Here the dashed lines show the prediction for perfect compensation for tool geometry (again, see text for details). Error bars show +/-1 SEM. Linear regression lines have been fitted through the data. N=12.

A 4 x 6 x 3 (grasp type x size x distance) repeated measures ANOVA revealed a main effect of object size ($F(1.49,16.34)=400.97$, Greenhouse Geisser corrected, $p<.001$). The fact that we have found scaling of both peak end-effector aperture with object size and peak velocity with object distance using the tools supports the concept that an internal model of the tool, based on the forward model used in normal grasping, is being utilised during tool use, as these features are found in normal grasping movements with the hand (Jeannerod, 1981; 1984; 1997; Smeets & Brenner, 1999, Wing et al., 1986).

Earlier it was discussed that one possible pattern of results was that performance with the blue tool and the hand might be very similar, whereas the red and yellow tools might differ. This was posited because the blue tool does not alter the 'gain' between the hand opening and the tool-tip opening in the way that the other two tools do. Because of this if the brain was trying to control the end-effectors in the same manner we might still see differences with the other two tools as the added complexity of these tools could lead to biased internal models towards the hand or a consistent adjustment in peak end-effector apertures to build in a margin-for-error. Figure 3.6a shows that the peak end-effector apertures produced with the hand were very similar to those produced with the blue 1:1 tool. This suggests that simply using a tool does not necessarily alter peak end-effector apertures (c.f. Bongers, 2010; Gentilucci et al., 2004; Zheng & Mackenzie, 2007). However, the peak end-effector apertures produced with the red and yellow tools are very different to those produced with the blue one. To investigate this further we can look at the results of the previous ANOVA. There was a main effect of grasp type on peak end-effector aperture ($F(1.30,14.24)=72.71$, Greenhouse Geisser corrected, $p<.001$). Planned contrasts show that there was no significant difference between the peak end-effector apertures produced with the hand and the 1:1 tool ($F(1,11)=0.34$, $p=.573$). However there was a significant difference between the peak end-effector apertures produced with the yellow tool ($F(1,11)=129.85$, $p<.001$) and the red tool ($F(1,11)=83.67$, $p<.001$) when compared to the blue tool. This is confirmed by Figure 3.6a as it can clearly be seen that participants opened the tool tips much more when grasping an object with the red 1.4:1 tool and much less when using the yellow 0.7:1 tool when compared to the blue 1:1 tool.

By running a second ANOVA on the peak hand aperture data we can investigate whether participants significantly altered their hand apertures when using the three tools. A 4 x 6 x 3 (grasp type x size x distance) repeated measures ANOVA revealed a marginally significant main effect of tool type ($F(1.31,14.45)=4.16$, Greenhouse Geisser corrected, $p=.051$). Using planned contrasts it can be seen that participants produced significantly smaller peak hand apertures with the red tool than they did with the blue one ($F(1,11)=6.50$, $p=.027$). However, although hand apertures were consistently larger with the yellow tool compare to the blue tool, there was no statistically significant difference ($F(1,11)=2.47$, $p=.145$).

Thinking about these findings in terms of end-effector control we can think about the concepts of perfect and zero compensation for tool ratio discussed previously. For perfect compensation, we would expect to see peak *end-effector* apertures produced with the three tools that were not significantly different to one another. For zero compensation, we would expect to see peak *hand* apertures produced with the three tools that were not significantly different to one another. For the red 1.4:1 tool it is clear that something in between these two extremes has occurred with both peak end-effector apertures and peak hand apertures being significantly different to those produced with the blue 1:1 tool. However, with the yellow 0.7:1 tool we saw no significant difference between the hand apertures produced compared to the blue tool. This suggests that participants were opening their hand the same amount regardless of whether they were using the blue or yellow tool.

Figure 3.7 plots (a) peak end-effector apertures and (b) peak hand apertures at each object distance (collapsed across object size). Usually in reaching and grasping experiments with the hand, peak grip aperture varies with changes in object size and object distance has little effect (Jeannerod, 1984; Kudoh, Hattori, Numata & Maruyama, 1997). In our data, when grasping with the hand, object distance also had no effect on peak end-effector aperture. However, it can be seen in Figure 3.7a that increasing object distance lead to increased peak end-effector apertures with all three of our tools.

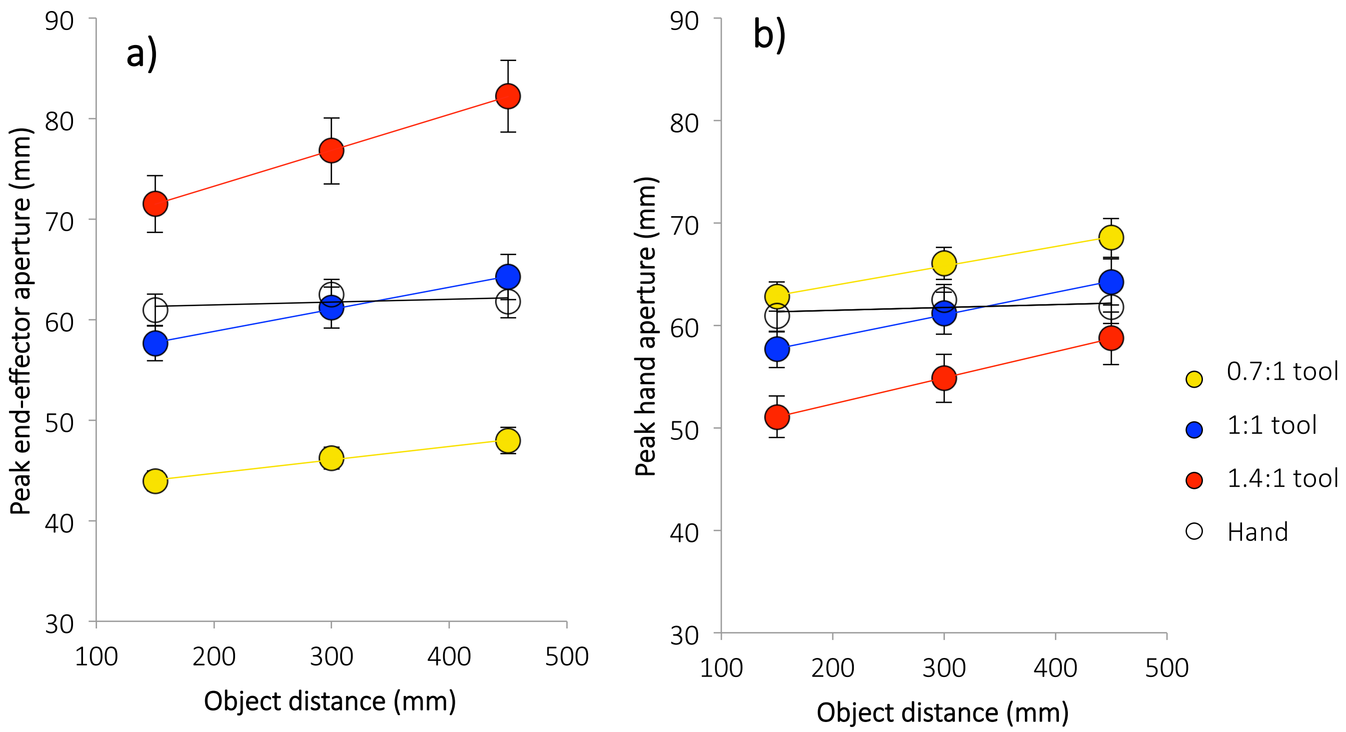


Figure 3.7. Aperture data as a function of object distance, collapsed across size. (a) Plotted in end-effector units (b) The same data plotted in hand aperture units. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=12.

Looking at the ANOVA that we ran previously on peak end-effector apertures it can be seen that there was a main effect of distance ($F(1,11)=63.42$, $p<.001$), suggesting that object distance had a significant effect on the peak end-effector aperture. There was a significant grasp type x distance interaction ($F(3.35,36.81)=585.49$, Greenhouse Geisser corrected, $p<.001$), suggesting that the peak end-effector apertures formed are affected by distance differently. Looking at Figure 3.7 it can be seen that this interaction is caused by the fact that peak end-effector apertures produced with the hand do not vary with object distance, whereas those produced with the three tools do.

The fact that this effect is present in our tools and not the hand could be due to an increase in motor noise or uncertainty at further distances when using the tool that is not present when using the hand. This could be the case because participants may be relying more on visual feedback when using the tools than when using their hand or due to the amplification of end-effector noise when using the tools. Proprioceptive information may be poorer when using the tools than with the hand so it is possible that visual information could play more of a role in grasping with a tool (van Beers, Wolpert & Haggard, 2002). When picking up an object at a farther distance this information will not be as precise and so uncertainty about the movement could increase. If this were the case then increasing peak end-effector aperture could be one method to compensate for this uncertainty, as it would reduce the chance of colliding with the object.

3.3.5 Compensation factors

As discussed, peak end-effector apertures that are different from both the perfect and zero compensation predictions indicate some level of compensation for tool ratio. To investigate this in more detail, throughout the thesis we will carry out an analysis called a compensation factor. This measures how well a participant has compensated for the ratio of the yellow 0.7:1 tool or the red 1.4:1 tool. This is calculated using this formula (shown here calculating for the red 1.4:1 tool, where HA means hand aperture): The numerator gives a measure of how similar the observed hand apertures are for the

$$\frac{(\text{(Observed HA for 1.4:1 tool - Observed HA for 1:1 tool) / Observed HA for 1:1 tool})}{(1-1.4)/1.4}$$

1.4:1 tool and the 1:1 tool. The denominator then normalises this value so that the 0.7:1 and 1.4:1 tools are directly comparable. Without this compensation factors for one tool would always be negative and factors for the other tool would always be positive and this would make comprehension more difficult. We compare performance to the hand apertures produced with the blue 1:1 tool rather than the hand alone as this should account for any generic effects caused by using our type of tool and will stop these from being included in the factor.

If the resulting compensation factor is equal to 1 then the participant has fully compensated for the tool ratio, meaning that they opened the tool tips the same amount regardless of what tool they are using. If the compensation factor is equal to 0 however, the participant failed to compensate for the tool ratio at all, this means that they are doing the same thing with their hand regardless of the tool that they are using. These factors can be calculated for individuals or as an average compensation factor of all participants. They can also be calculated over the different blocks of an experiment so that it can be seen whether compensation improved or remained constant.

The average compensation factors for the red 1.4:1 and yellow 0.7:1 tools in this experiment can be seen in Figure 3.8. These factors confirm that some compensation was shown for the tool ratio with both the red and the yellow tools, but compensation was not perfect. It also confirms that participants compensated more for the tool ratio when using the red tool than they did when using the yellow one.

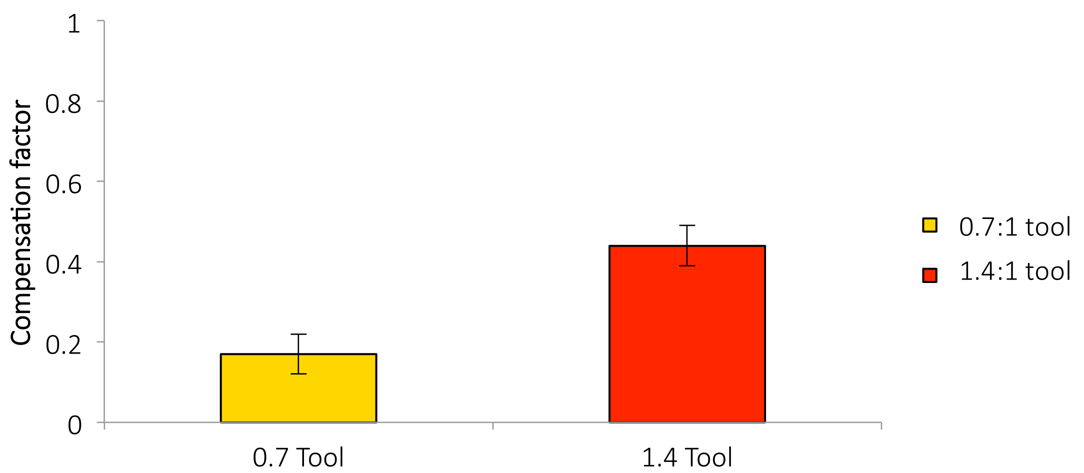


Figure 3.8. Average compensation factors for the yellow 0.7:1 tool and the red 1.4:1 tool. Error bars show +/-1 SEM. N=12.

It should be noted that these compensation factors are a hypothetical concept based on our model that the brain is trying to control the tool tips in the same manner, quantitatively, as the finger and thumb. Even if the brain is encoding movements in end-effector units we would still be unlikely to see a factor of 1 because of noise in the system. Using a tool adds motor noise to the movement. If the brain understands this then the model is likely to be biased towards the hand as the sensitivity to the noisy internal model could cause a drift back to the default or typical mapping of 1:1. Because of this, even if our model were correct it is unlikely that we would ever see perfect compensation. However, by calculating these compensation factors we can use them as a benchmark for performance throughout the thesis and see how different manipulations might affect the degree of compensation for the tool ratio.

Figure 3.9 shows the average compensation values for each participant. While there was considerable variability in individual compensation, the overall asymmetry between the two tools was present in every participant except one (WW, who showed equal levels of compensation for the two tools). It can also be seen that five participants showed essentially no compensation at all for the yellow 0.7:1 tool.

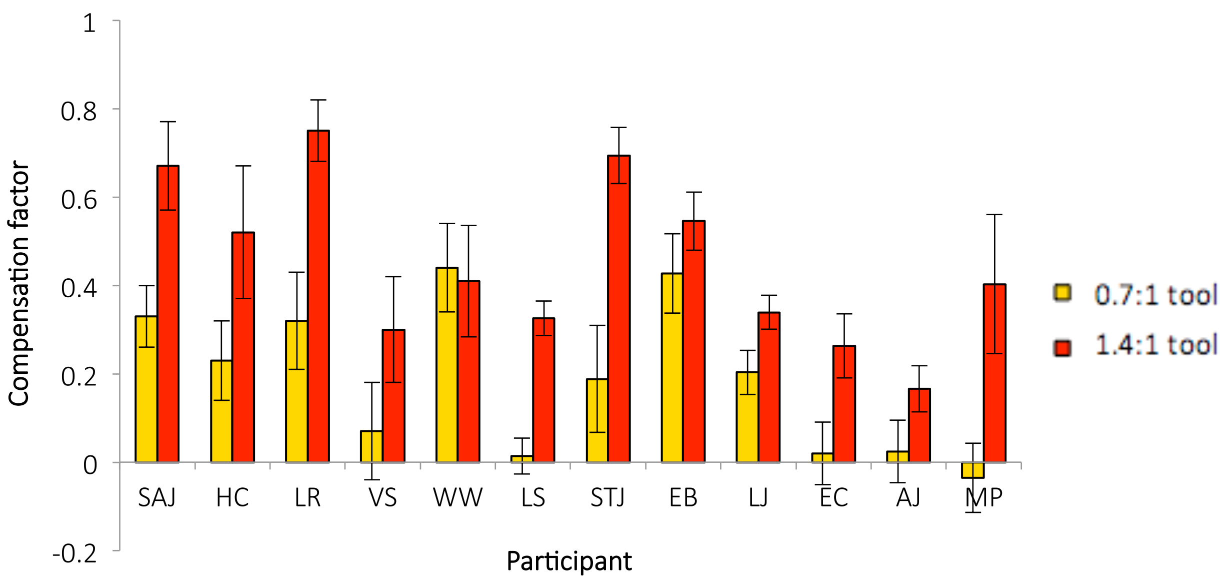


Figure 3.9. A bar graph showing the individual participant's compensation factors for the 0.7:1 yellow tool and the 1.4:1 red tool in this experiment. Error bars show+/-1 SD.

Figure 3.10 shows the compensation factors for the red and yellow tools broken down by the three blocks of the experiment. We looked at the data this way to examine whether the low levels of compensation for the yellow tool could simply be a result of lack of sufficient experience with the tool. It is arguably a less common transformation of tool than the red one and as Itaguchi and Fukuzawa (2014) demonstrated, familiarity can have an impact on the degree of precision with which one can use a tool. Assuming participants will develop their internal tool models throughout the experiment, if participants were still developing this internal model when our experiment ended, we would see an upward trend in compensation values across all three blocks. Figure 3.10 shows that compensation for the red tool changed very little over the course of the experiment. However, the compensation factor for the yellow tool did change slightly, increasing as the experiment went on.

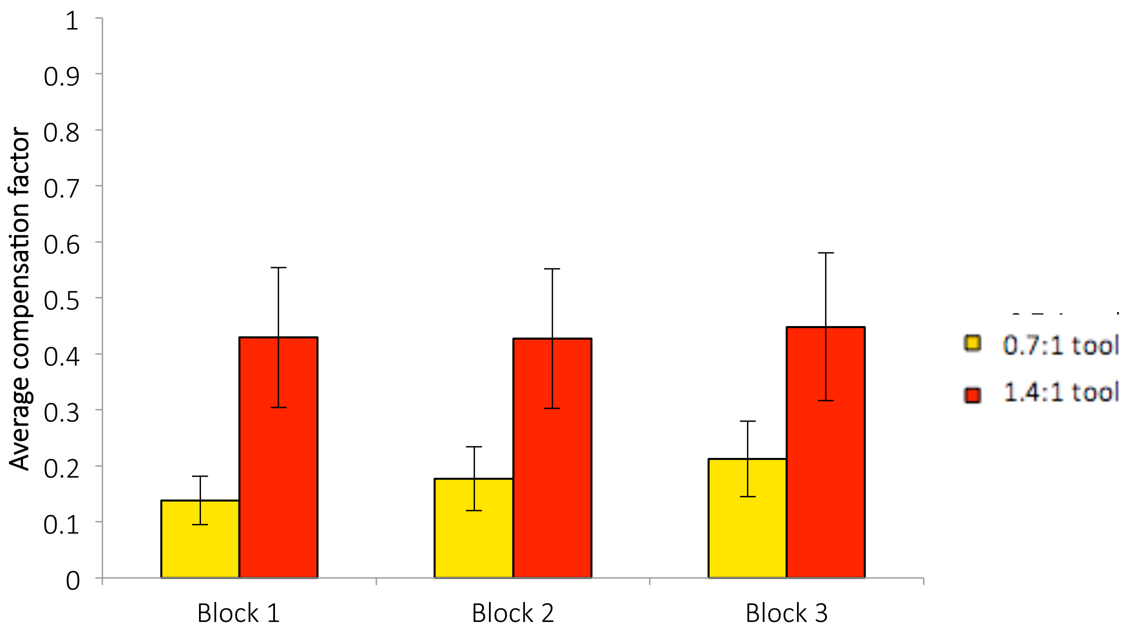


Figure 3.10. The change in compensation factor over the three blocks of the experiment for both the 1.4:1 red and the 0.7:1 yellow tool. Error bars show +/- 1 SEM. N=12.

A 2 x 3 (tool x block) repeated measures ANOVA showed this increase was not significant ($F(1.34,14.78)=2.62$, Greenhouse-Geisser corrected; $p=.120$). Thus, our data do not provide support for the idea that with more time the internal models of the tools would be further refined. As said, at the beginning of the experiment participants had no experience of using the tools so we expected compensation might be rather low initially, and increase throughout the experiment as they learned. One possibility for why we do not see this pattern here is that the learning took place too quickly for a block-by-block analysis to capture it. But this cannot explain the relatively low compensation values eventually achieved. It is also possible that, as the experiment was conducted over different days, participants learnt an internal model of the tools within a block, but forgot it before the start of the next block, resulting in similar data for each session.

3.3.6 Time to peak end-effector aperture

Figure 3.11 plots the time taken to reach the peak end-effector aperture, (a) as a function of distance, collapsed across size and (b) as a function of size, collapsed across distance. With the hand and the three tools the time taken to reach the peak end-effector aperture grew as the objects were placed at farther distances from the participant. It also shows that for this index there may be a difference between the hand and the 1:1 tool. Participants appear to take slightly longer to reach the peak end-effector aperture with the hand than they do with the 1:1 tool. There also seems to be a difference between the three tools with participants reaching the peak end-effector aperture with the red 1.4:1 tool the fastest and the yellow 0.7:1 the slowest. Finally, object size seems to have more of an effect on the tools than it does on the hand with this index. This effect is most pronounced for the yellow tool, which appears to be affected as the object size increases.

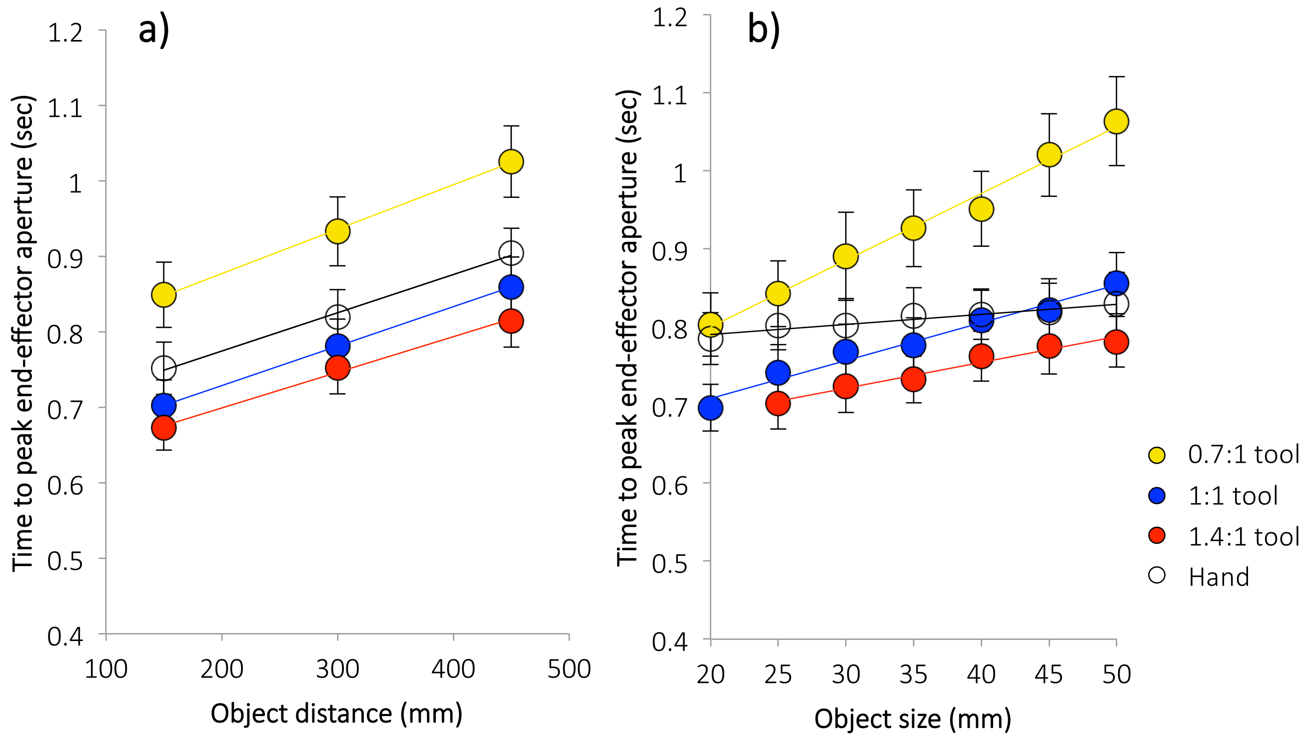


Figure 3.11. Time taken to reach the peak end-effector aperture in seconds. (a) As a function of object size, collapsed across distance. (b) The same data as a function of object distance, collapsed across size. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=12.

A 4 x 6 x 3 (grasp type x object size x object distance) repeated measures ANOVA revealed a main effect of distance ($F(2,22)=330.58$, $p<.001$). The ANOVA also showed a main effect of grasp type ($F(1.47,16.19)=18.80$, Greenhouse Geisser corrected, $p<.001$). Overall, it can be seen by looking at Figure 3.11a that people took longer to form their peak end-effector aperture when using the 0.7:1 yellow tool than they did with the other tools or the hand. Planned comparisons show that the difference between the time taken to reach the peak end-effector aperture with the yellow tool ($F(1,11)=84.52$, $p<.001$) and the red tool ($F(1,11)=40.77$, $p<.001$) were both significantly different to the blue tool, whereas the hand was not ($F(1,11)=0.76$, $p=.401$). Using a tool did not therefore cause a difference in the time taken to form the peak end-effector aperture. However, tools that had a more complex ratio than our standard 1:1 tool did have a later peak effector-aperture. It can be seen by looking at Figure 3.11b that the difference between the yellow and blue tools is much larger when grasping a larger object. This suggests that for larger objects it took people much longer to reach their peak end-effector aperture when using the yellow 0.7:1 tool than it did with the blue 1:1 tool.

Figure 3.11b shows that the time taken to reach the peak end-effector aperture for different object sizes was relatively constant for the hand, but increased as object size increased when using the tools. The increase was small for the blue and red tools, however for the yellow tool time to peak end-effector aperture increased more as object size increased. The ANOVA showed a significant main effect for object size ($F(5,55)=67.28$, $p<.001$), with time to peak end-effector aperture increasing as object size did. There was also a significant grasp type x object size interaction ($F(5.08,55.85)=13.56$, Greenhouse Geisser corrected, $p<.001$). Looking at Figure 3.11b it can be seen that object size seems to have little effect when grasping with the hand, however time to peak end-effector aperture seems to increase with object size when using the tools. It can also be seen that this effect seems to be more pronounced with the yellow tool than with either of the other tools. The mechanics of the yellow tool meant that opening the tool tips a set amount required a larger hand movement than the other two tools (the smallest one was required for the red tool). Because of this, some variation in time to peak end-effector aperture might be expected across the tools. Because of the tools' geometries it may be that participants would reach the peak end-effector aperture fastest with the red tool and slowest with the yellow tool simply because of how much they have to move their hand. However, the difference between the time to peak end-effector aperture with the yellow and blue tools is much larger than that with the red and blue tools. This suggests that something more is going on with the yellow tool because the tool ratios are the reverse of one another so it would be expected that the effects would be equal in opposite directions.

In Gentilucci et al.'s (2004) experiment, participants reached the peak end-effector aperture significantly faster when using a tool than when using the hand. We found no differences between the hand and the 1:1 tool. However, we did find that changes in the tool's ratio had an effect, as our other tools were significantly different to the blue one. This could suggest that rather than tool use *per se* being responsible for the faster time to peak effector aperture in Gentilucci et al.'s (2004) experiment, instead it may have been something about the specific tool that they used that caused the effect. The fact that it was so heavily spring-loaded may have meant that participants just squeezed it hard to open it and this could lead to shorter times to peak end-effector aperture.

3.3.7 Overall movement time

Another index that can be looked at in a reaching and grasping movement is the amount of time the participant took to lift the object, also known as overall movement time. In our experiment, this was the time from the lifting of the start button to lifting the object. This is an interesting index to look at because if a participant is uncertain about a movement then it is logical that they may take longer to lift the object up. Figure 3.12 plots the average overall movement times. Figure 3.12 shows that movement times were shorter with the hand than they were with the tools, replicating the findings of Gentilucci et al. (2004). It can also be seen in Figure 3.12a that object distance affected this index for both the hand and the three tools. Figure 3.12b shows that whilst the time taken to pick the object up did not increase as object size increased when using the hand, it did increase when using the tools.

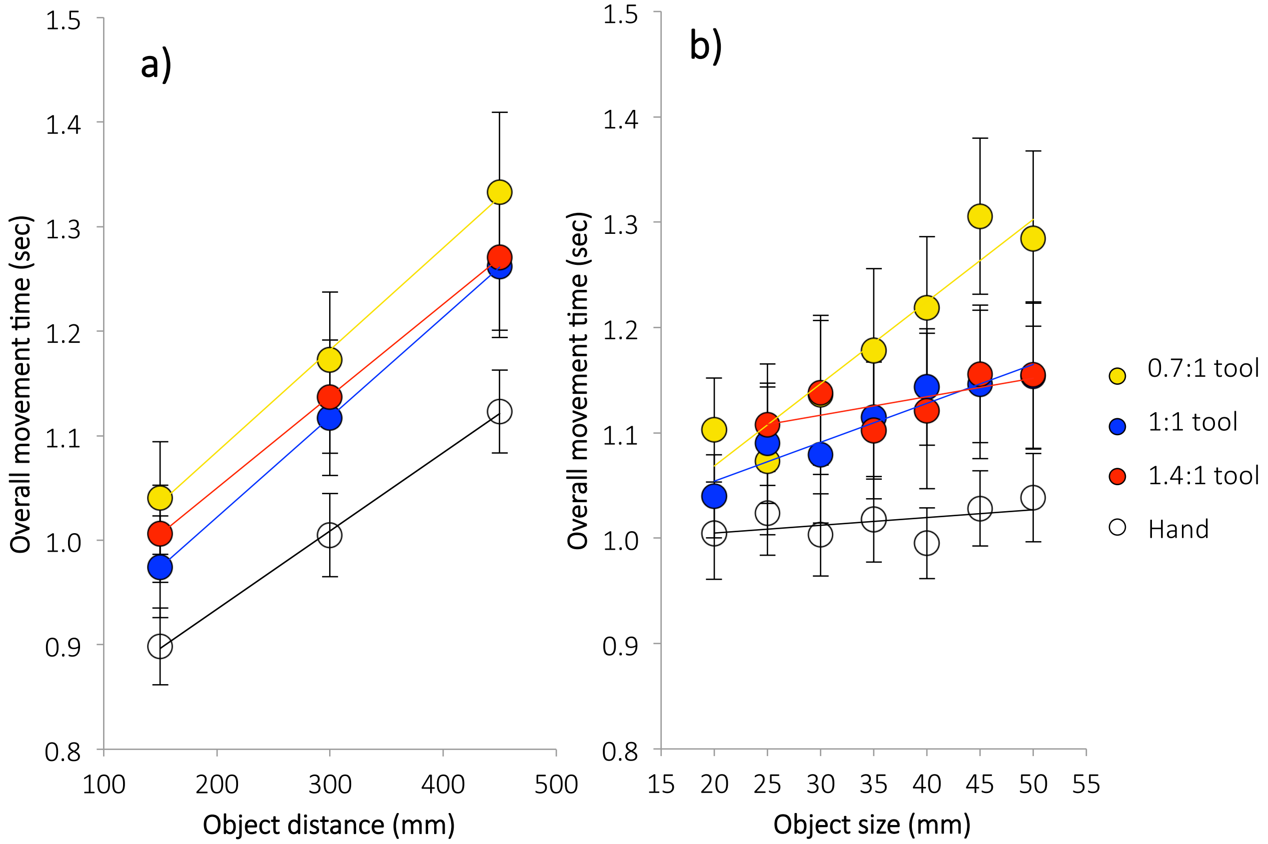


Figure 3.12. Data showing the overall movement time in seconds. (a) Average time to object lifted as a function of object distance, collapsed across size. (b) The same data as a function of object size, collapsed across distance. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=12.

A 4 x 6 x 3 (grasp type x object size x object distance) repeated measures ANOVA revealed a main effect of grasp type (F(1.30,14,28)=5.55, Greenhouse Geisser corrected, p=.026). Planned contrasts showed that there was no significant difference when using the blue tool and the hand (F(1,11)=3.78, p=.078) or when using the blue and red tool (F(1,11)=0.26, p=.623). Participants did however take significantly longer to lift the object when using the yellow tool than they did when using the blue one (F(1,11)=7.22, p=.021) (see Figure 3.12). There was also a significant main effect of object size (F(5,55)=24.29, p<.001). Figure 3.12b shows that increases in object size seem to have a larger effect when using the yellow tool than when using the blue or the red one. This is supported by the significant grasp type x object size interaction (F(5.10,56.11)=6.10, Greenhouse Geisser corrected, p<.001). As mentioned before, the largest object in this experiment was at the limit of some participant's hand opening when using the yellow tool. This could explain why participants took longer to lift the larger objects with the yellow tool, as they may have struggled to pick them up. As one would expect, there was also a main effect of object distance, meaning that movement time significantly increased as the object was placed further away from the participant ($F(1.34,14.76)=178.67$, Greenhouse Geisser corrected, $p<.001$).

3.3.8 Time in the slow phase

Overall movement time, in conjunction with time to object lifted can be used to calculate another measure – the time in the slow phase (see section 2.6.5 for further information on this measure).

Figure 3.13 plots the average time in the slow phase (a) as a function of distance collapsed across size and (b) as a function of size collapsed across distance. It can be seen that participants spent more time in the slow phase when using the three tools than they did when using the hand. This could be suggestive of the fact that more time is needed in the precise phase of the movement when using the tools. This could be due to needing to utilise visual feedback because of an uncertain or flawed internal tool model.

It also looks like time in the slow phase increased slightly overall with increased object size, this effect is most pronounced for the yellow tool. Finally, time in the slow phase increased with object distance with the hand and the three tools.

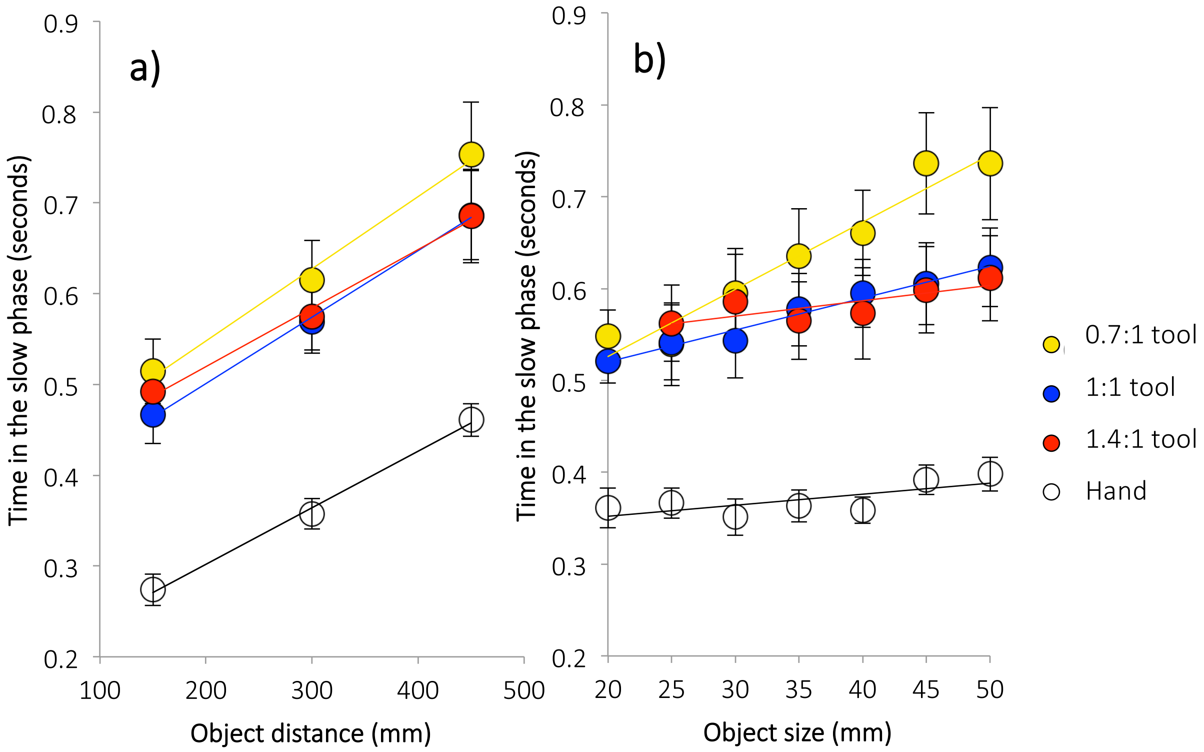


Figure 3.13. Data showing the time spent in the slow phase in seconds. (a) Average time in the slow phase as a function of object distance, collapsed across size. (b) The same data as a function of object size, collapsed across distance. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=12.

A 4 x 6 x 3 (grasp type x object size x object distance) repeated measures ANOVA revealed a main effect of grasp type ($F(1.58,16.70)=30.70$, Greenhouse Geisser corrected, $p<.001$). Planned comparisons show that there was a significant difference between the hand and the blue tool, with participants spending significantly less time in the slow phase with the hand ($F(1,11)=39.98$, $p<.001$). Participants also spent significantly longer in the slow phase with the yellow tool than with the blue one ($F(1,11)=5.91$, $p=.033$) but there was no difference between the red and the blue tools ($F(1,11)=3.14$, $p=.104$). This supports the idea that when using the yellow tool more time was needed in the precise end part of the movement. This was the case with all three of the tools, but even more so for the yellow one. There was also a main effect of object distance ($F(1.29,14.28)=93.97$, Greenhouse Geisser corrected, $p<.001$)

confirming that time in the slow phase increased as the object was placed farther away, possibly due to an increase in visual uncertainty at greater distances. Finally there was also a main effect of object size ($F(5,55)=24.76$, $p<.001$), where time in the slow phase increased with object size. This was accompanied by a significant grasp type x object size interaction ($F(5.13,56.38)=6.37$, Greenhouse Geisser corrected, $p<.001$) likely driven by the fact that the yellow tool seems to be more affected by object size than the other tools or the hand (see Figure 3.13b).

3.3.9 Average grasp profiles

We also created average grasp profiles for the hand and the three tools, to look at the movement as a whole rather than focusing only on somewhat arbitrary kinematic indices. As said previously, there is a danger with only looking at single indices and using these to make a judgement about entire movements. It could be that an index is the same across two conditions but only because a second index has changed. For example, you may see no change in peak end-effector aperture, but a large difference in peak velocity. By only looking at one index effects like this can be missed. Likewise, by collapsing a complex movement down to single values you risk not being able to see the overall picture. Figure 3.14 plots the average grasp profiles for (a) the hand and the blue 1:1 tool and (b) the three tools. These profiles were created using the data for the 35 mm object, at the 300 mm distance. We chose to use one size and one distance because the change in object size and distance affected the movements in different ways, so this allowed us to look at the profiles without the addition of this extra variability.

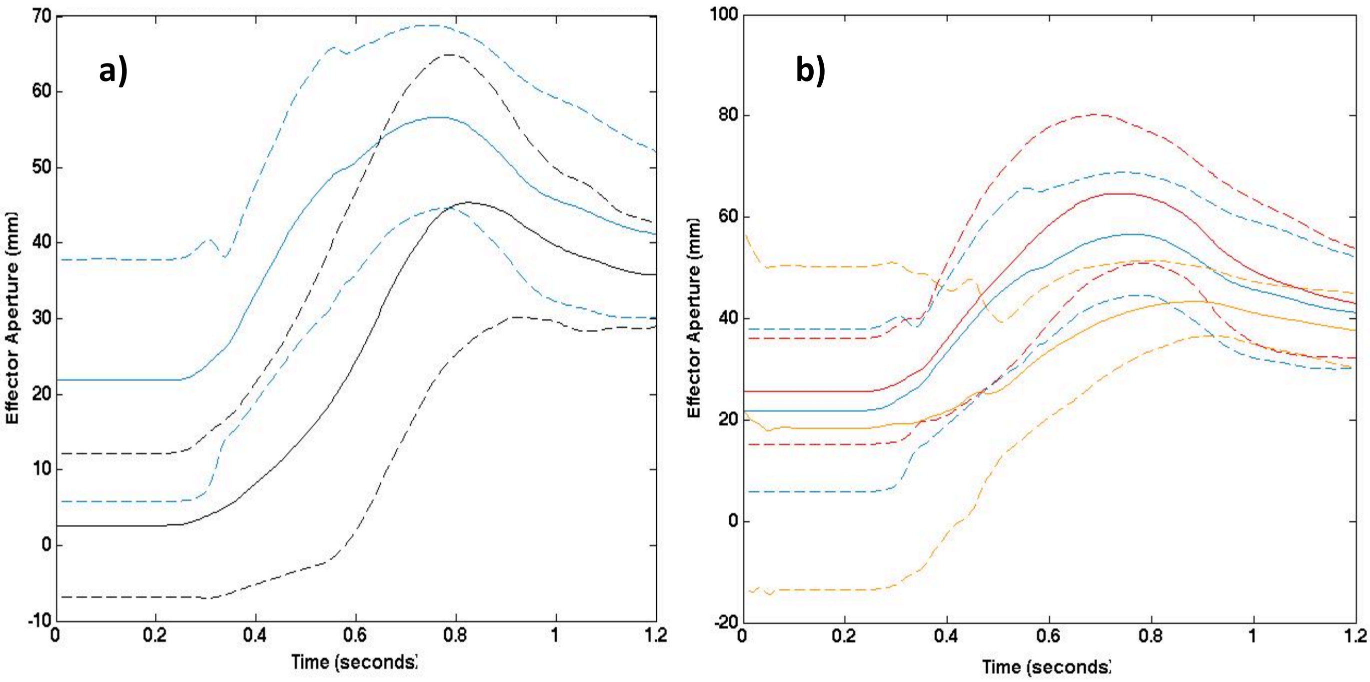


Figure 3.14. The average end-effector aperture profiles when grasping a 35 mm object placed 300 mm from the participant. (a) Average profiles for the blue 1:1 tool and the hand. (b) Average profiles for the blue tool, the red 1.4:1 tool and the yellow 0.7:1 tool. The lines are coloured according to tool colour, with hand data in black. Solid lines represent actual data and dotted lines show +/-1 SD. N=12.
Data in this plot has not been corrected for marker offset.

The movements made by all of the participants were averaged and plotted on a graph to show a typical movement when grasping an object. This was achieved by averaging the data for all participants at each frame of the movement to give one value for each time point that could then be plotted. Figure 3.14a shows the average grasp profiles for the hand and the blue 1:1 tool. It can be seen that the blue 1:1 tool and the hand look similar to one another. However, some interesting differences can be noted. For example, when grasping with the blue tool there is more of a plateau after reaching the peak end-effector aperture than there is when grasping with the hand. That is, when grasping with the hand the grasp profile is much narrower around the peak end-effector aperture than it is with the blue tool. Figure 3.14b plots the grasp profiles for the three tools and when looking at the curve around the peak end-effector apertures for the yellow and red tools, the same plateau can be seen, with the curves looking flatter and wider than when grasping with the hand. This suggests that there could be something different about how the peak end-effector aperture is formed when grasping with a pair of tongs than when grasping with the hand. Even though the blue tool and the hand look similar in terms of individual kinematic indices, globally the movements are different. When using the blue tool participants seem to open and close the tool tips less abruptly than they did with the finger and thumb when using the hand. Looking at previous research the same plateau has been observed with tool grasping by Gentilucci et al. (2004), Itaguchi and Fukuzawa (2014) and Bongers (2010). Gentilucci et al. (2004) suggest that this plateau is present in tool grasping as there a lack of kinaesthetic information when using the tool that means that visual information must be relied upon more. This means that when opening the tool, the participant would have to visually judge when the aperture was correct rather than using proprioception and this may account for the plateau seen during tool use. If the brain had an accurate internal model of the tool this would presumably not be the case, because the brain could transform 'proximal' proprioceptive signals into appropriate tool apertures in the world. However, uncertainty about the tool model (or a lack of a useful model at all) could lead to a plateau in peak end-effector aperture. If the internal model is wrong then recalculations would have to be made mid-movement and including a plateau in the movement provides a chance to recalibrate online. Whether this is the reason behind our results cannot be said, as our experiment was not set up to test this. Our data nonetheless add to the existing evidence that the formation of the peak end-effector aperture is different when using a tool compared to the hand.

It can also be seen in Figure 3.14a that the peak end-effector aperture for the hand is smaller than that of the blue 1:1 tool, although overall, we saw no statistically significant differences between the peak end-effector apertures with the blue tool and the hand in this experiment. We likely see a difference here because there was a significant interaction in how the change in object distance affected peak end-effector aperture when using the blue tool compared to the hand. This was because object distance had no effect on peak end-effector aperture when using the hand to grasp, but when grasping with the blue tool participants produced larger peak end-effector apertures as the object distance increased. This means that by looking at single distances rather than the data overall, we can see some differences in the peak end-effector apertures produced with the blue tool and the hand. It can also be seen that the error bars on the graphs do overlap quite considerably, so this may also be the reason that we see no statistical difference here despite the traces themselves looking different to one another.

As mentioned previously, it is wise not to look at these indices in isolation of one another. Peak end-effector aperture should be looked at in tandem with peak velocity as these two indices will often trade off with one another – a slower peak velocity might allow for a more precise end-effector aperture, so smaller apertures may be seen. In this experiment, we were unable to produce average velocity profiles. This is because the wrist marker was attached over the pisiform bone (on the outside of the wrist) and at some points the marker moved outside of the field of view of our cameras and disappeared from some frames. This only occurred in trials that used the tools, as the wrist was that much further away from the table because of the offset introduced by the tool. This did not affect our ability to judge the peak velocity of the movement as on the rare occasion where the marker disappeared near the peak then these trials were removed from the analysis. Because of this we are unable to present average velocity traces, as they are noisy and hard to draw conclusions from. In later experiments the wrist marker was attached over the radius bone on the inside of the right wrist to prevent this problem.

3.4 Discussion

3.4.1 Background

In this chapter, we aimed to use kinematic analysis to investigate the concepts of internal tool models and encoding movements in end-effector units. We used multiple tools as previous experiments compared movements with the hand to those of one tool and some concluded that the differences were caused by tool use *per se*. However, as tools come in a wide variety of different types there are unlikely to be any overall tool effects that apply to every type of tool. We used a simple 1:1 tool that had motor equivalence with the hand (Arbib et al., 2009) and maintained the ratio between the hand and the world so that we could compare its movements to that of the hand. We could also then compare them to movements made with more complex tools that altered the ratio between the hand and the end-effector to try and probe our question further.

3.4.2 Comparing performance with the hand and the 1:1 tool

Contrary to some previous experiments (Bongers, 2010; Gentilucci et al., 2004; Zheng and Mackenzie, 2007) Experiment 1 showed that using a tool *per se* does not change the kinematics related to peak end-effector aperture in a reaching and grasping movement. Previous experiments have found that peak end-effector apertures are larger when using a tool than they are with the hand (Gentilucci et al., 2004; Zheng & Mackenzie, 2007) and that they occur earlier in the movement (Gentilucci et al., 2004). Contrary to this, we found in this experiment that there was no significant difference between the peak end-effector aperture or the time taken to reach it with the 1:1 blue tool and the hand. With participants displaying almost identical peak end-effector apertures and similar scaling functions overall. Our findings with the blue 1:1 tool suggest that the brain could be encoding movements in end-effector units and attempting to control the end-effectors the same regardless of the tool used. This would support the work that was discussed earlier by Umiltà et al. (2008) that found that there are neurons in the ventral premotor cortex that code for the opening and closing of the end-effector when grasping an object. However, it must also be considered that if the system knew nothing about the blue tool a similar pattern of results would have been found if participants had simply fallen back on normal hand grasping behaviour. Because of this, this conclusion cannot be made using data from the blue tool alone.

As discussed previously, past research may have found differences where we did not due to their tools being more complex than ours. If this is the case, then the brain may add a margin-for-error into the movements because it knows that the internal tool model is flawed. This could result in consistently larger peak end-effector apertures. Something else to consider is that the force required to open the tool in Gentilucci et al.'s (2004) study also differed depending on the tool aperture. It could certainly be argued that as different forces were needed at different apertures this added to uncertainty about the movement when using this tool. One way of dealing with uncertainty would also be to build in a margin-for-error by increasing peak end-effector apertures when using the tool (Keefe, 2010; Keefe et al., 2011; Schlicht & Schrater, 2007; Sivak & Mackenzie, 1990; Wing et al., 1986). This could also explain why peak end-effector apertures were seen earlier with the tool in Gentilucci et al.'s (2004) experiment as participants may simply have adopted a method of squeezing the tool quite hard in order to open it, meaning that it is hard to compare it directly to the hand.

We also found no significant difference in the peak velocity reached with the blue 1:1 tool and the hand; this supports some previous research (Gentilucci et al., 2004). However, other experiments have found that participants had higher peak velocities with the hand than they did with the tool (Zheng & Mackenzie, 2007). The fact that we found no differences also suggests that the brain may be using a common motor representation for the hand and the blue tool. Zheng and Mackenzie (2007) may have found differences in peak velocity due to their participants having an uncertain model of the tool and requiring online visual feedback to successfully complete the task.

There were differences between the hand and the blue 1:1 tool in the time taken to reach the peak velocity. We found that participants reached this point faster with the tool than they did with the hand. This is the opposite of what Zheng and Mackenzie (2007) found. We also found that participants had longer overall movement times when using the blue tool than they did with the hand and spent significantly longer in the slow phase of the movement as well (this was also found by Bongers (2010) and Gentilucci et al. (2004)). Each of these findings could suggest that the parts of the movement that require more precise control are harder to complete using a tool. Again, this does fit in with the idea of adjusting for a flawed internal model, by performing the final precise parts of the movement more slowly so that visual feedback can be utilised to adjust the movement accordingly. So, whilst the peak velocity reached is the same with the tools and the hand, participants needed to slow down much more as they reached the object to be able to grasp it successfully when using a tool.

Finally, we found that there was a broader peak around the peak end-effector aperture when grasping with a tool that is not present when using the hand, similar to that seen in previous research (Bongers, 2010; Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014). Gentilucci et al. (2004) suggested that this plateau could have been caused by a lack of kinaesthetic feedback when using the tool. By relying more on visual feedback, the closing of the tool happens later than it would do with the hand where proprioception is available. Bongers (2010) suggested that the plateau showed that opening and closing the hand during tool use are decoupled. When grasping with the hand the opening and closing of the finger and thumb are one smooth process. However, when grasping with a tool this plateau suggests that they might be two separate phases. This could theoretically be to allow time for online corrections between the opening and closing phases of the movement. Finally, Itaguchi and Fukuzawa suggest that the plateau is modulated by familiarity of the tool. This makes sense when using a tool that you do not have a precise internal model of, by opening the tool sooner and holding the peak end-effector aperture for longer you would be less likely to collide with the object, particularly when this is coupled with spending more time in the slow phase as was seen in Experiment 1.

3.4.3 Comparing performance across different tools

We chose to use three tools in our experiments instead of just one. By using three different tools, one of which preserved the ratio of the hand, we were able to probe the concept of internal tool models in a quantitative way. By being able to compare hand grasping data to data using our simplest tool and then comparing this tool to other more complex tools we hoped to probe further than other experiments had been able to in the past.

When comparing the kinematics of the three tools it can be seen that the peak end-effector apertures for the yellow 0.7:1 tool and the red 1.4:1 tool were both significantly different from the blue 1:1 tool in Experiment 1. The fact that the peak end-effector apertures were different shows that participants were not able to perfectly compensate for the tools' ratios. However, the fact that there was also a significant difference in peak hand apertures for the red and blue tools shows that our ‘zero compensation’ prediction was not the case here either. Although there was no significant difference in the hand openings of the blue and yellow tools there was a trend in the expected direction, with some small level of compensation shown. The fact that a degree of compensation has been shown demonstrates that participants are altering the control process to account for the tool, implying the presence of an internal tool model. Even if our theory of end-effector control was flawed, the concept of internal tool models still appears to be sound as you would only be able to do (sensibly) different things with your hand when using the three tools if you had a model to support your behaviour.

These findings are consistent though with the brain attempting to encode movements in end-effector units but doing this based on biased internal models of the tools. We see an under-opening of the yellow 0.7:1 tool and an over-opening of the red 1.4:1 tool which suggests that participants are tending back towards the hand when they are using these tools. This is understandable as if the brain is faced with a tool that it does not have a tried and tested model of, it may rely more heavily upon what it knows, the hand. Tools add a certain amount of uncertainty to a grasping movement by adding motor noise, spatial variability and with a novel tool, unfamiliarity as well. It is not implausible therefore that if a robust model has not been acquired that movements may tend back towards those of the hand. It is also possible that the brain is relying solely on the tool model but that this model is flawed. For example, imagine that you were attempting to control the end-effector in the same manner when using the blue and yellow tool but in your model of the yellow tool you had miscalculated the tool ratio. Then it is possible that you could see an under-opening of the end-effector despite attempting to control them in the same manner because you are working off an incorrect model and therefore any movement calculations will be wrong. These two explanations can account for the patterns of end-effector results seen in the current experiment and previous research (Bongers, 2010; Gentilucci et al., 2014 Zheng & Mackenzie, 2007)

These differences show that even similar tools can produce very different kinematics. All three of our tools were the same except for their ratios. Yet altering the ratio significantly affected the peak end-effector apertures produced and the time taken to reach them.

Altering tool ratio had no effect on the peak velocities reached in this experiment, although there was a trend towards participants moving more slowly when grasping larger objects with the yellow tool. This could have been caused by the fact that people were at the limit of their hand opening when picking up the larger objects and were therefore forced to move more slowly to be able to complete the movement successfully. This was taken into account for the other experiments and we will not use such large objects in the future. The fact that peak velocities were the same with the three tools is interesting however. It was expected that we might see slower movements with the red and yellow tool compared to the blue one because of their complexity. In past experiments comparing the hand and a tool lower peak velocities have been noted (Zheng & Mackenzie, 2007). This is suggestive of the need for additional online visual feedback to be able to successfully complete the grasp. It seems that this was not needed with any of our tools in this experiment, which helped to add weight to the idea that a common motor representation was being used when grasping throughout the experiment. If the same forward model (Wolpert & Flanagan, 2001) that we use to program movements with the hand is being utilised with the tools then participants would not need to rely as heavily on visual feedback during the movement and could therefore move just as quickly with the hand and the tools.

None of the findings in this experiment contradict the idea that movements are being programmed in terms of end-effector units. Where differences have been seen between the hand and the tools they are explainable by a bias in the internal tool model, a need to rely on the understanding of the hand or a need for online information not required when using the hand.

It was shown in Experiment 1 that compensation for our two tools was not equal, with 11 out of 12 of our participants compensating more for the red tool than they did for the yellow one. One reason for this imbalance in compensation with the yellow and red tools could have been that the yellow tool required much larger hand openings than the red and the blue tool for the same objects. This is a possibility as peak velocity was lower for the larger objects when grasping with the yellow tool (although not significantly so), whilst object size had no effect on the other tools or the hand. Time to peak end-effector aperture was also comparable across the tools with smaller objects but at larger objects people took much longer to reach their peak end-effector aperture with the yellow tool. To investigate this further an experiment was run to ensure that the results were not caused by a difficulty in opening the hand wide enough (see Appendix A). The results of this study were inconclusive as a lack of end-effector aperture scaling was seen with an increase in object size and this is contrary to typical findings (Jeannerod, 1981; Jakobson & Goodale, 1991). We are content that if an inability to open the hand wide enough was causing the lack of compensation seen with the yellow tool then we would see poor compensation for the larger object only. This is not the case as we see poor compensation across the range of object sizes with the yellow tool and participants have produced larger hand apertures using the other two tools with no issue (participants opened their hand 53mm on average when grasping a 20mm object with the yellow tool. However, they opened their hand 72mm on average when grasping a 50mm object with the blue tool. This shows that they were capable of reaching much larger peak grip apertures than they were utilising when using the yellow tool). We would also expect to see a flattening out of hand openings, or a ceiling effect, as objects got larger and participants reached their maximum hand openings. Despite this explanation for the effects seen, participants reported finding the yellow tool difficult to use, so another study with a larger object set would be a good avenue for the future to make this conclusion stronger.

Chapter 4: What are the cues to a tool mapping state?

4.1 Experiment 2: How does the brain identify the current tool mapping state?

In Experiment 1 the tool that the participant used was chosen at random at the start of each trial, meaning that a different tool was used on most trials to the one that had been used previously. Despite this, participants compensated significantly for the geometry of the red tool, and to a lesser extent for the yellow tool as well. Even though the difference between the yellow and blue tools was not significant, participants still altered their behaviour in the appropriate direction. This pattern of results is consistent with the brain developing and utilising internal models of the tools, allowing it to adjust for the visuo-motor remapping induced during tool use. Normal reaching and grasping movements are programmed using a forward model (Wolpert & Flanagan, 2001), where the brain predicts the trajectory of a limb during a given movement and adjusts this online if necessary. Arguably, participants would only be able to do (sensibly) different things with the three tools if they had some form of internal tool model that worked on a similar predictive basis to support this behaviour. What is not known based on the previous experiment is how this is possible. Experiment 1 shows that there must be a cue from the three tools that prompted the participants to use them differently. It is however currently unknown what information it is about a tool that allows this behaviour to take place. Here we address the question of how the brain identifies which visuo-motor mapping is appropriate. Or more specifically, what cue from a tool enables us to utilise the appropriate internal model.

4.1.1 Storing models in memory or making calculations on-the-fly?

A feature of Experiment 1, and some previous experiments (Imamizu et al., 2003; Takahashi, 2012, Takahashi & Watt, 2017), is that people appear to be able to switch between using different tools (and therefore different internal models) rather rapidly, possibly even on a trial-by-trial basis. There are a few possibilities for how we can switch between these models so seamlessly. We could store information about tools that we have recently encountered and this information could then be retrieved from memory (i.e. cued) when that tool is picked up or about to be used. Another possibility is that we do not store information about the tools that we use at all, and instead make quick, ‘on the fly’ calculations as we begin to use the tool, to determine its properties. A kind of hybrid of these two mechanisms is also possible, whereby the system stores generic information in memory about broad ‘classes’ of tools, and makes specific calibrations on-the-fly, as the tool is being used. For example, a broad class of tool such as ‘tongs’ could be stored in memory, and this model could then be adapted to suit the finer details of a specific pair of tongs during tool use.

Previous research has shown that there are networks within the cerebellum that exist for tool use and that models of tools may be stored there as well (Higuchi, Imamizu & Kawato, 2007; Imamizu et al., 2000; Imamizu et al., 2003). It has also been shown that the cerebellum may play a role in acquiring these models when novel tools are used (Imamizu, et al., 2000). Imamizu et al. (2000) have shown that regions in the cerebellum are active when individuals use a novel mouse to track an object across a screen. They suggest that this is evidence that a model for this mouse is being stored within the cerebellum and that it is likely to represent the attributes of that mouse that differ to the standard type of mouse that we would usually use. They argue that this is the case because no activation was seen in the same area when a normal mouse was used. Because of this they suggest that the model for the normal mouse must be stored elsewhere in the brain. This supports the concept that models of basic tools that we use on a regular basis may be stored in one part of the cerebellum and then details about tools that are an alteration on these base models are stored in a separate area. Imamizu et al. (2003) have also demonstrated that when using different types of novel mice to perform a tracking task, activation is seen in distinct but adjacent locations in the cerebellum. This suggests that each mouse has its own model stored in a distinct part of the brain. They did also however observe some overlap in the activation of these brain areas and suggest that this could relate to the shared features of the mice, but more research would be needed to make this claim definitively.

As far as using more complicated tools, such as a pair of tongs, it is not known whether the findings found here would be the same. Arguably a computer mouse is a much simpler tool than even a basic pair of tongs. When using a mouse, you simply have to move it around to control it with no fine motor movements needed. With even a basic pair of tongs you not only need to move the tool towards the object that you are interacting with, controlling the speed and direction of this movement as well as co-ordinating the movements of your joints, but also you need to open and close the tool in a precise manner to be able to use it successfully. This requires a much finer control of hand posture than using a mouse would. It also involves having to compensate for a remapping in global hand position – when using a mouse, the hand is over the mouse itself, when using a pair of tongs, it is spatially offset from the end-effector and this adds a further level of complication to the movement. Because of this more research would be needed into different types of tools before an argument could be made about how tool models may be stored in the brain and the role of the cerebellum.

As mentioned previously, it has been suggested that internal models of tools stored in the brain could be switched between rapidly when we pick up a new tool (Imamizu et al., 2003; Takahashi & Watt, 2017). We showed in Experiment 1 that participants were able to partially compensate for the different ratios of our three pairs of tongs. Our participants significantly altered their peak hand apertures when using the blue and red tools and differences approached significance when using the blue and yellow tools. Participants did not compensate fully for the ratio change, as there was also a significant difference between the peak end-effector apertures produced with the three tools. However, they did use the three tools in quantitatively different ways, suggesting that there was some compensation for tool ratio. Despite the tools in Experiment 1 being randomly interleaved participants altered their behavior in the appropriate direction when using each tool. Logically, there must be a cue (or some combination of cues) that provides the brain with the correct tool-mapping to allow the tool to be used. It could be that the cue allows us to pull up a model from memory or it could allow for the calculation of information about the tool as it is being used.

4.1.2 What cues might be utilised during tool use?

There is a wealth of information about cues to visuo-motor adaptation states from classical adaptation studies that may provide some clue to what mechanisms are employed. When an individual experiences adaptation (for example to a pair of prism glasses), the brain must learn a new model for its environment. Arguably this process of adaptation is similar to what must happen when we use a tool. The brain must adapt to a new visuo-motor mapping (or internal tool model) and so it could be that similar mechanisms are employed. Adaptation literature shows that there are different cues that can be used to inform a person of their adaptation state. Imamizu et al (2007) suggest that there are two types of information that are important to allow switching between internal models; one being contextual information (information that can be picked up before you move) and the other being sensorimotor feedback (information that is picked up after movement has begun by assessing the difference between predicted and actual movements). This suggests that a certain amount of information could be garnered before the tool is even lifted, and this could then be monitored and corrected online as the tool is being used.

Mistry and Contreras-Vidal (2004) carried out work that supported Imamizu et al.'s (2007) concept as they showed that colour alone was a strong enough contextual cue to allow partial adaptation in a rotated cursor task, with participants behaving appropriately with different mouse functions based only on a colour cue to tell them which adaptation state they were in on a given trial. However White and Diedrichsen (2013) found that visual cues only work when they are relevant to the task. This means that cues such as colour may only be useful in certain situations. Therefore, it is possible that contextual information is only helpful when it is related to the task itself.

Other ideas for possible cues can also be taken from literature about the incorporation of tools into the body schema, or tools that change our concept of peripersonal space. A lot of literature has looked at the difference between passively holding a tool and actively using it (Brown et al., 2011; Farnè et al., 2005a*;* Iriki et al., 1996). It has been suggested that motor-feedback may be a necessary part of incorporation when using a more complex or novel tool, whereas visual-feedback provides enough information for successful incorporation when using simpler tools with known inertial properties, such as a stick (Brown et al., 2011). So, it is possible that when using a very simple tool just seeing it is enough to cue an appropriate internal model. However, if the tool is completely new to you, or a more complex tool, it may need to be used before you are able to acquire a model of the tool.

4.1.3 Our approach

We aim to assess which different cues to the tool being used on a coming trial would be enough to allow participants to behave appropriately with a given tool, and therefore potentially have activated the correct tool model. We will present different types of cue throughout the experiment and assess their effectiveness in allowing accurate tool use. Having seen an alteration in peak hand apertures for the three tools in Experiment 1 this can be used as a measure of successful tool use. Compensation factors can therefore be used to assess whether the cue on that trial was enough to allow understanding and appropriate use of that tool. If participants do not alter their peak hand apertures with the three different tools after being exposed to a certain cue then the compensation factors will be zero. It could then be argued that the cue did not give participants enough information to be able to use the tool correctly and therefore they could not access an appropriate tool model. If, however they were able to alter their peak hand apertures for the three tools, and particularly if the compensation factors were equal to those seen normally, then this would suggest that that cue was enough to allow successful tool use and utilisation of an appropriate internal model. The cues that we will use in this experiment have been chosen to tap into different mechanisms based on the literature previously discussed.

One cue we investigated was an arbitrary cue of colour. Each tool that the participant was trained on was a different colour and we investigated whether presenting them with just the colour of the tool and no other information about it was enough to allow the participant to use the tool successfully. We chose to use this cue because of the adaptation literature mentioned previously (Imamizu et al., 2007; Mistry and Contreras-Vidal, 2004; White and Diedrichsen, 2013) and because other studies using novel mice as tools have shown that colour can be used successfully as a cue to which tool will be used on a coming trial (Imamizu et al., 2003).

A second cue that was assessed in this experiment was a 'static' cue. Here, participants were able to see the tool that they would be using on the coming trial but they were not able to see it move (it should be noted that participants were still able to see the tool's colour in this condition). This cue therefore potentially provided information about the form of the tool, and its ratio, but no information about its dynamic properties. For example, the participant was not able to tell for certain how moving the tool's handles would affect the movement of the tool's tips. This condition was included to see whether passive visual information about a tool's structure was enough to allow understanding of its mechanics or whether active movement has to be experienced. This is a distinction that has been raised in the body schema literature (Brown et al., 2011; Farnè et al., 2005a; Iriki et al., 1996) as well as in the experiment by Imamizu et al. (2007) that distinguishes contextual and sensorimotor cues.

A third cue used was a 'passive movement' condition. In this condition, the participant could only see how the movement of the handles of the tool affected the movement of the tool tips (all other information about the tool, including colour, was removed – see section 4.2 for more information). This allowed the participant to see the effect of movement at the hand, but not to see the form of the tool or to actually move the tool themselves. This condition was used to further probe the difference between passive and active feedback. Here participants got a lot of information from the tool about how it moves and the difference between the opening at the hand and the tool tips, but they still did not get any motor-feedback as they only passively viewed its movement. In the study by Brown et al. (2011) it was shown that when the experimenter moved the participant's arm whilst they passively held the tool that the participants did not display the spatial adaptation shown when they actively used the tool themselves. Other studies have also shown similar things. Farne et al. (2005a) showed that in a patient with cross-modal extinction that this extinction extended to the tip of a tool that they had used for five minutes. However, if the patient simply sat and held the tool this extinction did not occur at the tool tip. Finally, Iriki et al. (1996) showed that neurons that had a visual receptive field that surrounded the space near the hands began to fire for activity around the tip of the tool after five minutes of use. These findings all suggest that we need to move tools ourselves and see the effect of our actions on the tool to be able to learn use it appropriately. If this were the case then this cue would not be enough to allow understanding of the tool.

The final single-cue used was an 'active movement' cue. This cue was similar to the passive movement cue, except here the participant moved the tool themselves, allowing visuo-motor-feedback to occur. Again, all other information about the tool, including its colour, was removed in this condition to try to limit the amount of passive information the participant could perceive from the tool. It has previously been suggested that motor-feedback may be an important stage of successful tool adaptation (Brown et al., 2011; Farne et al., 2005a; Iriki et al., 1996). If this is the case then it is likely that this is the only single cue that would allow participants to be able to successfully use the three tools.

Finally, we included a 'full cue' condition. Here the participant got to see all the information about the tool before they used it. This condition was included to ensure that we had an adequate control condition to compare performance in the single-cue conditions to. This was necessary because the experiment was carried out using visually open-loop grasping (hereafter, "open-loop"). This means that no visual feedback was available to the participants during the grasp (though proprioceptive feedback remained available, of course). The experiment had to be run in this way to avoid the participant seeing the tool whilst they are using it, which would provide all of the above signals to the current mapping state. It is already known that grasping open-loop can change the way that people grasp, either by causing people to move more slowly, to produce larger peak end-effector apertures, or to reach peak velocities and peak end-effector apertures later in the movement than usual (Connolly & Goodale, 1999; Gentilucci, Toni, Chieffi & Pavesi, 1994; Jakobson & Goodale, 1991). Because of this it was important for us to have a baseline condition that showed the effect of grasping with our three tools open-loop, but with all cues to tool geometry/mapping state available. By collecting this information, we can compare the other experimental conditions to this one, rather than to a closed-loop grasping condition, where performance would differ for reasons not of interest to our study. Participants will however also grasp closed-loop in blocks throughout the experiment. This will give them an opportunity to learn to use the tools and to remind them of the tools throughout the experiment. The data from the closed-loop blocks will be used to see if we have replicated the effects seen in Experiment 1 but will not be compared to the experimental conditions for the reasons outlined above.

These different cues allowed us to investigate what information is important for participants to develop and utilise internal models of the tools. It may be that there is not any one cue alone that is enough to allow the participant to do this and that some combination of information is instead necessary. If an arbitrary cue such as colour were enough to recover the appropriate visuo-motor mapping, it becomes harder to tell what is occurring in the other conditions. This is because each of the conditions arguably contains 'recognition cues', based on the fact that the three tools look different. Therefore, depending on the pattern of results seen in this experiment there may be a limit to what we can understand, but it should show us enough to inform further experiments on the topic.

4.2 Methods

4.2.1 Participants

Ten right-handed participants were recruited from the Bangor area through opportunity sampling (six female, four male). There was a mix of participants who were either naïve or practiced with our tools (four practised, six naïve). All participants had either normal or corrected to normal vision and no known motor issues that would affect their ability to make a normal grasp.

4.2.2 Stimuli and Apparatus

The experimental area was the same as that used in Experiment 1 (see Figure 3.1), except for the inclusion of a lamp placed above and behind the participant.

The experimental objects were similar to those used in Experiment 1 but in the present experiment they ranged in size from 25 - 45 mm in 5 mm increments. 45 mm was the biggest object used in this experiment to try and avoid the problems that we had in Experiment 1 with people struggling to grasp the largest object with the yellow tool.

A pair of liquid crystal shutter glasses (PLATO Vision Occlusion Spectacles, Translucent Technologies Inc., Canada) were used in this study to accurately control when the participant could and could not see.

The privacy screen, start button, markers, tools and cameras are the same as those described in the general methods section (section 2.4).

4.2.3 Procedure

The experiment was run in five separate sessions. Each session consisted of five closed-loop blocks and five open-loop blocks alternated with one another. During open-loop blocks the participants were required to make the grasp without vision. Here the PLATO googles were used to obscure their vision once they released the start button, so that they could not see whilst making the actual grasp. Participants were required to complete all of their sessions within a one-week period.

During the closed-loop blocks a lamp placed above and behind the participant's head was used to illuminate the experimental area for the duration of the trial. The participant was passed one of the tools and was instructed to depress the start button with the tips of the tool in the closed position. In the closed-loop sessions the privacy screen was always clear and the participant could see the tool on the start button. Once the start button was depressed the experimenter triggered the PLATO goggles to turn opaque whilst an object was placed on the table. The goggles were then turned transparent allowing the participant to see the object on the table in front of them. After 1 second a beep sounded signalling the participant to pick up the object and place it to the right-hand side of the experimental area before returning to the start button. One closed-loop block consisted of 15 trials (one repetition of each of the five sizes with each of the three tools) and took the participant 5-10 minutes to complete.

The objects were placed at a random distance on each trial and could appear anywhere between 200-350 mm from the participant. Distances were binned for analysis, from 200-249 mm were labelled 200 mm, from 250-299 mm were labelled 250 mm and from 300-349 mm were labelled 300 mm. The position of the object was randomised in this experiment to attempt to increase demand on the participant to avoid the lack of scaling seen in Experiment 7 (see Appendix A). This was a concern because we had reduced the number of object sizes in this experiment after participants had struggled to grasp the larger object with the yellow tool in previous experiments.

A retroreflective marker was attached to the participant's right wrist over the radius bone and they were given the PLATO goggles to wear.

During the open-loop blocks each trial consisted of two parts; a “mapping acquisition” phase, in which the participant saw the cue specific to the condition, and a “grasping phase” in which they grasped with their vision occluded from movement onset. During the open-loop trials the privacy screen was always set to opaque to prevent participants from seeing the tool whilst it was on the start button (as this would provide information about the tool other than that provided in the mapping acquisition phase). The five open-loop conditions were full cue, arbitrary cue, static cue, passive movement cue and active movement cue. Details of how these conditions were run is explained in more detail below.

In the full cue condition participants could see everything about the tool during the acquisition phase and were able to move it themselves. In this condition, the room was illuminated by the lamp throughout the whole trial. The participant was handed a tool and asked to open and close it three times while watching it. The PLATO goggles were then turned opaque and the participant was instructed to depress the start button whilst an object was placed on the table. The goggles were turned transparent again to allow the participant to see the object’s location on the table. After 1 second a beep sounded to signal to the participant to pick up the object. When the start button was released, the goggles turned opaque within a few milliseconds, no visual feedback was available during the movement. Participants placed the object to the right-hand side of the table (if they successfully grasped it) and put the tool down ready for the next trial. If the participant failed to grasp the object then the experimenter removed it from the table. The trial was not considered void in this situation as we were interested in how participants behaved regardless of their ultimate success. For example, if a participant did not open their hand wide enough to grasp the object, this would result in a failed grasp but would provide interesting information about the participant's ability to successfully use the tool on that trial.

In the arbitrary cue condition, participants were only given a colour cue to which tool they would be using on each trial. At the start of each trial the participant was shown one of three coloured sticks, corresponding to the colour of one of the tools, and was told, "You will be using the yellow/red/blue tool on this trial". The PLATO goggles were turned opaque and the participant was handed the tool (meaning that they never saw the tool). They were then instructed to depress the start button whilst an object was placed on the table and from here the trial was the same as in the full cue condition.

In the static cue condition, the participant saw the tool that they would be using on that trial, but they were not allowed to see it move. The experimenter picked up the tool and showed it to the participant in its closed position. (This gave them information about the form and structure of the tool, but no information about how it moved). The PLATO goggles were turned opaque and the participant was handed the tool. They depressed the start button and the trial was the same as the full cue condition from here onwards.

In the passive movement condition, the participant saw how the tool moved but information about the form and colour of the tool was removed. This was achieved by temporarily extinguishing the lamp (controlled by the computer), and using luminous dots attached to the tips and the handles of the tools to show their positions. The experimenter moved the tool in the dark for the participant to see, opening and closing it three times. The PLATO goggles were then turned opaque, the lamp was turned back on, and the tool was handed to the participant. They depressed the start button and again the trial was the same as the full cue condition from here onwards.

In the active movement condition, the participant saw how their actions affected the movement of the tool tips, but again form and colour information were removed using the method above. The lamp was off at the start of each trial, and the participant held the tool and opened and closed it themselves, three times. The PLATO goggles were turned opaque and the participant was instructed to depress the start button. Again, from here onwards the trial was the same as the full cue condition.

The five open-loop blocks in each session consisted of one block of each of the five experimental conditions. The order of these was counterbalanced across both session and participant. The open-loop blocks also consisted of 15 trials, one repetition of each object size, with each tool.

The procedure for identifying void trials was the same as in Experiment 1, These trials were repeated at the end of each block as in previous experiments.

Table 4.1. A summary table of the experimental conditions for reference.

Condition	**Properties**
Arbitrary Cue	Only colour of tool visible
Static Cue	Tool completely visible, not seen moving
Passive Movement Cue	Only tool tips and handles visible, moved by experimenter
Active Movement Cue	Only tool tips and handles visible, moved by participant
Full Cue	Tool completely visible, seen moving

4.3 Results

4.3.1 Closed-loop performance

The closed-loop blocks in this experiment served as a reminder to participants of the three different tools, but also allowed us to see if we had been able to replicate the effects seen in Experiment 1 with a new set of participants.

Figure 4.1 plots (a) the peak end-effector apertures and (b) the peak hand apertures produced with the three tools during the closed loop blocks (as a function of object size, collapsed across distance). Looking at Figure 4.1 it can be seen that the pattern of results is similar to that seen in Experiment 1. Participants scaled their peak end-effector apertures with all three of the tools as the size of the object increased. Figure 4.1b also shows that participants displayed some alteration of hand opening when using the three different tools, but again it seems asymmetric in favour of the red 1.4:1 tool.

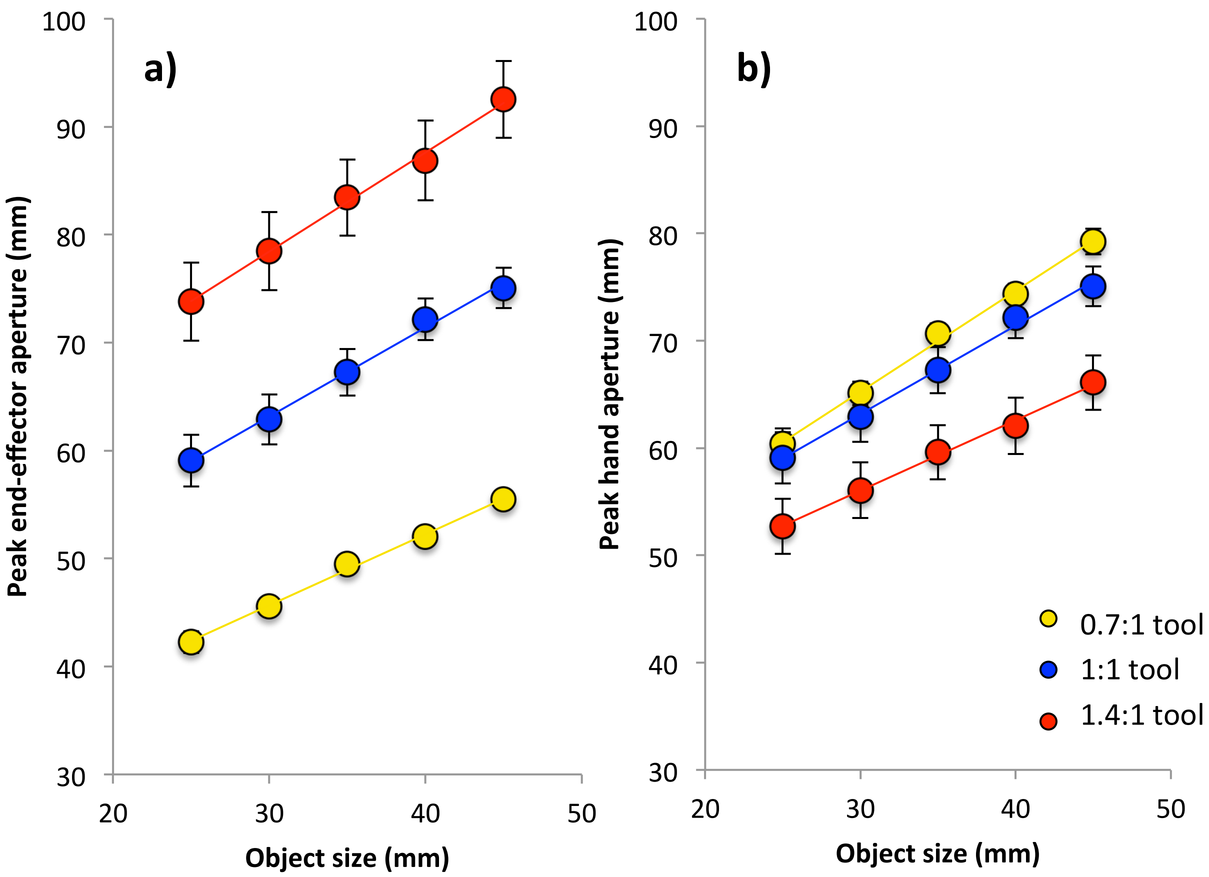


Figure 4.1. Closed-loop aperture data as a function of object size, collapsed across distance. (a) Average peak end-effector apertures (b) The same data plotted in units of hand aperture. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=10.

By running a 3 x 5 repeated measures ANOVA (tool type x object size) on the hand aperture data we find a main effect of tool type (F(1.27,11.46)=30.25, Greenhouse Geisser corrected, p<.001), suggesting that some modulation of hand aperture is occurring with the different tools. Using planned comparisons it can be seen that the differences are only approaching significance for the blue and yellow tool ($F(1,9)=4.25$, p=.069). However, there is a significant difference between the red and blue tools ($F(1,9)=69.29$, p<.001). This directly replicates what we found in Experiment 1. Participants have significantly altered their hand movement when using the red tool compared to the blue one, however it is only approaching significance when comparing them for the yellow and blue tools, possibly suggesting a biased or flawed internal model of the yellow tool. Participants did not pick up objects with the hand during this experiment so the performance with the blue 1:1 tool cannot be compared to that of the hand.

As said previously participants appear to have compensated more for the red 1.4:1 tool than they did for the yellow 0.7:1 tool. Figure 4.2 compares the compensation factors seen in Experiment 1 and the present experiment. Compensation appears similar across the two experiments with both tools, although marginally reduced in the current experiment.

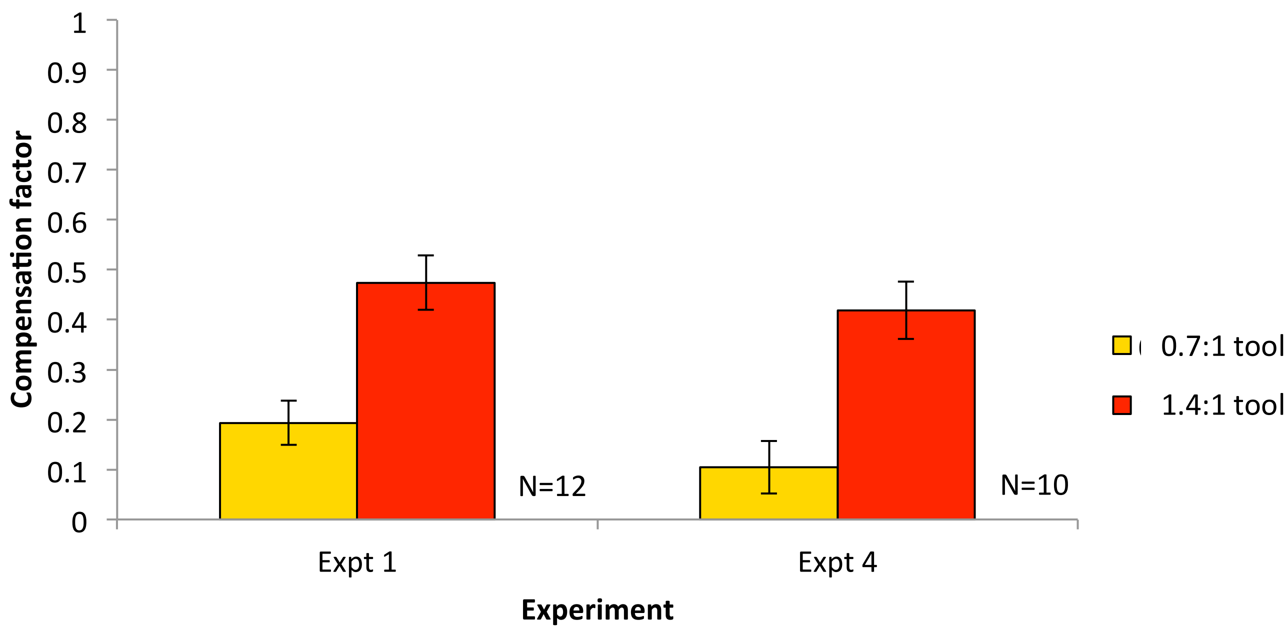


Figure 4.2. Average compensation for the yellow 0.7:1 tool and the red 1.4:1 tool from Experiment 1 and the closed-loop trials of this experiment. Error bars show +/-1 SEM.

4.3.2 The effect of grasping visually open-loop

We included a full cue condition in this experiment as it was expected that participant's performance would drop when grasping open-loop. By including a condition that had all of the information about the three tools present but was carried out under open-loop conditions, we were able to see the exact effect that open-loop grasping had on performance and could then use this as a control for the other conditions.

It can be seen by looking at Figure 4.3 that completing the grasp open-loop seemed to have little effect on the peak velocity of the movement.

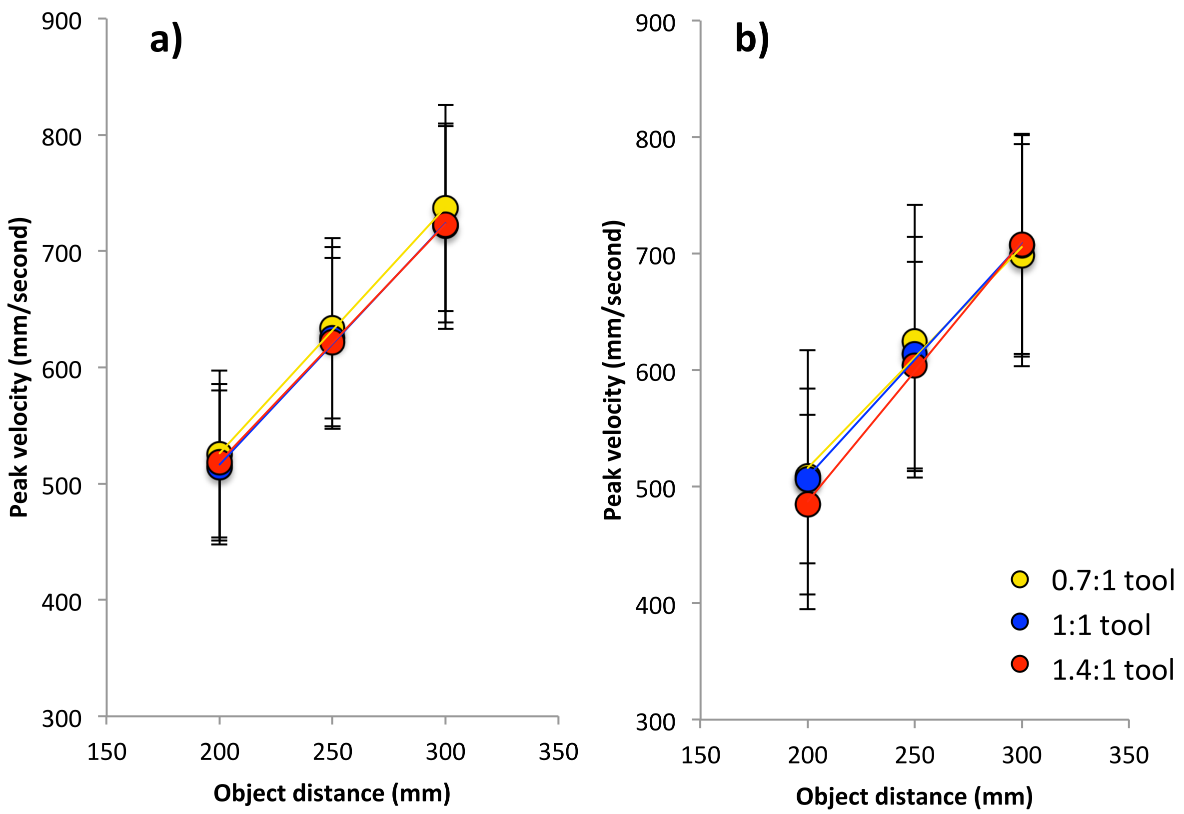


Figure 4.3. Peak velocity data as a function of object distance, collapsed across size. (a) For the closed-loop trials (b) For the full cue open-loop trials. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=10.

Planned comparisons on an omnibus ANOVA of all of the conditions show that there was no significant difference in the peak velocity reached in the closed-loop and full cue open-loop conditions ($F(1,9)=1.95$, $p=1.96$). Therefore, any changes in peak velocity between other conditions are unlikely to be caused by the fact that the participant is making the grasp visually open-loop.

Figure 4.4 shows the peak hand apertures produced in (a) the closed loop condition and (b) the full cue open-loop condition. Participants still adjusted their hand apertures when using the red and blue tools under open-loop conditions, although possibly slightly less than under closed loop ones. However, participants opened their hand less when using the yellow tool than they did with the blue one under open-loop conditions. This is the opposite of what we would expect if participants were using the yellow tool correctly.

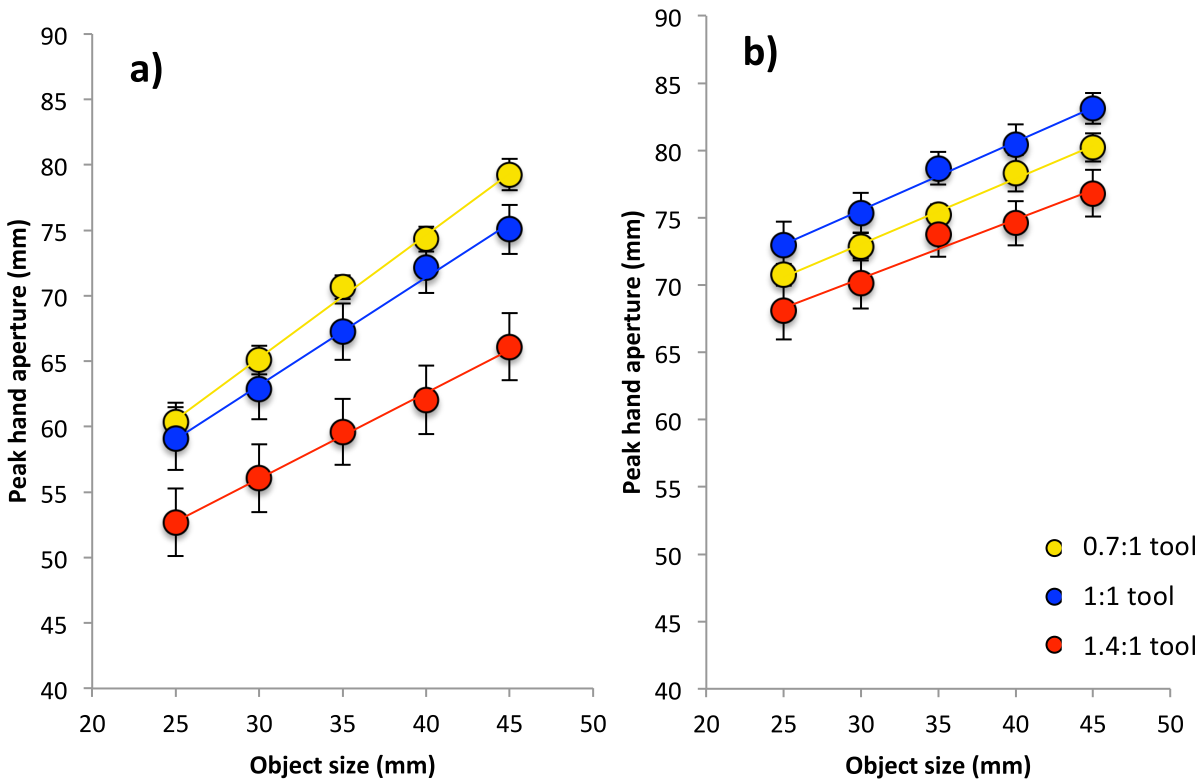


Figure 4.4. Peak hand aperture data, as a function of object size, collapsed across object distance. (a) For the closed-loop condition (b) For the full cue open-loop condition. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=10.

Planned comparisons show that the peak hand apertures produced in the closed-loop and full cue open-loop conditions were significantly different from one another ($F(1,9)=43.59$, $p<.001$), this is not altogether unexpected as past research has shown that grasping open-loop has an effect on peak grip aperture (Connolly & Goodale, 1999; Gentilucci, Toni, Chieffi & Paveshi, 1994; Jakobson & Goodale, 1991). Peak hand aperture still scales with object size however, so the data is still sensible and we should be able to draw some meaningful comparisons.

Figure 4.5 shows the compensation factors for the red and yellow tools in these two conditions. It can be seen that overall compensation is lower open-loop. Compensation for the tool ratio is in fact so poor with the yellow 0.7:1 tool in the full cue open-loop condition that we see a negative compensation value. This is caused by participants opening their hand less when using the yellow tool to grasp an object than they were when using the blue one (as seen in Figure 4.4b).

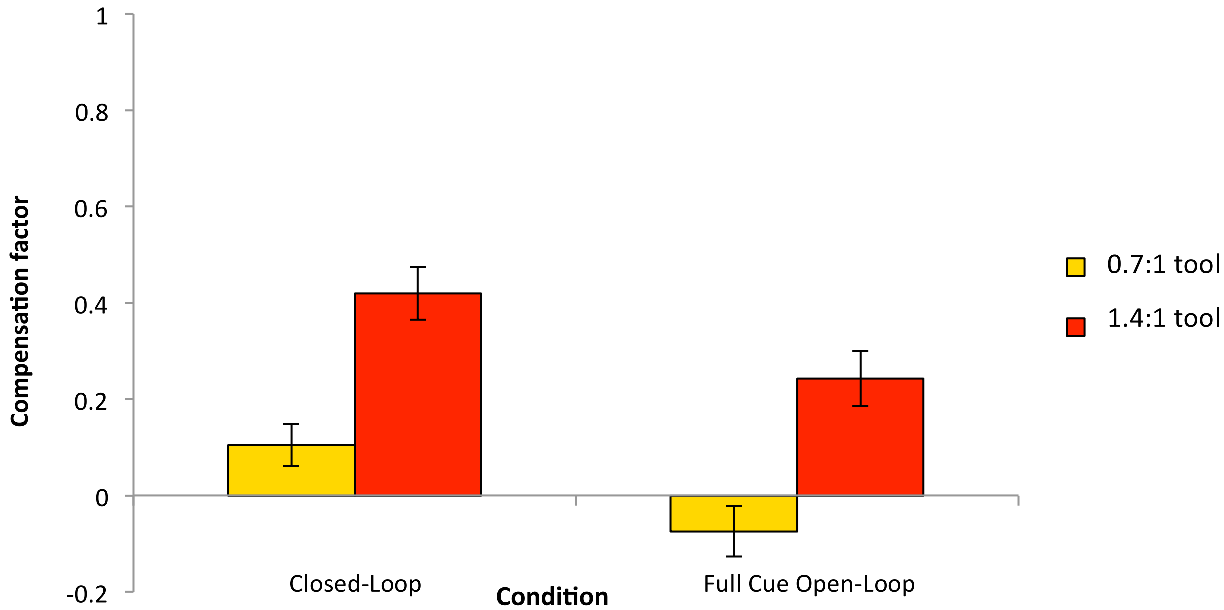


Figure 4.5. Compensation in the closed-loop condition and the full cue open-loop condition. Error bars show +/-1 SEM. N=10.

The negative compensation factor for the yellow tool makes it hard to draw any conclusions about this tool during this experiment because all the other experimental conditions will be compared to the full cue condition. If compensation is non-existent here it makes interpreting the data difficult. The red tool on the other hand has a reduced but still meaningful level of compensation. The results with the yellow tool are not entirely unexpected as it was shown in Experiment 1 that there was a difference between participants ability to compensate for the yellow and red tools. It is therefore again apparent that the yellow tool is compensated for less than the red one, although it is unclear why this might be the case.

4.3.3 Peak velocity

Figure 4.6 shows the peak velocities reached with the three tools in each of our conditions. These plots show that participants reached similar peak velocities with the three tools in each condition. This is confirmed by a 6 x 3 x 5 (condition x tool type x object size) repeated measures ANOVA that showed no main effect of tool type ($F(2,18)=1.43$, $p=.266$). This means that participants moved equally quickly with the three tools in each of the conditions. This makes any potential differences in peak hand aperture between the tools easier to interpret later, as they do not have to be understood in tandem with peak velocity effects.

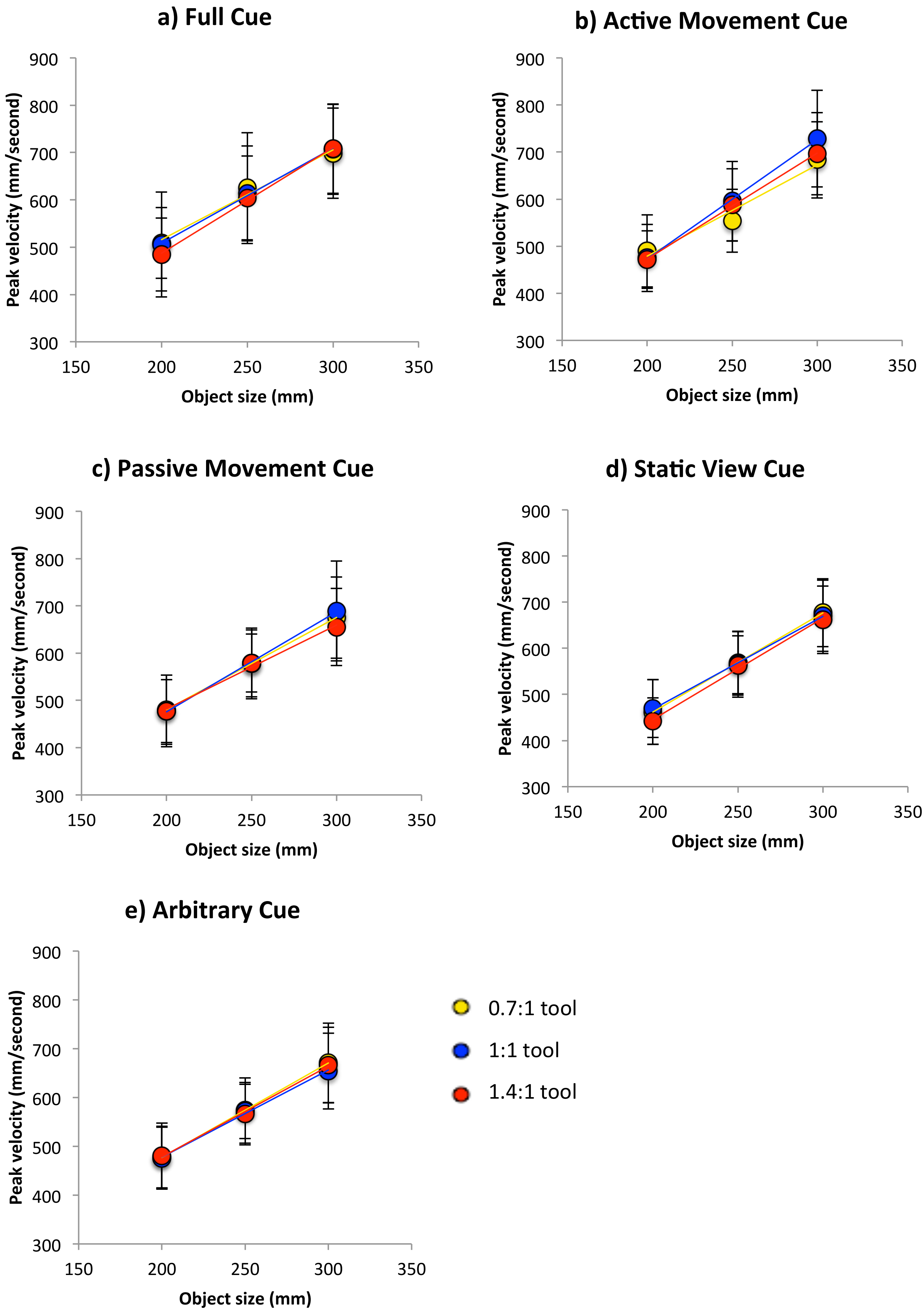


Figure 4.6. Peak velocity data as a function of object distance, collapsed across size. (a) Full cue (b) Active movement cue (c) Passive movement cue (d) Static view cue (e) Arbitrary cue. Error bars show +/-1 SEM. Linear regression lines are fitted through the data. N=10.

There appears to be little difference in peak velocity across the five conditions. However, it is difficult to compare peak velocities across the conditions in Figure 4.6 due to the number of conditions. We can however look at these differences statistically. The ANOVA ran on peak velocities previously does show a main effect of condition ($F(5,45)=6.55$, $p<.001$). Planned comparisons that compare each of the conditions to the full cue condition show that peak velocities reached in the active movement cue condition were not significantly different to those in the full cue one ($F(1,9)=0.86$, $p=.378$). The differences in the other three conditions were also non-significant but were approaching significance; arbitrary cue ($F(1,9)=4.46$, $p=.064$), static view cue ($F(1,9)=4.98$, $p=.053$) and passive movement cue ($F(1,9)=4.04$, $p=.075$) with participants moving more slowly in these conditions than the full cue one. As these effects are approaching significance then it could be argued that participants were unable to perform in these single-cue conditions as well as they could when they had all the information about the tool (in the full cue condition). These conditions arguably provide less information than the full cue condition or active movement condition and therefore they may not have given participants enough information to provide an appropriate internal tool model. If the brain knows that its internal model is flawed or biased then slower movements would allow the incorporation of visual feedback. However, as the effects are only approaching significance this cannot be confidently stated.

4.3.4 Compensation factors

To calculate compensation factors in these single-cue conditions the peak end-effector apertures produced with the red and yellow tools were compared to those produced with the blue tool in the same condition. We could also have calculated them using the apertures produced with the blue tool in the full cue condition as this represented ideal performance. However, it was decided that we could see a consistent under or over opening with all the tools in some of the conditions due to uncertainty. In this case, even if participants modulated their apertures with the three tools (showing that the cue was enough to provide an internal tool model), this form of compensation factor would show poor compensation as we would be comparing to the ideal performance of the blue tool. Therefore, these compensation factors are calculated within condition.

Figure 4.7 shows these compensation factors for the red 1.4:1 and yellow 0.7:1 tools in each of the conditions. Each of the single-cue conditions provided enough information for some level of compensation with the red 1.4:1 tool. However, the under-opening seen with the yellow tool is present in all of the conditions making it hard to interpret those effects.

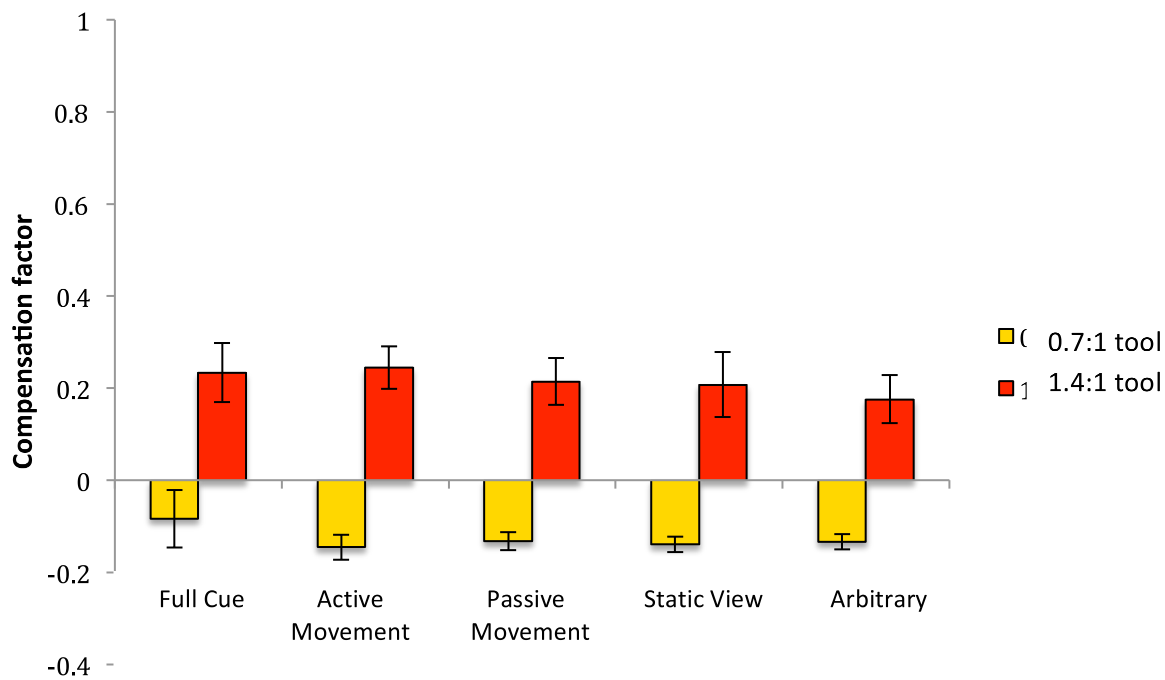


Figure 4.7. Compensation factors for the yellow 0.7:1 and red 1.4:1 tools in the full cue and single-cue conditions. Error bars show +/-1 SEM. N=10

A 5 x 2 (condition x tool type) repeated measures ANOVA showed no main effect of condition ($F(2.09,18.81)=1.49$, Greenhouse Geisser corrected, $p=.251$), showing that there was no difference in compensation across the conditions. Therefore, each of the single-cue conditions provided enough information for participants to alter their peak end-effector apertures for tool ratio in the same manner as in the full cue condition. It is hard to draw conclusions about the yellow 0.7:1 tool due to the under-opening seen in every condition in this experiment. However, the compensation values for the red 1.4:1 tool suggest that even when only presented with a single arbitrary cue this may have been enough to invoke an appropriate internal model for this tool.

4.4 Discussion

In Experiment 1 we found that participants were able to alter their peak hand apertures in the expected direction to compensate for a change in tool ratio. Whilst this compensation was only approaching significance with the yellow tool, it was significant with the red one. This suggested to us that users must be able to extract some information from a tool that allows them to use it appropriately. We posit that this is likely to be in the form of utilising an internal model of the tool that is either stored in memory or developed on-the-fly during use. This experiment aimed to find out what information provided by a tool allows this internal model to be identified and used appropriately.

4.4.1 Colour as a cue

As discussed previously, it has been suggested that colour can be a strong enough cue to prompt the current adaptation state when using different types of computer mice (Imamizu et al., 2007; Mistry and Contreras-Vidal, 2004). Our compensation factor findings seem to support this as we saw no significant difference in compensation for tool ratio between the arbitrary condition (where only colour was presented) and the full cue condition. This means that participants were able to compensate for the ratio of the red 1.4:1 tool just as well when they were only presented with the colour of the tool as a cue as they did when they had all of the information about it. This suggests that the arbitrary colour cue allowed participants to access an internal model of the tool and use this information during this condition. Earlier, we discussed the idea that it was not known how these internal tool models were acquired; whether they were learnt and stored in memory or whether they were calculated during tool use based on information gathered from the tool. The fact that participants compensated an appropriate level for the red 1.4:1 tool in this experiment helps to answer this question. As participants never actually saw the tool they would be using in the arbitrary colour condition memory must play a part in the process, as no information was available to base calculations on in this condition. It is likely that when information is available that this is used to hone and develop the internal model of the tool. However, it seems that once this model exists that it can be pulled up from memory, based on a cue, and used without any online feedback in a relatively successful manner. Participants were able to learn the properties of the three tools during the closed-loop grasping condition throughout this experiment. But to be able to appropriately adjust the peak end-effector apertures when using the blue and red tools, without ever actually seeing the tools themselves in the arbitrary condition, memory must be playing a role in using the appropriate tool mapping to plan the necessary movement.

Because the arbitrary colour cue proved to be a good enough to elicit some understanding of the tool then less can be said about the other experimental conditions. This is because colour was an arbitrary ‘recognition’ cue in this experiment; it gave no information about the tool itself and merely allowed the participant to recognise the tool they were about to use. These recognition cues were arguably present in all of the conditions in the experiment due to the fact that the three tools look different to one another. Even in the conditions where the tool was reduced to four dots or simply held up to the participant, the tools were easily distinguishable from one another by how they looked.

Even though there were no significant differences in the levels of compensation seen with the tools across the conditions, there does seem to be a trend. The more information a cue provided the higher compensation was, although not significantly so. When looking at the peak velocities reached in each of the conditions no significant differences were found either. However three of the conditions were approaching significance when compared to performance in the full cue condition. These were the arbitrary cue condition, the static view condition and the passive movement condition. These three conditions arguably gave the participants less information about the tool than the active movement condition did. Brown et al. (2011) suggest that motor feedback is necessary in adapting to a tool. The fact that we saw marginally better performance in the active movement condition than the other three conditions when compared to full cue does seem to support this. The trend that was seen for slower movements in these conditions and slightly lower compensation could suggest that participants were less confident about their internal tool model in these conditions. If this were the case then participants may not have performed as accurately with the tools under these conditions. However, considering our effects are all only approaching significance further research would definitely be needed to reach any definitive conclusions.

4.4.2 Applications of our findings and further research

By finding out what information about a tool enables the user to access an internal tool model and use the tool appropriately, we hope that tools can be designed in the future which are more intuitive to use. By demonstrating that an arbitrary cue such as colour was an informative cue to the tool mapping state then in the future tools can be created with this in mind.

Now that tools are becoming so complicated with advances in robotics, understanding how we are able to use such a wide variety of tools could not be more important. With the development of robotic tools for use in areas such as bomb-disposal, work in unsafe environments, and surgery we can benefit from findings that could make tools more intuitive to use. Our findings would be particularly applicable when utilising tools where the user is able to manipulate many different effectors using the same control panel. For example, in some modern surgical systems the surgeon can change tools at the press of a button and manipulate different effectors with a range of functions from the same set of controls. Our findings suggest that by associating each effector with a distinct colour cue this could allow the brain to utilise an internal tool model, and possibly make the tool more intuitive to use, reducing the chance of user error. More research would definitely be needed however, to ensure that arbitrary cues are informative for a wider range of tools. Firstly, we only looked at a single class of tool – pairs of tongs. And secondly, we were only able to show effects with one of our tools because participants were unable to use the yellow 0.7:1 tool under open-loop conditions. It also must be pointed out that the active movement cue did seem to offer some advantages over the other cues in recognising the tool, even if not significantly so. Participants could arguably use the tool in a more precise manner when this cue was used. By investigating this further with different types of tools other than just tongs it could be seen whether the effect was replicable with other classes of tool and therefore whether it would be a useful feature to build into more complex tool designs in the future.

Chapter 5: Reasons for partial and asymmetric compensation

5.1 Partial and asymmetric compensation

The previous experiments have shown that whilst participants do compensate somewhat for the ratio of the tool that they are using, perfect compensation is not seen. There has also consistently been an asymmetry demonstrated in the degree of compensation for the two tools, with participants showing more compensation for the ratio of the red 1.4:1 tool than they do with the yellow 0.7:1 tool. Experiment 2 showed that participants compensated somewhat for the ratio of the red tool even when they were only aware of the colour of the tool that they were using and did not see the tool itself during the trial. This behaviour demonstrates that participants in that experiment were likely utilising a predictive internal model of the red tool to perform the grasping movements. This is because they consistently altered their hand apertures in a sensible direction despite being provided with nothing but an arbitrary identity cue and making the grasp visually open-loop. Some kind of memory-based model must therefore have been utilised to behave in an appropriate manner. Performance in Experiment 2 with the yellow 0.7:1 tool, however, did not convincingly demonstrate that participants were utilising an internal model of this tool. They showed low compensation when using the yellow tool visually closed-loop (under normal conditions, see Figure 3.5, Section 4.3.2). They were also unable to compensate for the yellow tool's ratio at all under visually open-loop conditions (see Figure 3.7, Section 4.3.4). This behaviour points towards participants either failing to develop an internal tool model for this tool, or relying on an internal model that it is noisy or biased, leading to incorrect movement calculations. These effects of partial compensation for both tools and the asymmetric compensation demonstrated have appeared consistently throughout the experiments so far and so a next logical step is to investigate some of the possible causes for these results.

There could be numerous reasons why individuals would not display complete compensation for the ratio of the tool that they are using. It has been stated previously that even if people are attempting to control the tool tips in the same manner as the finger and thumb that we might not see perfect compensation. If participants had a biased internal model of the tool then this could lead to non-perfect compensation. This is because the calculations when using the two tools would be based on an incorrect model and therefore movements would never be the same in terms of the end-effector. There is a logical reason for this, if the brain is unsure about the reliability of the internal model then it makes sense to adjust based on prior reliable models such as the hand. This is sensible behaviour in an uncertain situation; relying on knowledge of the normal relationship between haptic signals about hand opening and object size in the world (information that the brain has been shown to utilise (Takahashi & Watt, 2017)). Tool models could be unreliable for any number of reasons including the fact that spatial variability in hand posture is amplified at the tool tip and the additional motor noise added by using a tool. This could account for the partial compensation seen in both tools so far, tending back towards the mapping of the hand would lower compensation factors seen with both tools. Another possibility is that rather than being biased the internal tool model is simply incorrect, this would also lead to lower compensation as movements would again be based on incorrect calculations.

We will investigate the possibility of (and potentially the accuracy of) internal tool models during this chapter by measuring participants' size perception of an unseen object when using our three tools. Similar to grasp control, accurate size perception when using the different tools requires transforming the proximal haptic signal (hand opening) - taking account of the tool geometry - in order to 'recover' the opening of the tool tips. Thus, if participants report the size of the same object differently with each of the three tools then this would suggest an error in the understanding of the tools, and possibly highlight a bias in the internal tool models. As said previously, it is possible that a bias in a tool's model may tend towards the opening of the hand. If this were the case then when participants report an object's size they would underestimate whilst using the red 1.4:1 tool and overestimate when using the yellow 0.7:1 tool. This is because for the same object the hand is open less than the tool tips when using the red tool, and more than the tool tips when using the yellow one. Therefore, if you were supplementing the internal model with information from the hand then this would bias responses in opposite directions.

Another possibility for the low levels of compensation seen with the tools in previous experiments is that when we use a tool we do not get as much tactile feedback as we do when grasping with the hand alone. This is because the tactile 'contact signals' – the signal that we have successfully contacted/grasped the object is lessened when using a tool. When grasping with the hand there is a very clear cue that the object has been grasped as you can feel the pressure on your forefinger and thumb. However, when you grasp an object with a tool, there is already pressure here caused by the act of holding the tool's handles. When an object is then grasped this pressure increases, but it is arguably not as clear a signal as we get when grasping with the hand alone. This issue is exacerbated with our tools, as they have rubber tips. This therefore damps the signal which would normally be very high frequency and sharp (Johansson & Flanagan, 2008) It has been shown in past research that visuo-motor feedback may be a very important part of learning to use a tool (Brown et al., 2011), so the fact that tactile feedback is potentially reduced during tool use could mean that models of more complex tools are not always developed properly. It is therefore possible that individuals may never learn to use these tools as deftly as they can use their hand and are unable to totally compensate for the tool ratio.

This reduction in tactile feedback also affects movement kinematics (Gentilucci, Toni, Daprati & Gangitano, 1997; Johansson & Flanagan, 2008) as well as the potential to learn a tool model, and this could be a further reason why we have seen reduced compensation factors thus far. Gentilucci et al. (1997) asked participants with anaesthetised fingertips to reach and grasp objects. When participants' fingers were anaesthetised their peak grip aperture occurred later in the movement and was also larger when compared to a normal grasp. Previous studies have also shown that patients who have reduced sensitivity at the fingertips often produce grip forces that are much larger than healthy controls (Johansson & Flanagan, 2008). This shows that a grasping movement can be affected when tactile feedback is removed or reduced. We also plan to investigate the effect of the reduction in tactile feedback in this chapter by getting participants to make comparative judgements about the size of two objects using their hand and the three tools. As tactile feedback may be largely reduced when using the tools then it is expected that participants will not be able to differentiate between smaller size changes in the objects as when using their hand.

Another possibility is that if the internal model of the tool is flawed this will lead to a lower compensation factor. This is because haptic size estimates (which come from feeling the object) are based on proprioceptive signals regarding hand posture or position. During tool use these signals would need to be multiplied by the ratio of the tool to be able to get an accurate perception of object size. If the tool model is noisy or flawed then this calculation will not occur correctly. In this case, general errors would then be made where the tool is not being controlled as intended due to the flawed model, leading to a reduction in the compensation factor.

It is also worth considering how the different ratios of the tools may impact this concept further. To be able to successfully grasp an object you must transform signals from the hand to size in the world and vice versa. This process arguably must be based on a predictive model and if this model is noisy then this process will be flawed. Previous research using virtual tools has suggested that sensitivity to object size at the hand is constant regardless of the tool used (Takahashi and Watt, 2014). However, patterns of results in previous experiments suggest that tool use, particularly with our yellow tool, seems to make sensitivity at the hand worse. It could be that signals are noisier when using the yellow tool because when grasping the same object, the hand is always going to be open wider compared to the other two tools. Because of these factors it is possible that we will see a difference in performance at this task with the three different tools. Depending on what pattern of results we see, we could also learn more about the differences in performance that we have seen with the three tools throughout the thesis so far.

Finally, by getting some participants to carry out both the size perception task and the size discrimination task as well as some normal reaching and grasping with the tools we will be able to see how these factors interact with one another. If the individuals perform similarly and the asymmetry is still present across the tasks then this would be suggestive of a common tool model being used throughout.

It is expected that we will see a difference in the accuracy of size perception with the three different tools, based on performance in past experiments. It is also expected that people will be worse at the size discrimination task with the tools than they will be when using the hand alone due to the potentially reduced tactile feedback when using the tools. Finally, it is thought that we may see a difference between the three tools in people's ability to discriminate sizes.

5.2 Experiment 3: Is perception of size biased when using tong-type tools?

This experiment will investigate whether people perceive size differently with the three tools, and with the hand, and whether this is consistent with the incomplete compensation for tool ratio that has been seen in previous experiments. As stated in section 5.1, a difference in the ability to perceive size with the three different tools could indicate a biased internal model of the tool. If participants tend back towards the appropriate opening of the hand rather than the tool tips then this would lead to incomplete compensation. By getting participants to judge the size of an unseen object with the hand and the three tools we hope to be able to investigate whether a biased internal tool model may be one of the reasons for the incomplete compensation seen in the experiments so far.

5.3 Methods

5.3.1 Participants

Eight right-handed participants (five female, three male) from the Bangor area were recruited to take part in the experiment through opportunity sampling. None of the participants had taken part in any experiments using our tools before. All had normal or corrected to normal vision and no motor impairments that would affect the ability to make a normal grasp.

5.3.2 Stimuli and Apparatus

Figures 5.1 and 5.2 show the set-up of this experiment.

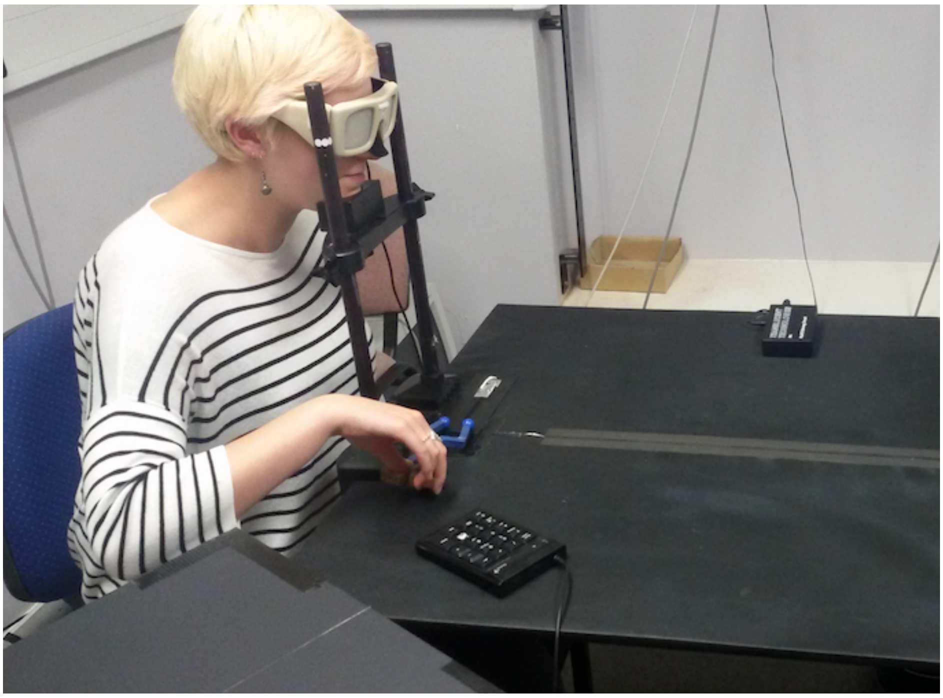


Figure 5.1. A participant in position to complete the grasping component of a trial in this experiment.

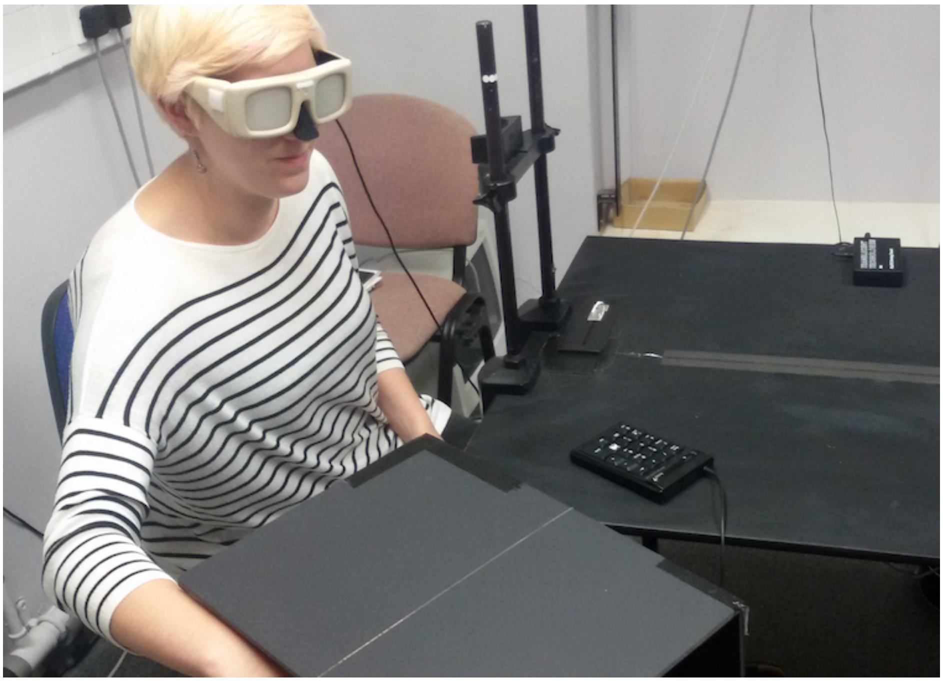


Figure 5.2. A participant in position to complete the perceptual component of a trial. The silver guideline showing object position can be seen on the occluder.

The experimental set-up was similar to that used in Experiment 1 but with some additions:

An occluding box was placed in front of the participant off to the right-hand side of the table. This was used to obscure both the tool and/or hand and the object from view during the perception trials (participants were required to feel the object with their hand and the three tools without being able to see it). The occluder had a silver line about a millimetre wide down the centre of the box to act as a guide to where the object was located. The object would always be centred below this line. Where necessary, verbal guidance from the experimenter was used to ensure the object was being grasped correctly.

The to-be-grasped object lay on a high friction material to keep it in place under the occluder (Grip Strip; Firebox, London UK; a grippy but not sticky polymer compound, see Figure 5.3). We were concerned that otherwise participants may move the object whilst they attempted to locate it when they were using the tools due to the potentially reduced tactile feedback.

Figure 5.3. The Grip Strip used to hold the object in place under the occluder whilst participants felt it during the perception component of each trial.

Two sets of objects were used in this experiment, one for the grasping trials and one for the perception trials. Both sets comprised the same object sizes (25 mm to 50 mm in 5 mm increments). The objects for the grasping trials were made out of balsa wood, as in previous experiments, so that they were easy to lift with the tools. The objects for the perception trials were made out of heavier pine wood, so they were hard to knock over when participants were feeling them under the occluder. During the grasping trials, the objects were placed at one of five distances along the body midline (200, 250, 300, 350, or 400 mm, selected at random on each trial). During the perception trials objects were always placed in the same location under the occluder to make it easier for participants to locate them without vision.

5.3.3 Procedure

Retroreflective markers were attached over the radius bone and to the thumb and forefinger if participants were taking part in a block using the hand. Whether participants started the experiment by using their hand or the tools was counterbalanced.

During the experiment, each trial was split into two parts, a grasping component and a perceptual component. Each trial began with the grasping component, the procedure for which was the same as the trials in Experiment 1. After this was complete, participants would move on to the perceptual component. The PLATO goggles would turn opaque whilst an object was placed under the occluder. The goggles were then cleared and the participant was instructed to open their hand, or the tool, widely and to reach into the occluding box along the silver guide line. Once they reached the back of the box they were instructed to close the tool/their hand slowly. The experimenter guided the participant verbally if they needed help to locate the object, and also ensured the object was being correctly grasped. The participant was able to hold the object for as long as they wanted to but could not remove it from the box. They then released the object and closed the tool/hand before removing their hand from the box. This was important so that participants could not use visual information by preserving their hand/tool aperture to complete the perceptual task. Participants reported their estimate of the object's size by adjusting the height of a thin white line displayed on a computer monitor placed to their right. Participants adjusted line height via key presses on a small handheld USB number pad, using their left hand. The line did not change in width. When it initially appeared on the screen it was a random height between 15-60mm. The grasping component of the next trial then began.

When taking part in a session using the tools, the tool used for the grasping component of a trial was changed for the perceptual component (making it one of the two tools not used in the grasping component of that trial). This was so that participants could not complete the perceptual task by mentally comparing their hand opening to those experienced during the grasping component. Over the course of each session each of the tools followed each of the other tools equally, so this selection process was not random. The tools in the grasping component were randomly ordered (as previously) so sometimes it was a repeat of the tool used in the previous perception component.

The experiment was completed in four one-hour sessions, three using the tools and one with the hand. Each session consisted of one block of trials. The first time the tools were used this block was 54 trials long and all the other blocks were 72 trials long. The first tool block consisted of fewer trials as pilot testing showed that participants tended to take longer to complete this block whilst getting used to the tools. In the shorter tool block, there were three repetitions of each of the six object sizes with each tool and in the longer ones there were four, giving 11 repetitions of each trial in total. In the hand block, there were 12 repetitions of each object size.

The experiment started with a short training session to get participants used to the timing parameters of the experiment, which were as previously. Unlike previous experiments however, void trials (releasing the start button too slowly, or too quickly) were not added on to the end of the block as this would mean that some tools were used more than others and we wanted people to be exposed to the tools equally in the grasping component of this experiment. By training the participants to understand the timing parameters of the grasp it was hoped that this would make them less likely to perform a void trial once the experiment started. Training trials were only completed using the hand and the 1:1 tool to ensure that participants were not exposed to our 0.7:1 or 1.4:1 tools before the experiment began.

5.4 Results and Discussion

5.4.1 Peak end-effector aperture

Figure 5.4a plots the peak end-effector apertures produced in this experiment. As in previous experiments, participants increased their peak end-effector aperture as the size of the object increased. It can also be seen that there appears to be little difference in the peak hand apertures produced with the hand and the blue 1:1 tool in this experiment. This is consistent with findings in past experiments. When comparing the peak hand apertures produced with the three tools it can be seen that there also appears to be little difference between the blue 1:1 tool and the yellow 0.7:1 tool. Participants do not appear to have altered their hand apertures with these two tools, suggesting little or no compensation for the yellow tool's ratio. There does appear to be some level of compensation for the red 1.4:1 tool however as participants have produced lower peak hand apertures with this tool when compared to the blue one.

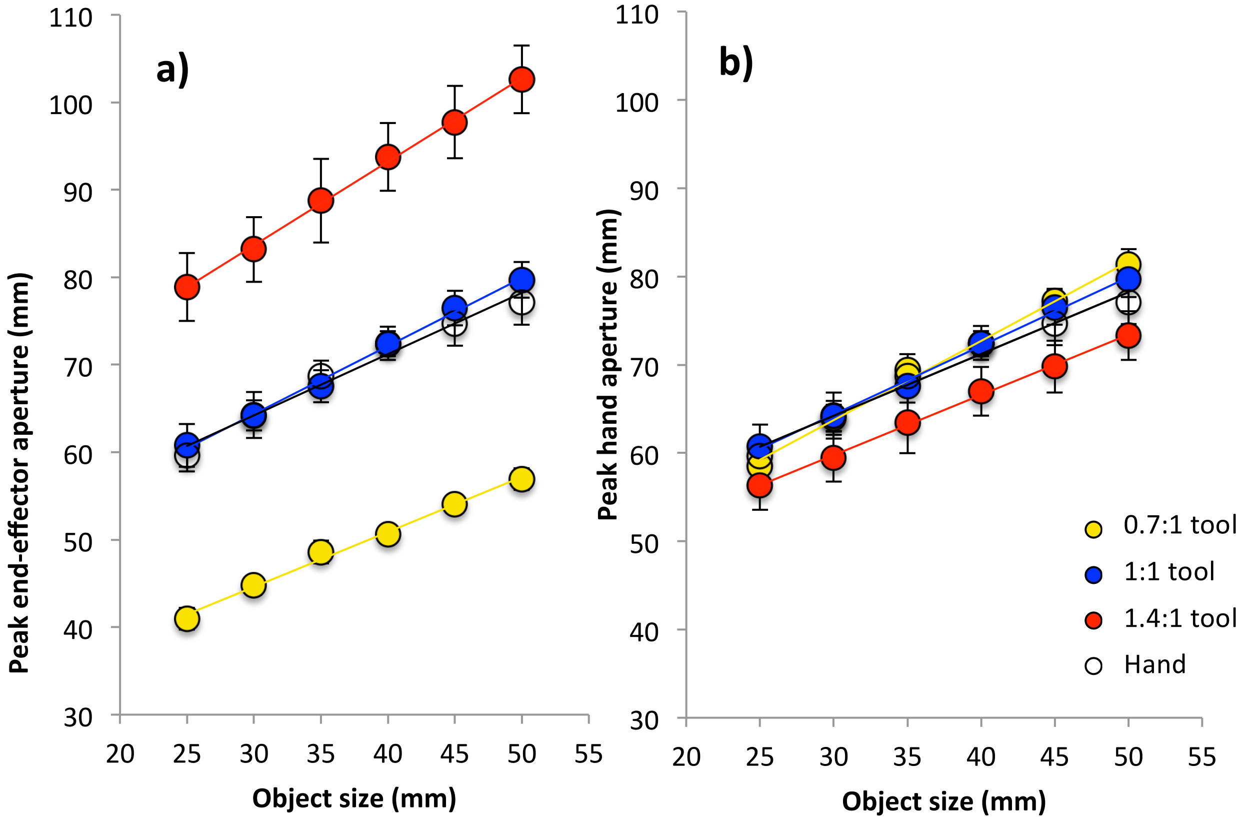


Figure 5.4. Aperture data as a function of object size, collapsed across distance. (a) In end-effector units. (b) The same data plotted in units of hand aperture. Error bars show +/-1 SEM. Linear regression lines have been fitted to the data. N=8.

A 4 x 6 (grasp type x object size) repeated measures ANOVA revealed a significant main effect of object size (F(1.57,10.97)=75.79, Greenhouse Geisser corrected, p<.001), which is in line with our previous experiments and past research (Gentilucci et al., 2004; Jeannerod, 1981; 1984; 1997; Smeets & Brenner, 1999, Wing et al., 1986; Zheng & Mackenzie, 2007). This shows that participants did alter their peak hand apertures based on the size of the object. Planned comparisons on the ANOVA were run which only compare the peak hand apertures produced with the red and yellow tools and the hand to those produced with the blue tool. This shows that there was no significant difference between the hand apertures produced with the blue tool and the hand (F(1,7)=.03, p=.860), replicating the findings of Experiment 1. We also find that there was no significant difference between the peak hand apertures produced with the yellow and blue tool ($F(1,7)=.03$, $p=.879$), but a small significant difference between the red and the blue one ($F(1,7)=8.23$, $p=.024$). This confirms that compensation is still asymmetric in this experiment. However, compensation also looks lower overall than it has been in previous experiments, with participants possibly not compensating at all for the ratio of the yellow tool.

5.4.2 Compensation factors

We can look at calculated compensation factors for the grasping component of this experiment to investigate this quantitatively. Figure 5.5 plots these and confirms that there was essentially zero compensation present for the yellow tool in this experiment. There was, however, some compensation present for the red tool (0.27), although this is lower than it was in both Experiment 1 (0.46) and the closed-loop component of Experiment 4 (0.42). So, this confirms that not only is the asymmetric compensation still present in this experiment but overall compensation was lower than our previous experiments as well.

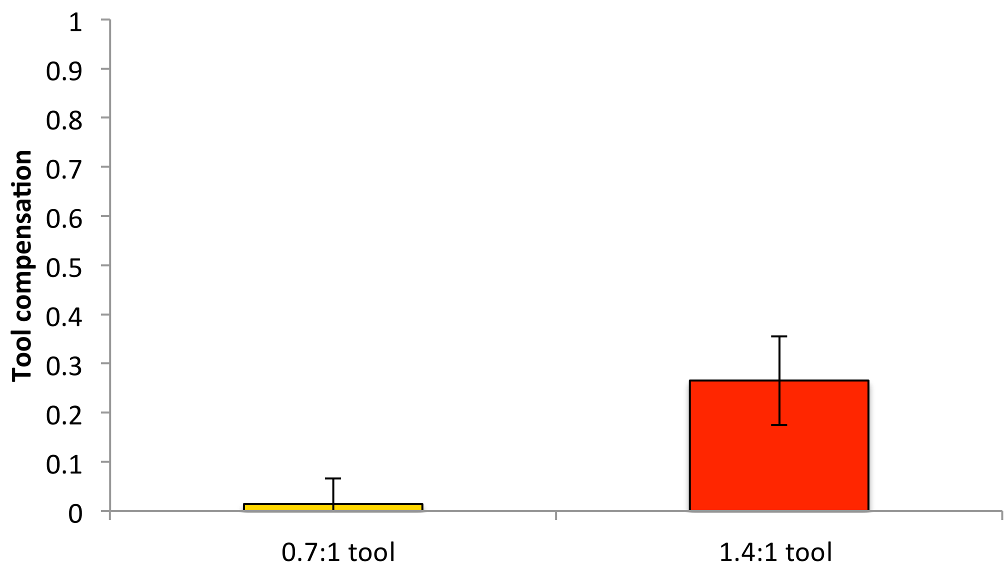


Figure 5.5. Average compensation factors for the grasping trials of Experiment 3. Error bars show +/-1 SEM. N=8.

Figure 5.6 presents the compensation figures broken down by experimental block. Here it can be seen that whilst the compensation factor for the red tool did not change throughout the experiment, the factor did increase for the yellow tool block-by-block. This suggests that participants' performance with the yellow tool may have been improving as the experiment went on, possibly suggesting slow learning of the yellow tool, although it still remained at a low level at the end of the experiment. A 2 x 3 (tool type x experimental block) repeated measures ANOVA confirms that the effect of block was not significant, however ($F(1.2,8.4)=.90$, Greenhouse Geisser corrected, $p=.390$).

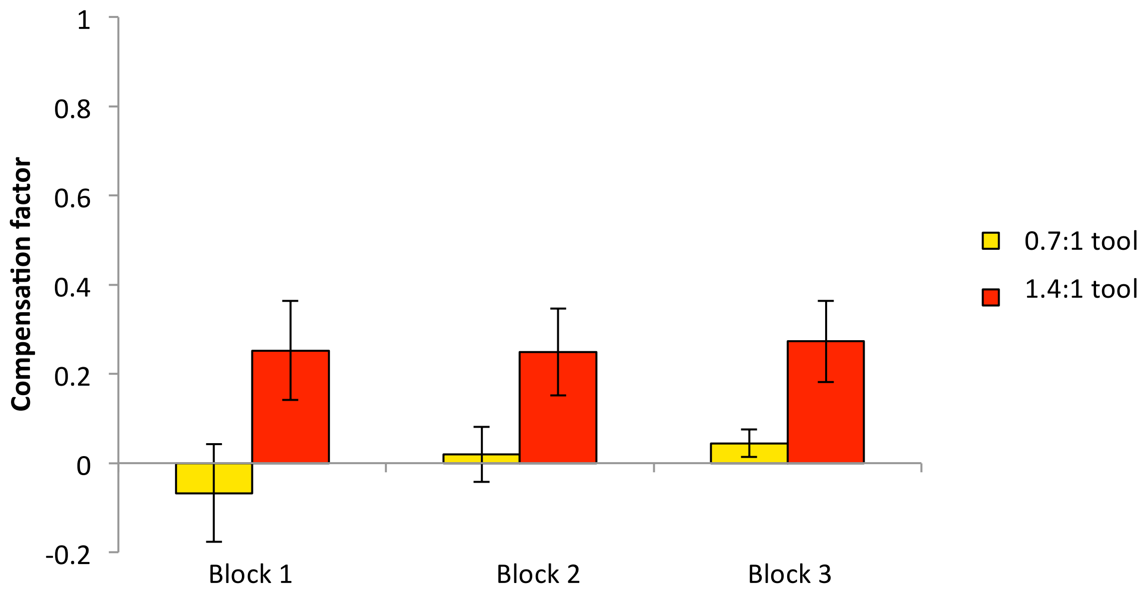


Figure 5.6. Compensation factors for each block of the experiment. Error bars show +/-1 SEM. N=8.

Figure 5.7 plots the compensation factors for each participant in this experiment. Here it can be seen that there are individual differences, with some participants showing much larger compensation factors than others, and with some not compensating for either tool at all. As in Experiment 1, there is also one participant who shows a larger compensation factor for the yellow tool than they did for the red one (PB).

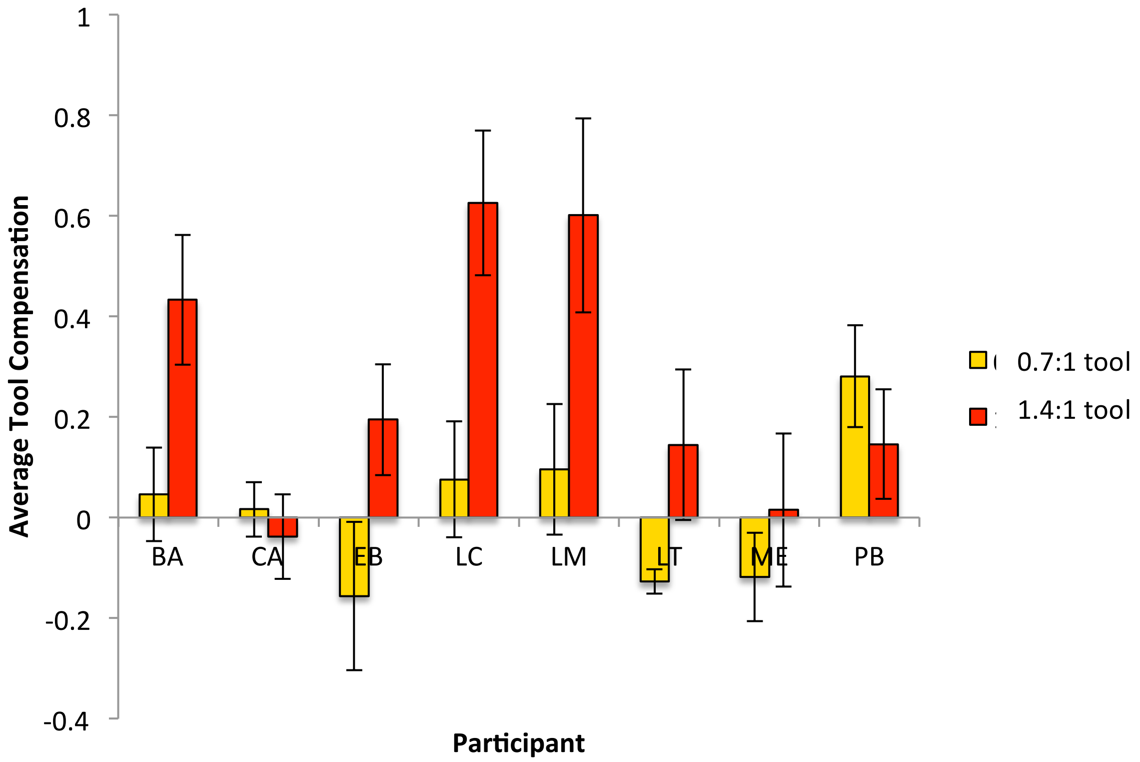


Figure 5.7. Compensation factors for each participant in Experiment 3. Error bars show +/-1 SD

5.4.3 Reported perceived size

Figure 5.8 shows the average reported perceived size of each object size when feeling the object with the hand and the three tools. The size estimates in all conditions had a smaller range than the actual variation in physical size (perfect performance indicated by the dashed line). We have assumed hand performance to be accurate and suggest that a range effect is likely present in this experiment, possibly caused by the response scale used. Whilst possible to correct for this by normalising the tool data with respect to the hand, it has been decided to present the 'raw' values in the thesis so as not to present adjusted values.

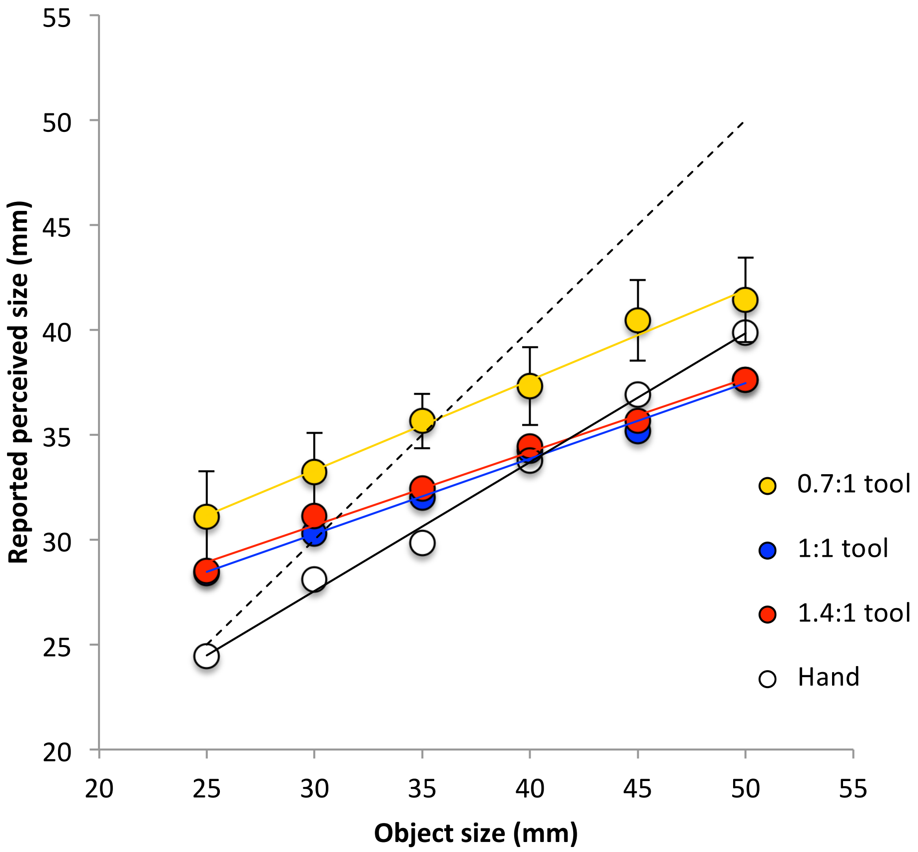


Figure 5.8. Average reported perceived size. Perfect performance is shown as a dashed line. Error bars show +/-1 SEM, but are too small to see on some data points. Linear regression lines have been fitted to the data. N=8.

The data with the hand is difficult to compare to the blue 1:1 tool visually based on the differences in scaling, so this will be discussed statistically shortly. It is clear, however, that performance with the red 1.4:1 tool and the blue 1:1 tool was very similar. This supports the idea of an accurate internal model of the red tool. Data for the yellow 0.7:1 tool however are slightly different. Whilst the slope of the scaling function appears similar to the other two tools, there is quite a clear offset in participants responses for the yellow tool, with participants consistently overestimating the size of the object with the yellow tool compared to the blue one. This could suggest a bias in the internal model of the yellow tool.

A 4 x 6 (grasp type x object size) repeated measures ANOVA reveals a main effect of object size ($F(5,35)=85.25$, $p<.001$). This confirms that while the response ranges are slightly suppressed that there is an altering of response based on the actual size of the object. The responses given for the hand alone condition have a slightly larger range than those with the tools, which is confirmed by a significant grasp type x object size interaction ($F(15,105)=3.54$, $p<.001$).

Planned comparisons on the ANOVA that compare reported perceived size for the hand, red tool and yellow tool to the blue tool show that there is no significant difference between the reported perceived size with the blue tool and the hand ($F(1,7)=.27$, $p=.617$) or with the blue tool and the red tool ($F(1,7)=.30$, $p=.600$). There was however a significant difference in the reported perceived size between the blue tool and the yellow tool with participants reporting the object size to be significantly larger when using the yellow tool ($F(1,7)=12.75$, $p=.009$). As discussed previously, an overestimation of object size with the yellow tool could be a sign that the participants' internal model of the yellow tool is biased towards the opening of the hand. If participants are overestimating the opening of the tool tips when using the yellow tool, based on this bias towards hand opening, then this could account for the partial compensation seen with this tool in previous experiments. Flawed calculations based on a biased internal model could cause participants to think that they are opening the tips wider than they actually are, and this behaviour would cause a reduction in compensation. Size perception with the red tool is no different to that with the blue one however, suggesting that a biased internal model may not be able to account for the partial compensation seen so far with this tool. This could account for the asymmetry in compensation that we have seen for the two tools throughout the thesis so far however. If something else is driving the overall incomplete compensation an additional bias in the yellow tool's internal model would lead to this asymmetry. Accounting for this bias could eliminate the asymmetry and then there is something else causing the overall under-compensation observed so far with both of the tools.

5.5 Experiment 4: The effect of tool ratio on haptic sensitivity at the hand

Experiment 3 demonstrated that perceived object size differed with the yellow tool compared to the blue and red tools and the hand. When using the red or blue tool to feel an object, participants estimated its size to be the same. However, they judged objects to be larger when they used the yellow tool to interact with them. Because participants judged object size in a similar manner with the blue and red tools it seems unlikely that a biased internal tool model can account for the overall reduction in compensation seen throughout the thesis so far. Therefore, the current experiment will investigate another potential cause for the partial compensation seen. Both tactile signals and haptic size estimates could potentially be affected by tool use. The damping that was discussed in section 5.1 with respect to tools in general, but particularly our rubber tipped tools, makes it less obvious to the user when they have contacted the object. Arguably this reduction in tactile signal could affect tool compensation because it reduces the certainty under which an internal model can operate. More importantly however, haptic size estimates which come from feeling the object, are based on proprioceptive signals regarding hand posture or position. During tool use, these would therefore be noisy estimates if they were calculated by estimating the hand opening and multiplying this by a noisy internal tool model. This issue could lead to a reduction in compensation for tool ratio.

This experiment will investigate whether there is a difference in participants' ability to differentiate between two object sizes when using the tools compared to the hand and whether their ability differs across the three tools themselves. Logically, if the participant's internal tool model is based on noisy haptic feedback then this could also lead to a difficulty in differentiating sizes. We planned to measure this and see whether the pattern of results could account for the performance seen in previous experiments. By also getting this sample of participants to complete a shorter version of Experiment 3 we were able to see whether the haptic sensitivity results link back to performance in the size perception and grasping tasks as well.

5.6 Methods

5.6.1 Participants

Six participants (5 females and 1 male) initially took part in the experiment. Two dropped out part way through, however; one due to a lack of time and the other due to a broken hand (leaving 3 females and 1 male who completed the experiment). Participants were recruited through opportunity sampling from a pool of previous participants, so none were naïve to the tools.

5.6.2 Stimuli and Apparatus

The experiment was split into two parts: (i) a shorter replication of Experiment 3, using the same apparatus and stimuli, (ii) and a perceptual size-discrimination task, completed separately. Therefore, for information on the stimuli and apparatus relevant to (i) see section 5.3.

For the size discrimination task, the start location was a ball of plasticine that participants could rest their finger and thumb or tool tips on at the edge of the scanner bed device (see Figure 5.9a).

The experimental objects were different to those used in the previous experiments. Different object “sizes” were created on a trial-by-trial basis using two moveable, motorised metal planes controlled by a computer (see Figure 5.9). Each plane could be moved independently to create differently sized “objects”, at different distances. The minimum size object that could be created was ~6.6 mm, and the resolution in size (2 x the smallest possible movement of the stepper motors controlling the plates) was ~0.1 mm.

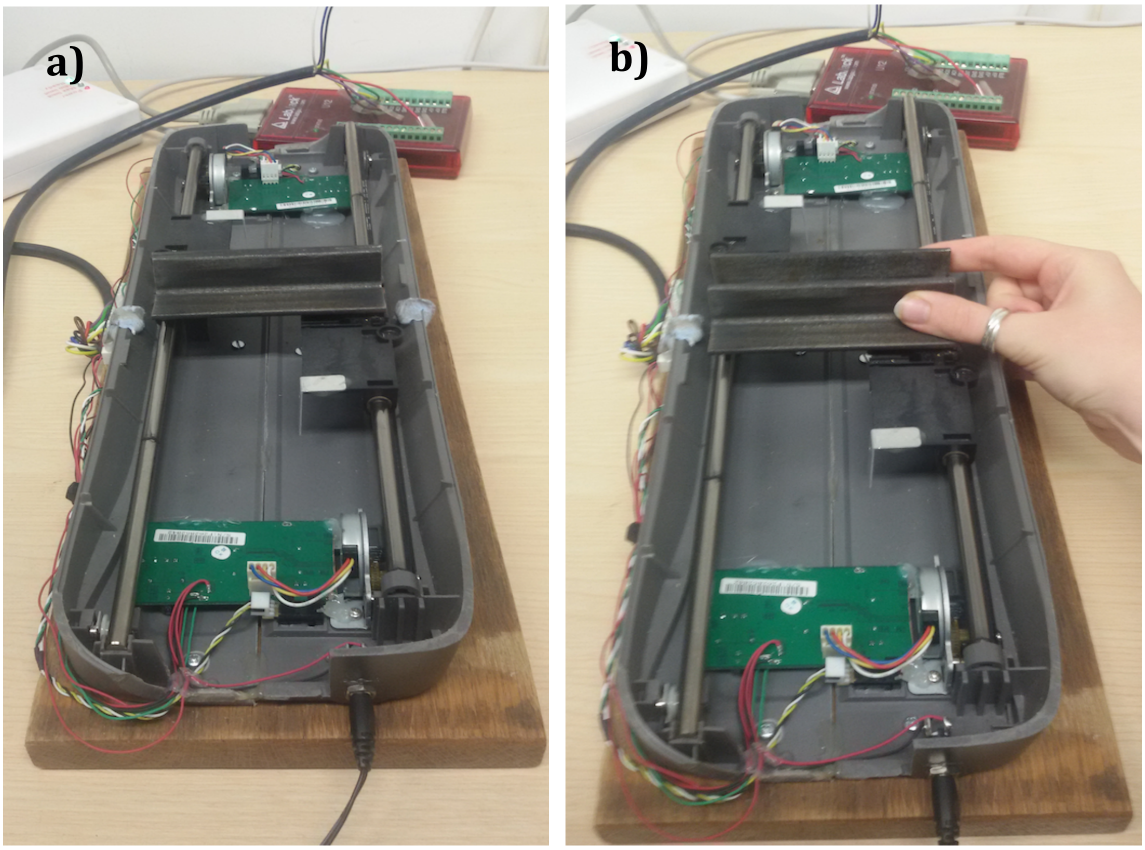


Figure 5.9. The machine used to create the objects in Experiment 4. (a) with no object created with the two planes flush together (b) a participant grasping an object with the hand.

Throughout the experiment there were base object sizes that participants compared on each trial to a larger or smaller comparison size. For the yellow tool, the base size was 28 mm and for the red tool the base size was 56 mm.

There were three base sizes used for the blue tool and the hand 28 mm, 40 mm and 56 mm. These base object sizes were chosen so that performance with the hand could be compared to that with the blue tool over a range of sizes. This was important as similar performance has been shown when using the blue tool and the hand in previous experiments and therefore by comparing haptic sensitivity performance in these two conditions we can start to answer the question of whether haptic sensitivity is generally poorer when using a tool compared to the hand. Using these base object sizes, performance with the blue tool can then be compared to that of the red and yellow tools. This is because the red (56 mm) and yellow (28 mm) base objects both result in a 40 mm hand opening when being grasped. By comparing performance with these two base object sizes with the 40 mm base object when using the blue tool comparisons of performance across tools can also be made.

An occluder (see Figure 5.10) ensured that vision could not be used to complete the task.

Figure 5.10. The experimental set-up showing a participant feeling an ‘object’ underneath the occluder.

The tools used in this experiment were the same as those described in the section 2.2 with one exception. During pilot testing of this experiment it became obvious that participants found it difficult to tell that they had grasped the object successfully, making the task difficult to achieve. This is linked to the reduction in tactile feedback mentioned above. We found that replacing the black rubber balls on the tips of the tools with solid plastic balls of the same diameter solved this problem (by increasing the tactile signal to object contact, and providing an auditory cue). After a brief training period, all participants were able to successfully tell when they were grasping the object.

5.6.3 Procedure

The order in which participants completed the two parts of the experiment (perception/grasping and size discrimination) was counterbalanced.

The procedure for the perception trials of this experiment was the same as Experiment 3, with the exception that participants completed fewer trials (to reduce the overall duration of the experiment). These trials were completed in one session of three blocks, one with the hand and two with the tools. As with Experiment 3, block order was counterbalanced.

For the size discrimination task, participants completed a 2-IFC task, feeling two objects, one after another, and quickly responding as to which was larger. Stimulus comparison was controlled using adaptive staircases (both 1 up, 2 down, and 2 up, 1 down) that responded to the participant's task performance – making the task easier as they got answers incorrect and harder when they got them correct. Once either 10 reversals or 100 trials had been completed then the block was over and the participant was given the chance to have a break or end the session. A reversal occurs when the staircase changes direction, for example in a 1 up, 2 down staircase getting one answer right would make the task harder, but you would need to get two answers wrong to make it easier. This means that if the participant gets an answer correct and then two wrong that will count as one reversal as the task would have got harder and then easier.

Each participant had a different randomised block order. Each block consisted of one of the two staircase rules, for one base object size using one of the tools or the hand. Each participant therefore completed 4 blocks with both the yellow and red tools (a base object size of 28mm and 56mm respectively with two repetitions of each staircase type) and 12 blocks with the blue tool and the hand (base object sizes of 28mm, 40mm and 56mm with two repetitions of each staircase type). This resulted in a list of 32 different blocks that was randomised for each participant. It was decided that because the task was not investigating learning then it did not matter how many sessions the participant took to complete the experiment. Typically, people completed 4-5 sessions of 2 hours, usually consisting of 8-10 blocks in each session.

Trial procedure was as follows. Two object sizes were presented, one after the other, in each trial. An audible beep indicated to the participant that the object had been formed and was ready to grasp. When not grasping the object, participants rest their tool tips/finger and thumb on the start position in a closed position. The participant’s task was to respond as to which interval (first or second) contained the larger object. They were instructed to answer as quickly as possible. If participants did not offer an answer immediately after feeling the second object the experimenter prompted them for an answer. Participants would always be comparing the base object size to a comparison size on any given trial, which order these were presented in was randomised. The size of the comparison object was adjusted based on the rules of the staircase and the previous answer of the participant. The objects moved in distance from the participant as well as in size on each trial to ensure that the task could not be done by simply comparing the position of a single digit across stimulus intervals.

Participants were trained at the start of each session to feel the stimulus for a certain duration and to get used to the 1.5 second inter-stimulus interval. This was because once a trial had started it continued automatically, therefore participants needed an understanding of what would happen during a trial. If they felt an object for too long, the trial would continue and the object would begin to move whilst they were still grasping it, and the second object would not properly form. Training avoided these issues as participants quickly picked up the timings of a trial. Any void trials that did occur were repeated immediately after the voided one, but participants were not aware that they were feeling the same two objects as before. No feedback was given to the participant regarding their performance during the experiment.

5.7 Results and discussion

5.7.1 Grasping results

Figure 5.11 shows the average peak end-effector apertures and the average peak hand apertures produced when grasping objects with the three tools and the hand. This is the data that was collected in the replication of Experiment 3. The results of this section will only be discussed briefly as a sanity check that sensible performance is being seen.

Peak end-effector aperture scales with object size, however, contrary to previous experiments, there is a difference in the apertures produced with the blue 1:1 tool and the hand. Here, participants produced a wider end-effector aperture when grasping an object with the hand than they did with the blue 1:1 tool.

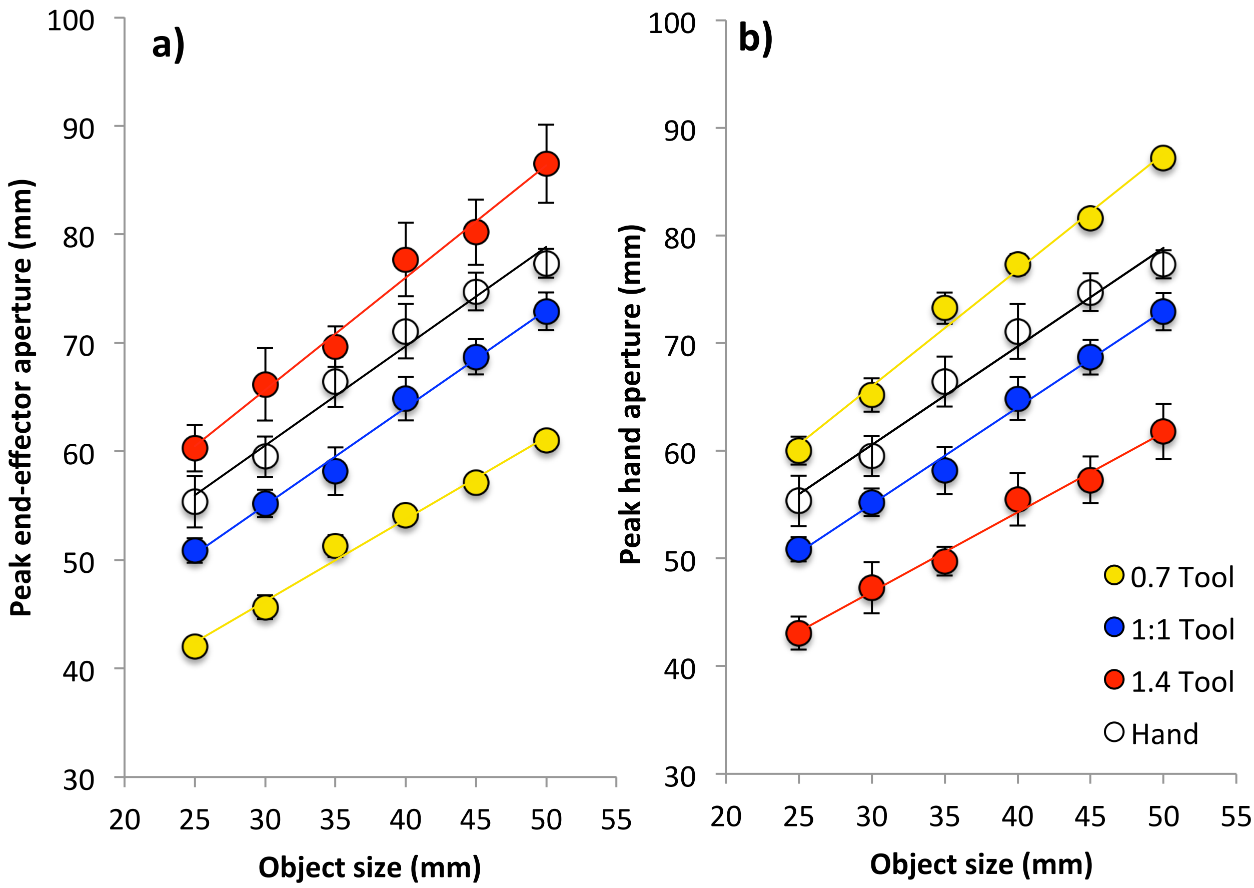


Figure 5.11. Aperture data from Experiment 4, as a function of object size collapsed across distance. (a) In peak end-effector units. (b) The same data plotted in units of hand aperture. Error bars show +/-1 SEM. Linear regression lines have been fitted through the data. N=4.

Looking at Figure 5.11 there appears to be no asymmetry in the degree of tool compensation for the yellow 0.7:1 and red 1.4:1 tools. Figure 5.12 shows that participants have compensated similarly for the two tools in this experiment. A paired samples t-test showed no significant difference between the compensation factors for the two tools ($t(3)=-0.33$, $p=.763$). Whilst compensation was still not perfect in this experiment it was equal across the two tools for the first time in our experiments. This may not be a ground-breaking finding however. All four participants had taken part in previous experiments for us and therefore were more practiced with the tools than some of our previous participants. Also, as mentioned previously there were individuals who compensated equally for the two tools in previous experiments, this was just a far more uncommon pattern of compensation. One of the participants who took part in the present experiment (WW) has shown either larger compensation for the yellow tool or equal compensation for the two tools in all of the experiments that he has participated in so far. However, as we only have four participants in this experiment, then getting one or two 'equal compensators' would have a much larger effect on the average compensation factors than it would have done in previous experiments with larger samples.

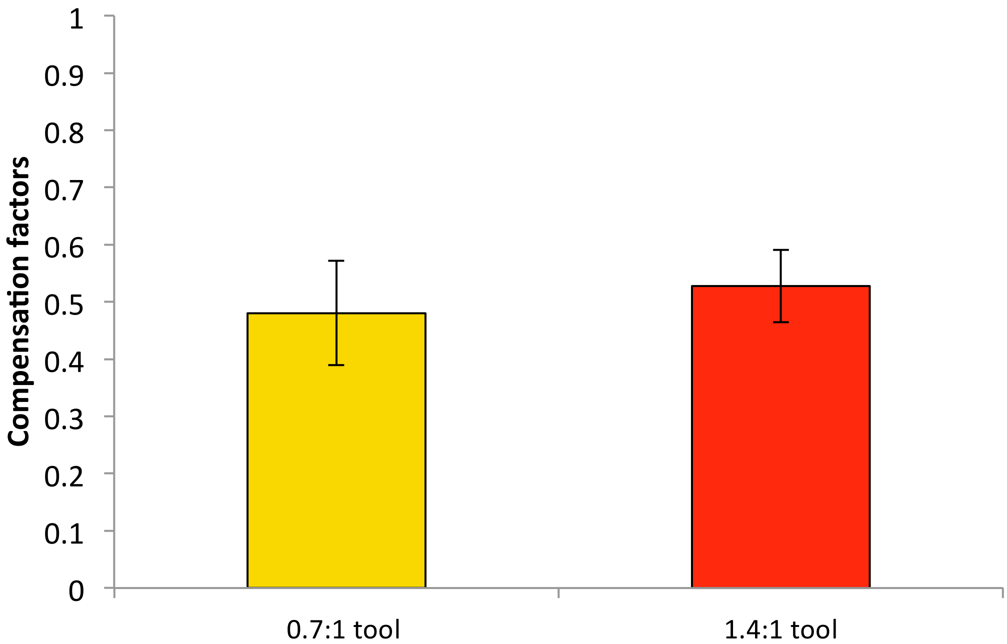


Figure 5.12. Tool compensation factors for the 0.7:1 and 1.4:1 tools. Error bars show +/-1 SEM. N=4.

Figure 5.13 shows the compensation factors for the four participants for the red and yellow tools. It can be seen that WW compensated much more for the ratio of the yellow tool than he did for the red one. KS appears to compensate for both tools equally and LR and SH both showed the asymmetric compensation in favour of the red tool that we have seen overall in the previous experiments.

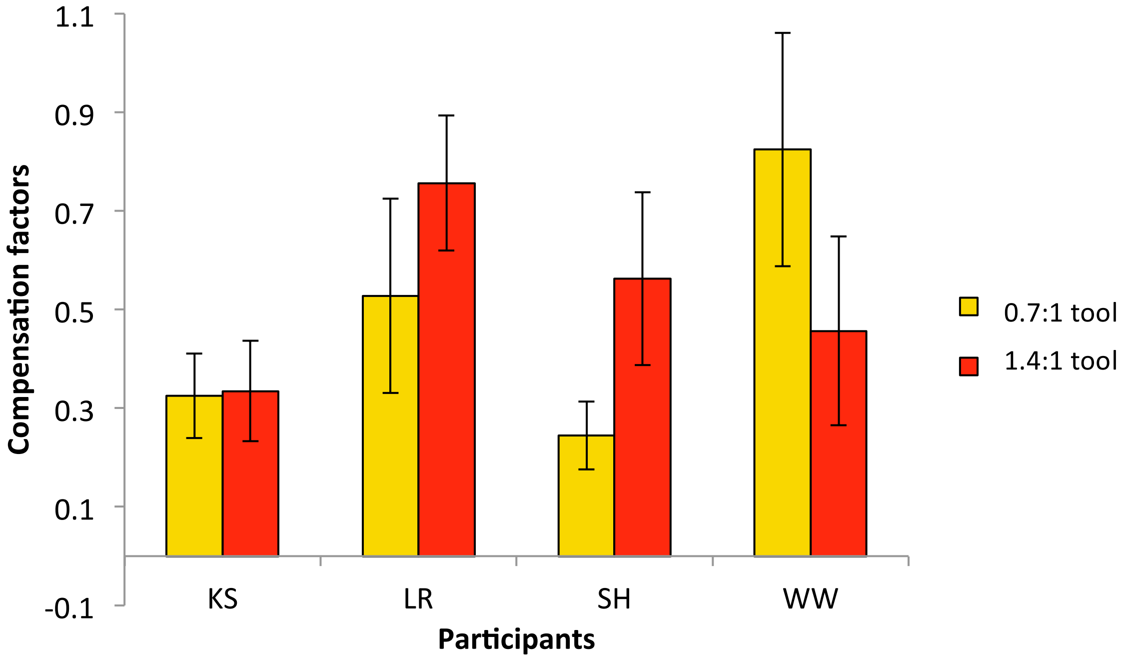


Figure 5.13. Individual participant's compensation factors for the 0.7:1 and 1.4:1 tools. Error bars show +/-1 SD.

5.7.2 Perception results

Figure 5.14 plots the average reported perceived object size for the three tools and the hand during this experiment. Performance appears to be broadly similar to that of Experiment 3. We see the same restriction in response scale with both the hand and the tools, however the effect is stronger in the tools. More importantly, we also see the same pattern of results with the three tools. Where participants have perceived size to be the same when using the blue 1:1 tool and the red 1.4:1 tool but have judged objects to be consistently larger whilst using the yellow 0.7:1 tool. Again, this is supportive of the idea that participants have a biased internal tool model for the yellow tool, and believe that the tool tips are opened more than they actually are. It is interesting however that in this sample of participants the asymmetry in compensation factor with the yellow tool is not present, however the overestimation in size still is.

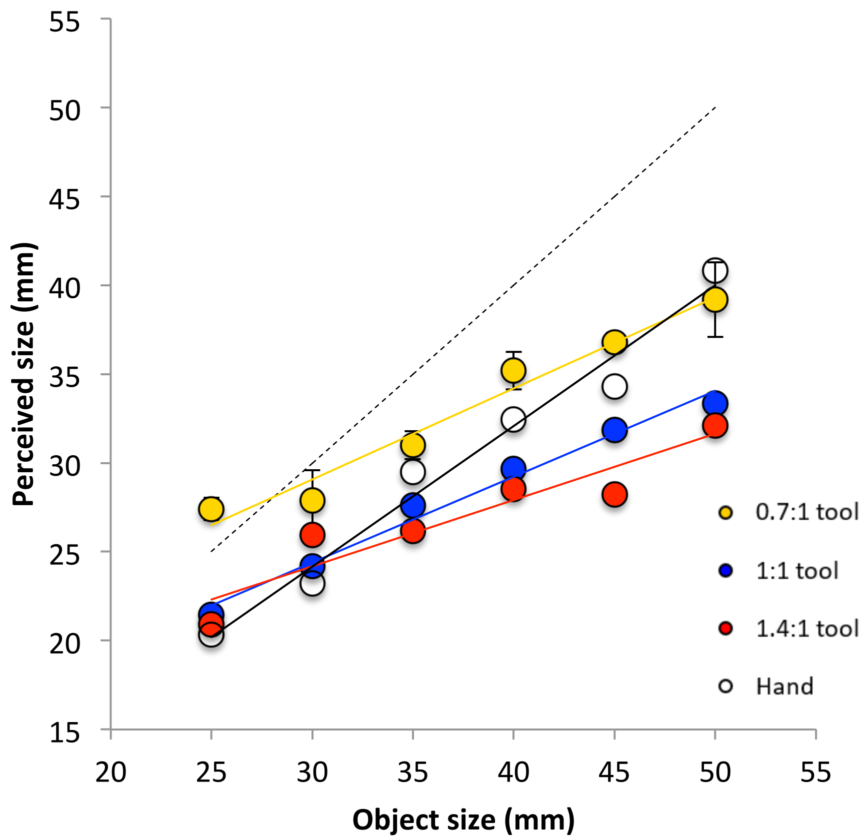


Figure 5.14. Average reported perceived size judgements with the hand and the three tools. Perfect performance is plotted as a dotted line. Error bars show +/-1 SEM and are small enough for the hand data to be concealed by the data points. Linear regression lines have been fitted to the data. N=4.

5.7.3 Haptic size sensitivity

Figure 5.15 shows the Just Noticeable Differences (JNDs) for the hand and the blue 1:1 tool in this experiment. In this experiment, a JND is the smallest size difference between the base object and a comparison object that can be reliably noticed. This was calculated by fitting a cumulative normal distribution psychometric function to the data and taking the standard deviation of this function. For the red and yellow tools, this was then divided by the tool ratio to transform the JNDs into hand units. Figure 5.15 shows that the JND increased as the base object size increased for both the hand and the blue tool. There also seems to be no difference in performance with the blue tool and the hand, although JNDs were more variable with the blue tool.

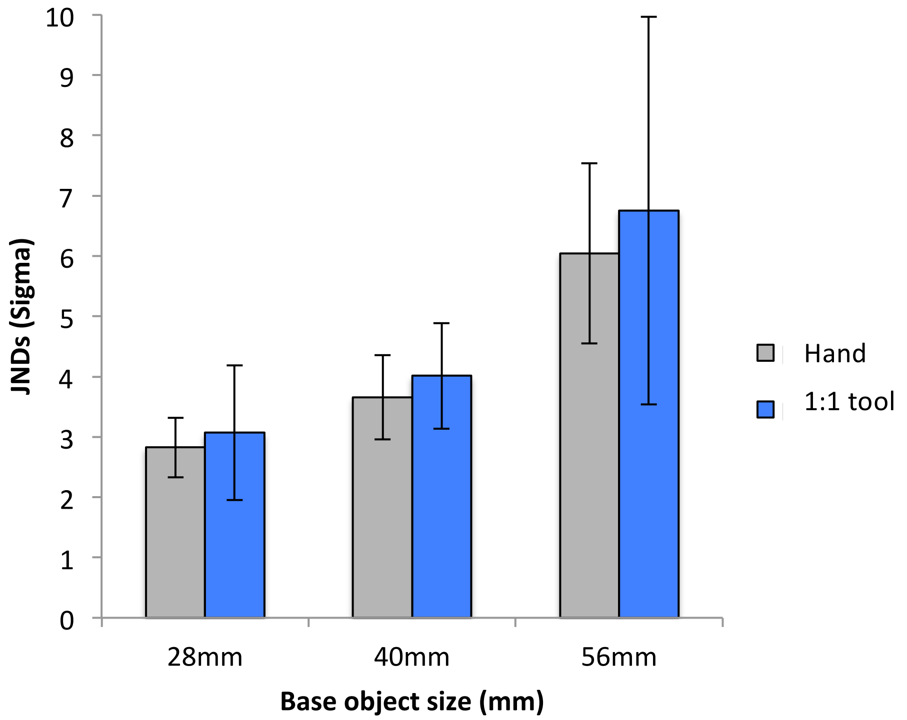


Figure 5.15. JNDs for the different base object sizes with both the hand and the blue 1:1 tool. Error bars show +/-1 SEM. N=4.

We hypothesised that haptic size estimates during tool use would be created by taking information known at the hand and multiplying this by a potentially noisy internal model for the tool. For our simplest case, the blue tool, participants were equally good at size discrimination when compared to the hand. However, the only transformation that participants needed to adjust for here is the spatial offset between the hand and the tool tips, there is no gain transformation to calculate making this a less complex calculation for the brain.

Figure 5.16 shows the JNDs for the hand and the three tools when the base object size related to a 40mm hand opening. It can be seen here that the JNDs for the hand, the blue 1:1 tool and the red 1.4:1 tool all seem to be a similar size. This means that participants seem to be equally good at size discrimination when using the hand or either of these two tools. The JND for the yellow 0.7:1 tool however is larger than the other three. This could suggest that when using the yellow tool that participants found it harder to discriminate between small changes in object size than when using the other two tools.

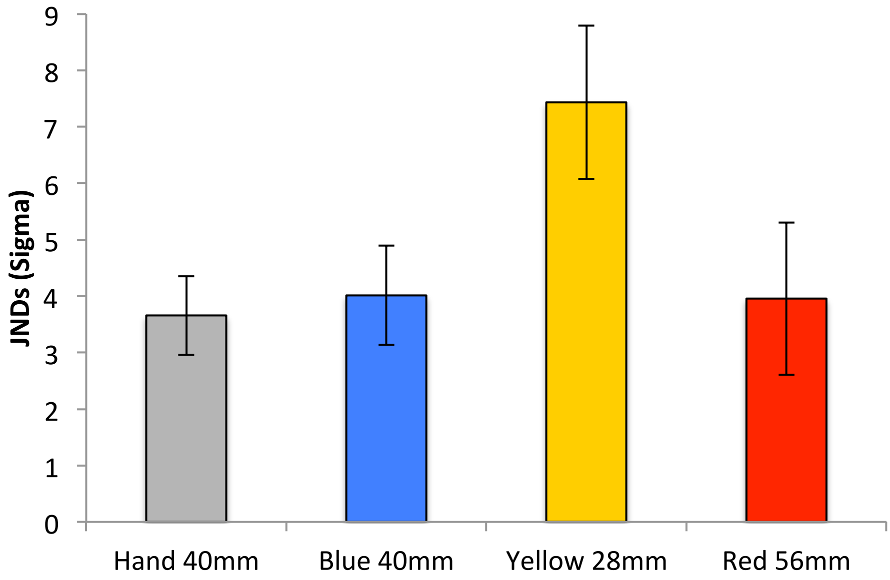


Figure 5.16. JNDs for the base object sizes that correspond to a 40mm base hand opening, for the hand and the three tools. Error bars show +/-1 SEM. N=4.

We hypothesised that a noisy internal tool model could lead to poorer haptic size estimates during tool use. We therefore expected that we could have seen larger JNDs for the red and yellow tools as these involved incorporating information about the tool ratio into any judgements about object size. If the information about the tool ratio is biased or incorrect then this would lead to poorer performance in this task and therefore a larger JND. It can be seen that this is partially the case. JNDs with the yellow tool were almost twice that of the blue tool. Whereas JNDs with the blue tool, the red tool and the hand all appear to be relatively consistent. One reason for this pattern of results would be that, as with the perception component of Experiments 3 and 4, that this biased model is only present for the yellow tool. Therefore, when using the red tool participants were able to perform the necessary calculations correctly. But working off an incorrect model for the yellow tool, performance suffered which led to higher JNDs. We only used one base object size for the red and yellow tools in this experiment due to the fact that the study was already very long without including multiple objects for each tool. It would therefore be interesting in a future experiment to assess whether different sized objects have different JNDs for tools with different ratios, as was seen in this experiment with the hand and the blue tool.

This experiment shows that using a tool per se does not appear to alter the haptic sensitivity at the hand. However, when using a tool where the tool tips are open less than the handles, as is the case with our 0.7:1 yellow tool haptic sensitivity does seem poorer. It was discussed in section 5.1 that sensitivity to hand opening appears to be poorer with the yellow tool. The results of this experiment confirm this as when JNDs are calculated in units of hand opening (as above), performance with the yellow tool is significantly poorer than the other two tools or the hand. This shows that participants are less sensitive to hand opening when using the yellow tool than they are in any other condition in our experiment. This pattern of results is all consistent with participants having a noisy internal model of the yellow tool.

As with the compensation factors in the grasping section of the experiment there were individual differences with the JNDs. Figure 5.17 plots the JNDs for each participant. When looking at the data at an individual level there is some evidence of the tools causing higher thresholds than the hand, and that performance with the red and yellow tools is often worse than performance with the blue one (although especially so with the yellow one). Therefore, it would be interesting to run this experiment again in the future with a much larger sample size to investigate this further.

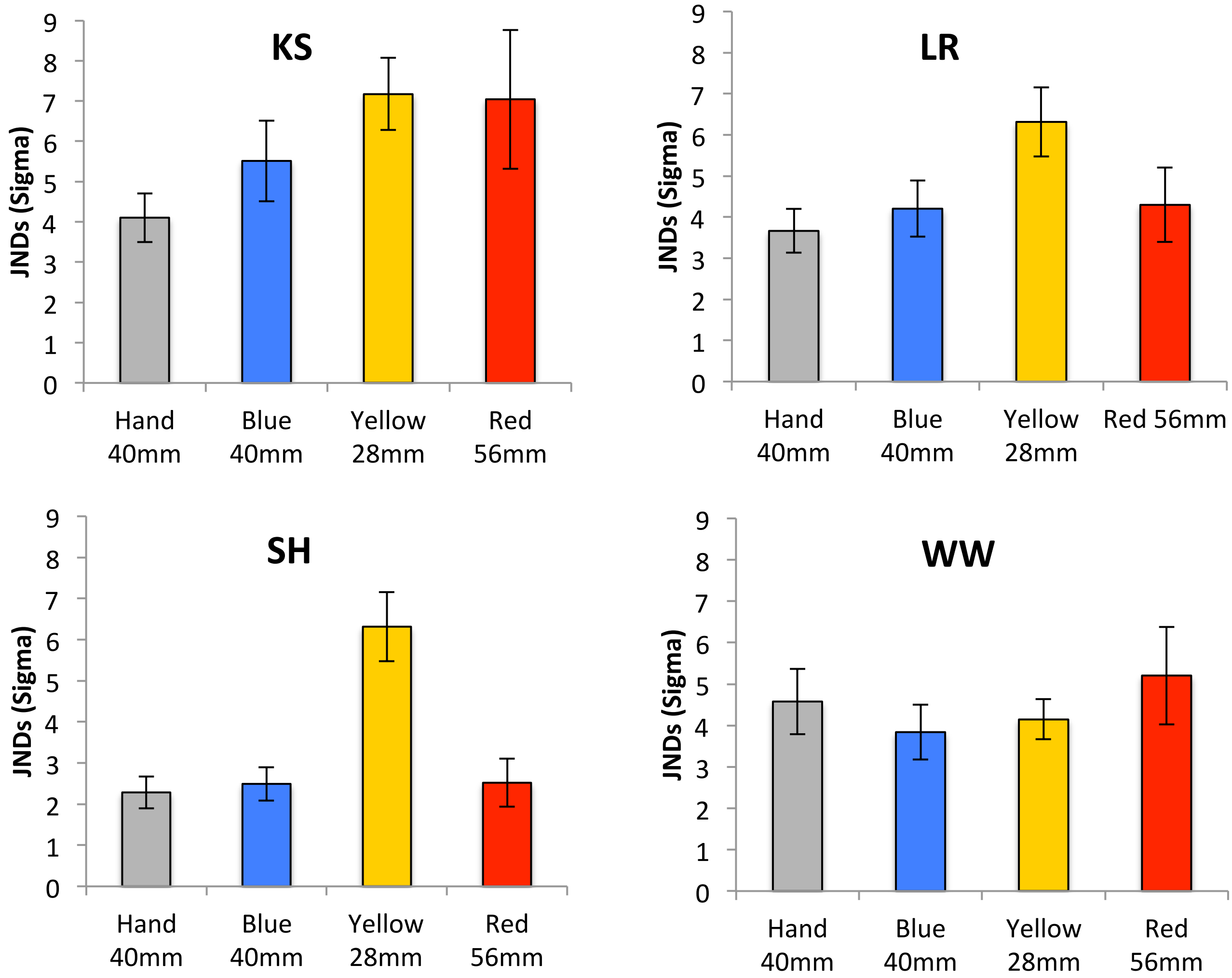


Figure 5.17. Individual JNDs for base object sizes that correspond to a 40mm hand opening. Error bars show +/-1 SEM.

appear to correspond to the levels of compensation seen in the grasping component of this experiment (Figure 5.13). Both LR and SH showed higher levels of compensation for the red tool than they did for the yellow one. When looking at their JNDs in Figure 5.17 it can be seen that they both have lower JNDs for the red tool than the yellow one. Further than this SH showed a larger asymmetry in her compensation factors than LR did, and she also shows a larger difference in JNDs for the two tools. WW compensated more for the yellow tool in the grasping component of this experiment than he did for the red one and again we see (slightly) lower JNDs for him when he uses the yellow tool than when he uses the red one. Finally, KS showed equal compensation for both the yellow and the red tools and shows equal JNDs for both as well. By running a one-tailed Kendall's tau (chosen due to the very small sample size) it can be seen that compensation factor has quite a strong negative correlation with JND ($\tau=-.62$, $p=.017$). This means that the higher the compensation factor is for a tool the lower the JND is likely to be.

This is confirmed by plotting the data on a graph (as we have such a small sample size). Figure 5.90 shows participants JNDs plotted against their compensation factors for the red 1.4:1 and yellow 0.7:1 tools. The strong negative correlation can be seen in both instances, although it is stronger for the yellow tool.

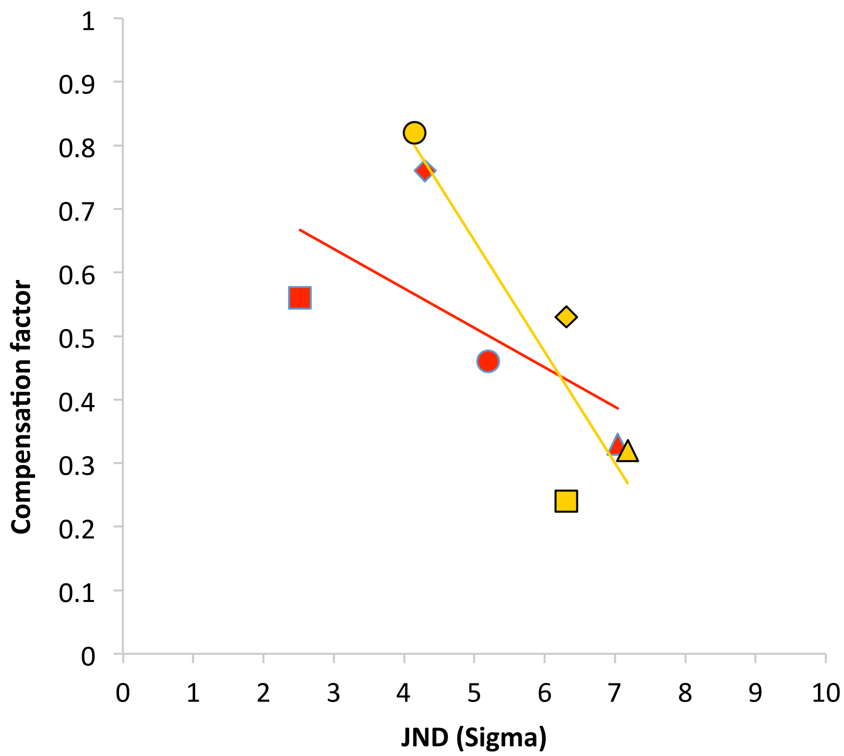


Figure 5.90. Participants compensation factors plotted against their JNDs for the red and yellow tools. Linear regression lines have been fitted to the data.

So, it would seem that when you are better at compensating for the ratio of a tool you will also be able to make finer size discriminations with it as well. This may demonstrate an overall better understanding of the transformation of the tool and this therefore allows better performance at all tasks with that tool. Or it could be that being able to tell smaller differences apart with a tool allows you to use it more accurately or vice versa. Uncertainty in a tool's model can lead to an estimate of tool ratio that is biased towards the typical, in this situation the hand or biased towards the mid-range. The pattern of results seen in this experiment suggests that this is what is occurring for the yellow tool. The brain knows that the internal model of the yellow tool is poor and is therefore uncertain about how using it in movement predictions will play out. It therefore biases the tool model towards that of the hand which it knows to be a reliable model, lowering compensation for tool ratio and reducing the ability to make fine size discriminations. This could therefore be the reason for the partial compensation seen in previous experiments with the yellow tool. We had initially suggested that potentially an overall problem with haptic size estimates when using the tools may have reduced compensation with both the red and the yellow tools. This however seems not to be the case as people were able to perform this task equally well with the hand, the blue 1:1 tool and the red 1.4:1 tool. However, this concept can help to explain the overall issues seen with the yellow tool throughout the thesis so far.

It would be interesting to find more participants who show the asymmetry in favour of the yellow tool and test them using the haptic sensitivity task and see if they too show larger JNDs for the red tool than the yellow one. This would involve testing a much larger range of individuals, as we have not found many people throughout all of the experiments we have ran so far who show this pattern of compensation. However, by running this experiment on a larger group of people hopefully a stronger case could be built up that these two factors are related to one another by testing more participants who show different patterns of compensation with the two tools.

5.8 Chapter discussion

In previous experiments it has been shown that participants only partially compensated for the ratio of the tool that they were using. It was also shown that participants generally compensated more for the red 1.4:1 tool than they did for the yellow 0.7:1 one. In this chapter, we examined whether the concept of a biased or flawed internal tool model could account for the overall under-compensation that we have seen with the tools throughout the thesis so far. If participants do indeed have internal models of tools as has been suggested in past research (Imamizu et al., 2000; 2003, Takahashi, 2012, Takahashi & Watt, 2017), then it is possible that a systematic bias in the model towards the opening of the hand or a general error in its calculation could lead to lower compensation for tool ratio.

Experiment 3 assessed participants' abilities to accurately judge the size of an object with the hand and the three tools. Here we demonstrated that participants perceived objects to be larger when using the yellow 0.7:1 tool than when using the hand, the blue 1:1 tool or the red 1.4:1 tool. Whilst this finding does not explain the overall under-compensation seen with both tools in the previous experiments, it does contribute to our understanding of the asymmetric compensation seen throughout the thesis so far. This overestimation of size with the yellow tool could suggest a biased internal model. If participants' estimates of end-effector aperture are biased towards the opening of the hand, this calculation will lead to the belief that tool tips are open further than they actually are. This would result in an under-opening of the yellow tool when grasping an object and a lower compensation factor. A bias towards hand opening is a sensible strategy if the reliability of the internal model is questionable. In this situation, it would make sense to revert to the known and tested model of the hand. This finding still fits with the concept of programming motor movements in terms of end-effector control (Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Umiltà et al., 2008). The brain could be programming movements in this manner but a bias in the internal model of the yellow tool prevents the movement from occurring identically across the end-effectors in our experiment. However, what Experiment 3 does not explain is under-compensation that is seen with both the yellow and red tool throughout the thesis so far.

Experiment 4 aimed to assess participants abilities to discriminate sizes with the hand and the three tools. We hypothesized that in order to judge the size of an object with a tool, participants must perform a calculation based on hand position and posture that accounts for the geometry of the tool. If participants did not have a robust and reliable internal tool model then performance in this task would suffer. We found that participants were unable to discriminate between two differently sized objects as well with the yellow tool as they could with the blue tool, the red tool or the hand. JNDs with the yellow tool were almost twice the size of those with either of the other tools or the hand. Again, this finding cannot be used to explain the overall low compensation seen throughout the thesis with both the red and yellow tools, as performance with the red tool was equivalent to the blue tool and the hand. However, it also contributes to the understanding of the asymmetric compensation seen with the yellow tool. This result is also supportive of the idea that participants had a biased or flawed internal model of the yellow tool, preventing them from making the accurate calculations needed to perform well in this task.

Possibly the most interesting finding however from Experiment 4 was the strong correlation between JND and compensation factor. The higher the JND for a specific tool, the less the participant compensated for the tool's ratio when grasping an object. It cannot be said for sure which one of these factors is driving the other, or whether a third factor is mediating the two. However, the finding does fit with our narrative of internal tool models. Grasping performance and performance at the size discrimination task both fall out of the quality of the internal model used for calculating the movement. If the model is poor then arguably it makes sense that performance in these two tasks will be poor as well. This can help to explain the under-compensation seen so far in both tools. Noise in the internal tool model will cause general poor performance across a variety of tasks – anything which relies on the internal model for a calculation. A noisy model would therefore lead to general reduction in compensation for tool ratio. So, it could be that the models for both our red and yellow tools were noisy, however the yellow tool model also included a bias that the red tool did not, leading to the asymmetry seen.

As mentioned previously it would be interesting to run further experiments on the different 'types' of compensators. So far it has been shown overall that most people compensate more for the red tool than they do for the yellow, but there are some people who compensate equally and others who compensate more for the yellow one. This highlights that there are individual differences in the way that people use tools, even when the tools have similar transformations. It would be interesting to try to find more people from these latter groups and then see how these three 'types of compensators' perform at different tasks. It could be that someone's previous experience of different tool transformations affects how quickly they can develop a robust model of a new tool. This makes sense based on past research, Imamizu et al. (2003) suggested that we have general internal models for an overall class of tool that we then adapt for new tools that we come across. It could be that compensators who showed equal compensation or better compensation with the yellow tool already have experience with that type of transformation. Therefore, the base calculations were already present, improving performance with this new tool compared to those who had little or no prior experience with this transformation. It would also be interesting to run longer experiments to see whether people are always the same type of compensator, or if more people may begin to compensate equally with the two tools when they have had more time to learn to use them. This would further support the concept that prior experience with a tool dictates what pattern of compensation would be demonstrated (Itaguchi & Fukuzawa, 2014). Finally, it would be interesting to re-run an adjusted Experiment 4 with a larger group of people to further strengthen the finding that compensation factors are related to JNDs. This was a long experiment and so we ended up with a much smaller sample size than we would have liked. However, now that we know that this finding has occurred we can tailor the experiment to test this finding further, with a larger set of people to see if it is robust.

Chapter 6: The effect of visual uncertainty on tool use kinematics: evidence of a similar control strategy to the hand?

6.1 Experiment 5: The effect of visual uncertainty on the kinematics of grasps made with tools

When reaching and grasping an object, environmental factors or properties of the object itself can alter how the grasp occurs. It has been reliably shown that when uncertainty about visual information regarding the target object's properties is introduced into a reaching and grasping task, that peak grip aperture increases (Keefe, 2010; Keefe et al., 2011; Schlicht & Schrater, 2007; Sivak & Mackenzie, 1990; Wing et al., 1986). Sivak and Mackenzie (1990) showed that when participants were made to grasp objects that were only visible in their peripheral vision that their peak grip apertures increased compared to normal grasping. It has also been shown that when participants are made to grasp an object with their eyes closed that the peak end-effector apertures produced will be larger (Wing et al., 1986). Keefe (2010) demonstrated that when the vision is blurred or when participants are asked to grasp with one eye closed, then peak grip apertures also increased compared to normal grasping conditions. Schlicht and Schrater (2007) showed that this increase in peak grip aperture is systematic as a function of the level of visual uncertainty. All of these situations add uncertainty about the grasp; they increase uncertainty about the initial properties of the object and about online visual feedback as well. The fact that these experiments have shown these effects may suggest that the brain builds in a margin-for-error when there is visual uncertainty present. This would be a sensible strategy as when you are uncertain about the grasp you are about to make increasing your peak grip aperture will increase the probability of making a successful grasp.

In this experiment, we examine whether this adaptive behaviour is exhibited when grasping with tools. Quantitatively, we would expect the increase in peak end-effector aperture to be the same under visually uncertain conditions if movements were being programmed in end-effector units. This would involve different movements at the hand to produce the same compensatory effect at the tool tips. However, if you are unable to precisely control the end-effectors then you are unlikely to be able to take appropriate action under conditions of uncertainty. In order to respond adaptively to uncertainty, the individual has to understand the effectors that they are using to make the grasp. Tool use arguably increases uncertainty compared to grasping with the hand anyway. Uncertainty or noise in the internal tool model will affect the forward model used to predict the movement of the end-effectors as well as the proprioceptive feedback from the tool tips (which involves adjusting the proprioceptive cues to hand position based on the internal model). If we still observed the same adaptive mechanisms when visual uncertainty regarding the object's properties is introduced into the task then this would be further evidence of a good internal tool model. This is because compensation for tool ratio is an adaptive, quantitative process which requires a solid understanding of how the tool moves for a given hand position or movement. Without this understanding, we would be unlikely to observe the same adaptive behaviours with the tools that we do with the hand. It could be that the blue 1:1 tool can utilise the existing hand motor program, because it preserves the ratio between the hand and the world, and therefore we may see the same response to visual uncertainty in this case. If there is an inadequate model for the other tools then this calculation cannot be done, so the response to visual uncertainty might not be appropriate. Experiments 3 and 4 demonstrated that participants seem to have a less reliable internal model of the yellow 0.7:1 tool than they do of the blue 1:1 or red 1.4:1 tools. This is also demonstrated by the asymmetry in compensation seen throughout the thesis, with participants compensating less for the yellow tool. It could therefore be expected that we would see a similar adaptive mechanism to the hand for visual uncertainty when using the blue or the red tool but not the yellow one. Performance in this task with the yellow tool will demonstrate the effect of a noisy internal tool model on adapting to visual uncertainty.

We plan to investigate this by blurring the participant's vision whilst they grasp objects with their hand and with the three different tools. We will compare performance in the blurred vision condition to the normal one to see whether similar strategies are employed when uncertainty is present during a grasp when using the hand or a tool. By degrading the participant's vision, uncertainty about the object's properties is increased, as is uncertainty of visual feedback during the grasp as well.

6.2 Methods

6.2.1 Participants

12 participants took part in this experiment (nine female and three male, seven had taken part in previous experiments with these tools). Participants were recruited through opportunity sampling and all had normal or corrected to normal vision and no motor impairments that would affect the ability to make a normal grasp.

6.2.2 Stimuli and Apparatus

The start button, tools, retroreflective markers, liquid crystal shutter glasses, and cameras are the same as those described in section 2.4.

See Figure 6.1 for an example of the experimental set-up.

Figure 6.1. A photo of a participant reaching for an object with the red 1.4:1 tool when her vision has been blurred using the stage-lighting gel.

The experimental objects were the same as those used in Experiment 2 (five objects ranging from 25–45 mm, in 5 mm increments). There were three 'base' object distances (200, 250, or 300 mm). However, we added a random jitter to the distance on each trial (uniform distribution, range 0-50 mm), so the distances varied randomly trial to trial in the range 200-350 mm, while being reasonably evenly distributed (i.e. not predominantly near or far, which can happen with an entirely random selection). We varied distance in this manner to increase task demands as we did not want participants to learn a set of movements and instead wanted them to have to actually plan and execute a new movement on each trial. Object distances were binned for analysis purposes. Any distances from 200-249 mm were labelled 250 mm, from 250-299 mm were labelled 300 mm and from 300-349 mm were labelled 350 mm.

The increase in visual uncertainty was achieved by blurring the participants' vision. To do this, a piece of stage-lighting gel (a uniform diffusing material) was used to cover the PLATO goggles in the relevant conditions (see Figure 6.2).

Figure 6.2. A rudimentary example of what the participant would see when grasping an object in the blurred vision trials of this experiment. This was achieved by taking a photo through the stage-lighting gel that covered the PLATO goggle in these trials.

6.2.3 Procedure

Except for the use of the stage-lighting gel to blur the vision, the procedure of normal or blurred trials was identical. The procedure for a trial, including identifying and dealing with void trials, was the same as in Experiment 1 (with the exception of the use of the calibration object and the position of the retroreflective wrist marker, which was the same as in Experiment 2).

Participants completed the experiment in two sessions, one of an hour and one of an hour and a half. The hour session consisted of two blurred viewing blocks and two normal viewing blocks interleaved and only involved the tools. The hour and a half session consisted of one block of blurred trials and one block of normal trials with the hand and four blocks using the tools (interleaved two blurred, two normal). Each of the tool blocks was 45 trials long (three repetitions of each of the five object sizes, with each of the tools) giving 12 repetitions of each trial type in total. Each hand block was 60 trials long (12 repetitions of five object sizes).

Whether participants started the experiment using their hand to grasp or the tools was counterbalanced, as was whether they started in a blurred or normal viewing block.

6.3 Results and discussion

6.3.1 Peak velocity under normal viewing conditions

It is sensible to look at the normal viewing condition alone first. We know based on past experiments what patterns of results we expect to find here. Therefore, once we have confirmed that performance is as expected in the normal grasping condition then we can begin comparing this to the blurred condition.

Figure 6.3 shows the average peak velocities reached with the hand and the three tools in the normal viewing condition. There appears to be a clear difference in the peak velocities reached with the hand and the three tools. Participants have reached higher peak velocities when grasping objects with the hand than they did with the three tools. This pattern of peak velocities is similar to the results of Zheng and Mackenzie (2007), but differs from what we found in Experiment 1 where we found no significant difference between the velocities reached with the hand and the blue 1:1 tool. This experiment does appear to have found no difference in peak velocities between the three tools however, and this is in line with our previous findings.

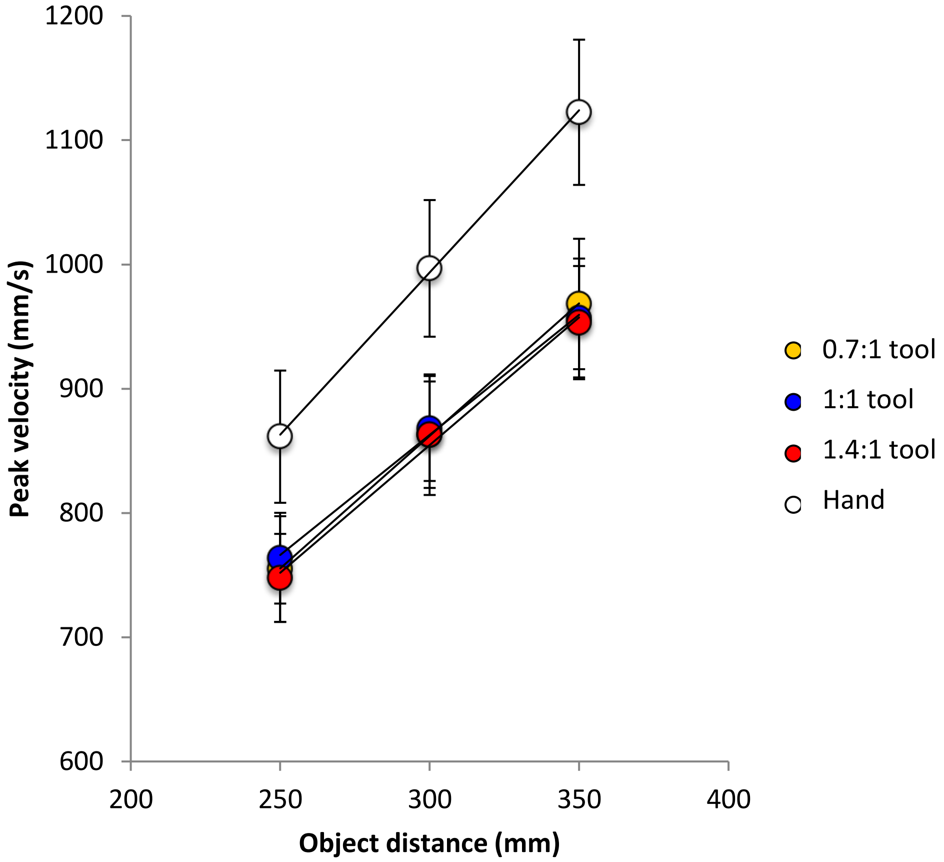


Figure 6.3. Peak velocity data from the normal viewing condition. Error bars show +/-1 SEM. Linear regression lines have been fitted through the data. N=12.

6.3.2 The effect of blurring the vision on peak velocity

Now that we have investigated peak velocities under normal viewing conditions we can assess the effect of blurring the vision (and increasing visual uncertainty). Figure 6.4 shows the peak velocities reached with the hand, and the three tools, when grasping under normal and blurred viewing conditions. It can be seen that in all conditions blurring vision had little effect on peak velocity.

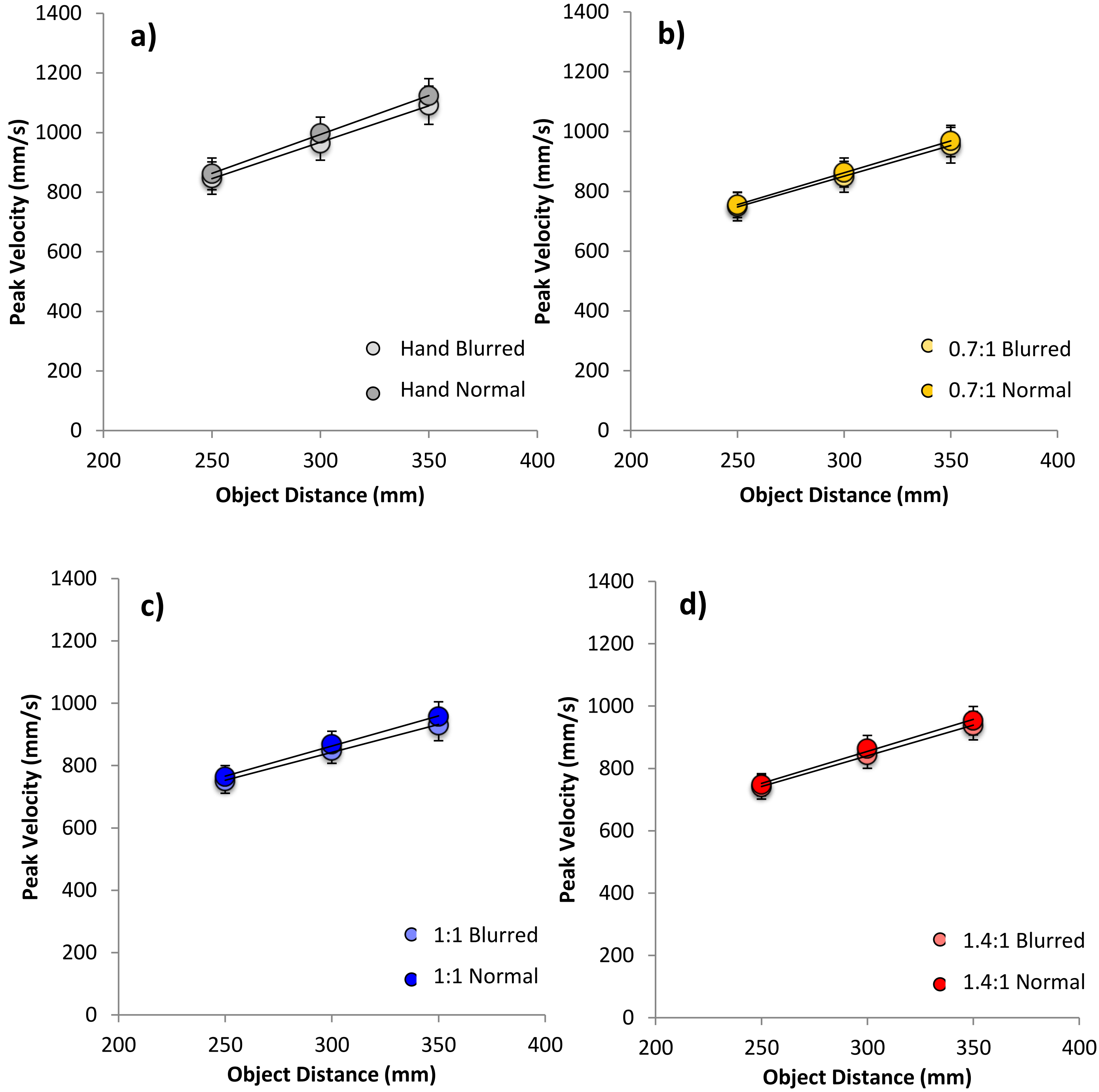


Figure 6.4. Peak velocity data from the normal and blurred viewing conditions for (a) the hand, (b) the yellow tool, (c) the blue tool and (d) the red tool. Error bars show +/-1 SEM. Linear regression lines have been fitted to the data. N=12.

A 2 x 4 x 3 (viewing condition x grasp type x distance) repeated measures ANOVA showed that there was no main effect of viewing condition on the peak velocities reached in this experiment ($F(1,11)=.30$, $p=.596$), meaning that participants reached the same peak velocities whether their vision was blurred or not. Planned comparisons show that there was no significant difference between the peak velocities reached with the blue tool and the red tool ($F(1,11)=1.20$, $p=.297$) or the blue tool and the yellow tool ($F(1,11)=0.01$, $p=.957$). There was however a significant difference between those reached with the blue tool and the hand, with participants reaching significantly higher speeds with the hand than with the blue tool ($F(1,11)=13.27$, $p=.004$). Finally, there was a main effect of distance ($F(1.14,12.59)=251.75$, Greenhouse Geisser corrected, $p<.001$) on the peak velocities reached in the normal viewing conditions of this experiment. Participants reached significantly faster speeds when the object was farther away.

6.3.3 Peak end-effector apertures under normal viewing conditions

Figure 6.5a plots the peak end-effector apertures produced with the hand and the three tools in the normal viewing condition. Figure 6.5b plots the same data but in terms of peak hand aperture. Again, we are plotting the normal data first to see how this compares to past experiments. Once we see how participants behaved under normal conditions we can begin to compare performance to the blurred condition. Figure 6.5 shows that there appears to be a difference between the peak end-effector apertures produced with the blue tool and the hand in this experiment. This is contrary to all of our previous experiments where this comparison has been made, where these have not been significantly different.

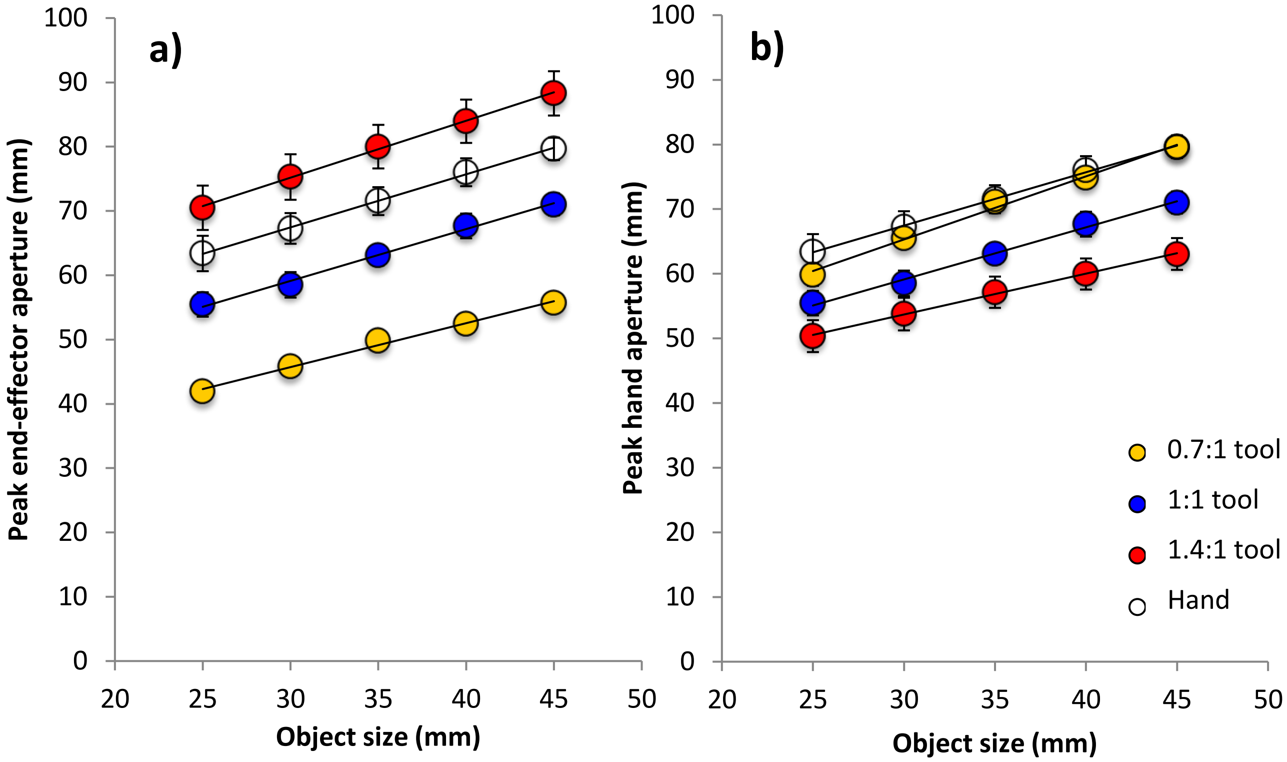


Figure 6.5. Aperture data from the normal viewing condition, as a function of object size, collapsed across distance. (a) Average peak end-effector apertures. (b) The same data plotted in units of hand aperture. Error bars show +/-1 SEM. Linear regression lines have been fitted to the data. N=12.

It should be remembered that participants reached a significantly higher peak velocity when using the hand compared to the blue tool in this experiment as well. This has not been the case in previous experiments where performance has been similar with the hand and the blue tool. One reason for this could be that the increased velocity seen here when using the hand may have led to the larger end-effector apertures. In a lot of processes there is a trade-off between speed and accuracy (Schmidt & Lee, 1999) and this is also true in reaching and grasping. It is possible that in this experiment participants did not need to utilise online visual feedback when grasping with the hand alone and therefore moved faster than with the blue tool, however this may have led to less precisely controlled peak end-effector apertures. It is unclear why this would be the case in this experiment and not in the previous ones, but it is possible that for the differences seen in peak velocity and peak end-effector aperture that one could be driving the other.

Figure 6.5b shows that participants have altered their peak hand apertures based on the tool that they were using to make the grasp, opening their hands wider with the yellow tool and narrower with the red one when compared to the blue tool for the same object size. Participants appear to alter their hand aperture relatively equally in this experiment for the yellow and red tools. This appears to be different to the pattern of results seen in the first three experiments where compensation was asymmetric, however compensation was equal in Experiment 4. Participants appear to be compensating somewhat for the ratios of both the yellow and red tools, but not completely. This can be investigated quantitatively using compensation factors as in previous experiments. Figure 6.6 plots the average compensation factor for the yellow 0.7:1 and red 1.4:1 tool in this experiment. It can be seen that the compensation factor for the yellow tool is higher than it has been in most of our previous experiments at 0.26 (although not as high as Experiment 4 where it was 0.48). However, compensation for the red tool is still higher than this at 0.35, but the difference is not as large as it has been in the past.

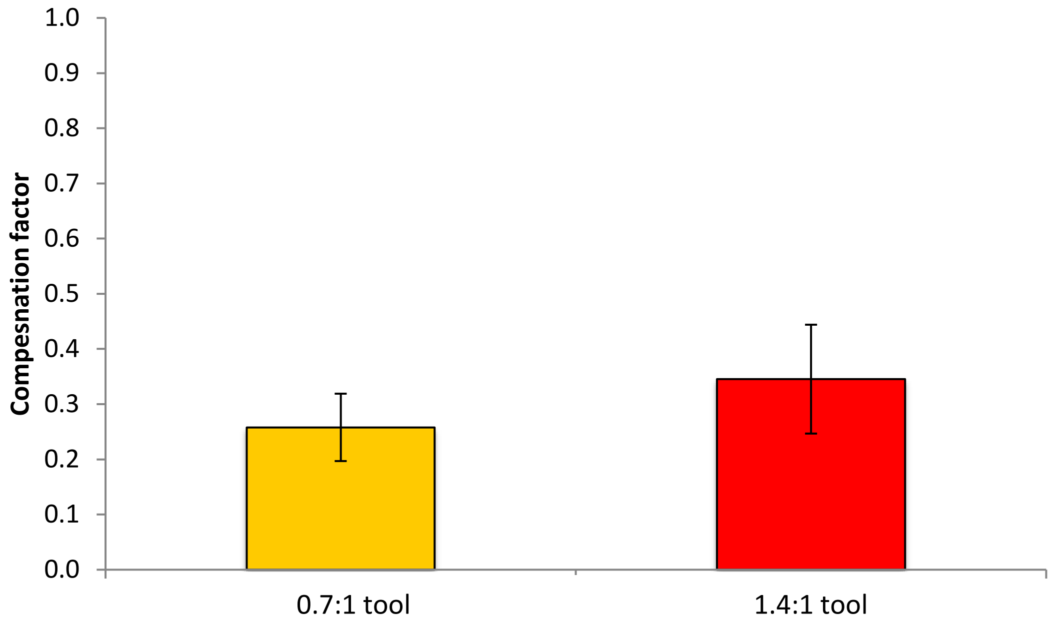


Figure 6.6. Compensation factors for the 0.7:1 and 1.4:1 tools in the normal viewing condition. Error bars show +/-1 SEM. N=12.

It makes no sense to look at the compensation factors for the blurred condition in this experiment. That is because compensation factor will be effected by any systematic altering in peak end-effector aperture that could be caused by blurring the vision. If participants open the hand systematically wider with the blue tool under blurred conditions, but not with the yellow or red tools then this will drop their compensation values. This will not be due to a lack of compensation for the tools' ratio though and instead would be caused by the different reactions to the blurred condition. Therefore, compensation factors will not be used any further in this chapter.

6.3.4 The effect of blurring the vision on peak end-effector aperture

Figure 6.7 plots the average peak end-effector apertures produced with the hand and the three tools under both normal and blurred viewing conditions in this experiment. Figure 6.7a shows the peak end-effector apertures produced with the hand. It can be seen that participants produced slightly larger peak end-effector apertures under blurred viewing conditions than normal ones, which is in line with past research (Keefe, 2010; Keefe et al., 2011; Schlicht & Schrater, 2007; Sivak & Mackenzie, 1990; Wing et al., 1986). This effect was more pronounced for smaller object sizes than larger ones. Figures 6.7c and 6.7d show that the same effect seems to be present when using the blue 1:1and red 1.4:1 tools, but to a lesser extent than with the hand. However, Figure 6.7b shows that blurring the vision did not seem to have any effect on the peak end-effector apertures produced with the yellow 0.7:1 tool. These results suggest that when using a tool, a similar adaptive mechanism for visual uncertainty can be utilised as performance has moved in the expected manner for the red and blue tool. As discussed previously however, performance with the yellow tool throughout the thesis so far has suggested a biased internal model for this tool. It seems that when a biased internal model is being used that the appropriate adjustment for visual uncertainty is not made.

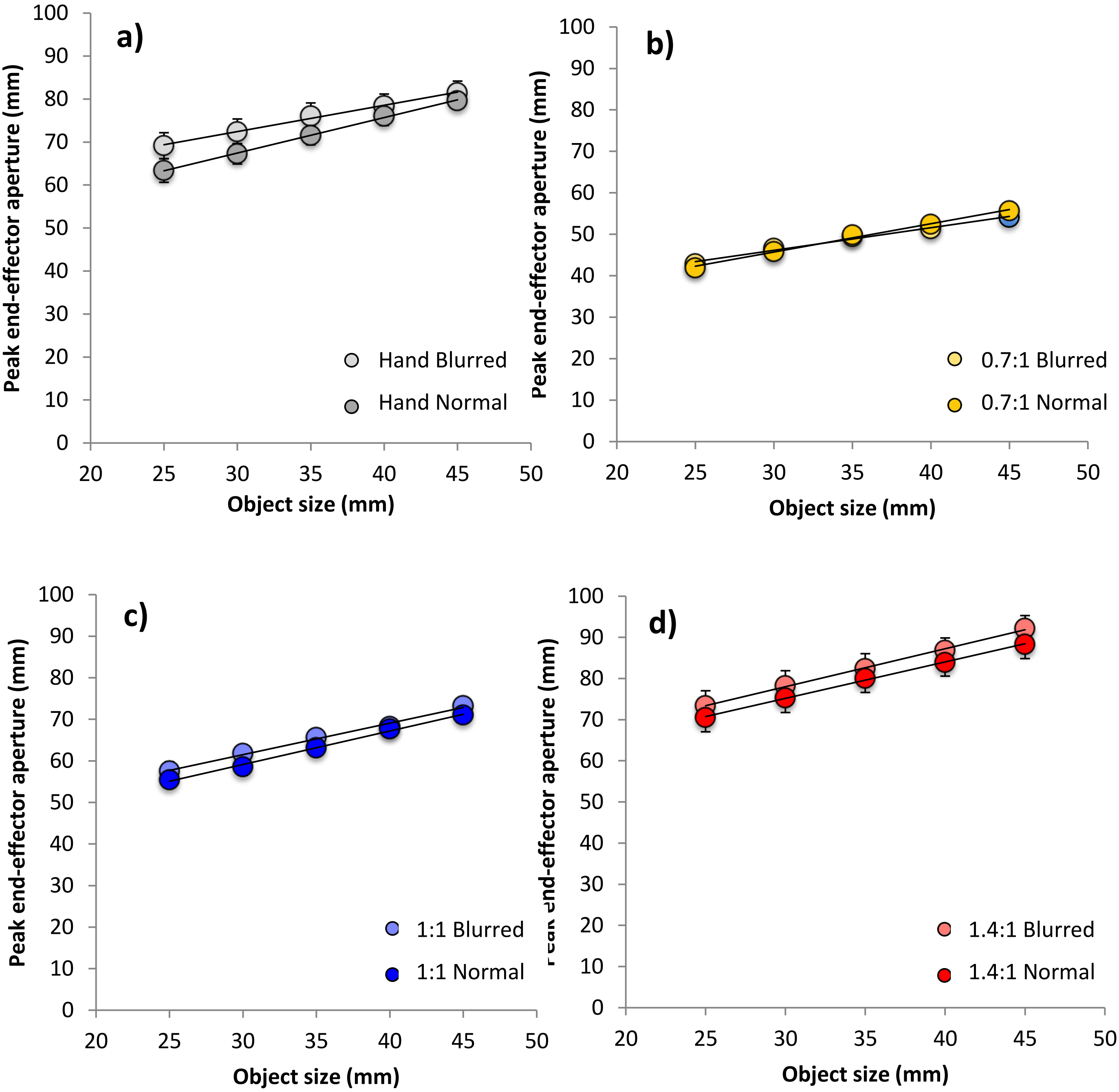


Figure 6.7. Aperture data from the normal and blurred viewing conditions as a function of object size, collapsed across distance for (a) the hand, (b) the yellow tool, (c) the blue tool and (d) the red tool. Error bars show +/-1 SEM, in (b) and (c) these are small enough to be obscured by the markers. Linear regression lines have been fitted through the data. N=12.

A 2 x 4 x 5 (viewing condition x grasp type x object size) repeated measures ANOVA on the peak end-effector apertures revealed a main effect of viewing condition ($F(1,11)=35.36$, $p<.001$). This shows that participants did produce significantly larger peak end-effector apertures when their vision was blurred compared to normal viewing conditions. However, as mentioned previously, this effect does not appear to be consistent across the different tools and the hand. This is confirmed by the significant viewing condition x grasp type interaction ($F(1.23,13.52)=238.18$, Greenhouse Geisser corrected, $p=.043$). When comparing the interactions for the red and yellow tools and the hand to the blue tool it can be seen that there is a significant interaction for the yellow and blue tools ($F(1,11)=31.67$, $p<.001$), but not for the hand ($F(1,11)=2.04$, $p=.182$) or the red tool ($F(1,11)=1.42$, p.259). This confirms that when grasping with the hand, the blue 1:1 tool or the red 1.4:1 tool that blurring the vision led to significantly larger and comparable peak end-effector apertures, but that this was not the case when using the yellow 0.7:1 tool.

These findings support what we suggested earlier, a similar adaptive mechanism for visual uncertainty to the one used when grasping with the hand (Keefe, 2010; Keefe et al., 2011; Schlicht & Schrater, 2007; Sivak & Mackenzie, 1990; Wing et al., 1986) is utilised when using the blue 1:1 tool or the red 1.4:1 tool. The adaptive effects seen with the hand, the blue 1:1 tool and the red 1.4:1 tool were small but they were comparable to the size of the effects seen in the experiment by Keefe (2010). This adaptive mechanism was not present however when grasping with the yellow 0.7:1. It has been demonstrated in this thesis repeatedly that participants seem to have a biased internal model of the yellow tool. In Experiment 3 participants overestimated the size of objects when using the yellow tool compared to the other two tools or the hand. This overestimation in size could have been caused by a bias towards the known hand opening caused by an unreliable internal tool model. It was also demonstrated in Experiment 4 that participants performed more poorly with the yellow tool in a size discrimination task, with JNDs almost twice the size as the other two tools or the hand. This suggests that the haptic size calculations were poorer when using this tool, again indicating a flawed internal tool model. It is possible that if participants do not have a reliable internal tool model for the yellow tool then this is what prevents them from performing in the standard manner under conditions of visual uncertainty. If the brain is already utilising a biased internal model, then the necessary calculations cannot be successfully completed.

The fact that the same adaptive mechanism was demonstrated for the hand, the blue 1:1 tool and the red 1.4:1 tool however does support the idea that the brain is encoding movements in end-effector units (Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Umiltà et al., 2008). The fact that a similar mechanism is used across these different end-effectors in reaction to visual uncertainty, is evidence that the brain is controlling the end-effectors in a similar manner. And that this is only not the case, when the participant is not able to back up the movement with a robust internal tool model, as in the case of the yellow 0.7:1 tool.

Chapter 7: The effect of motor equivalence on reaching and grasping with a tool

7.1 Experiment 6: Kinematics of grasping with a reverse tool

Different tools place different demands on the motor system. Some tools have motor equivalence, where the tool performs a movement that is motorically equivalent to what can be achieved with the hand (Arbib et al., 2009). It is not a huge leap of inference that a tool that has motor equivalence to the hand could be used by adapting existing motor programmes compared to needing to develop a new one (Telgen, Parvin & Diedrichsen, 2014). The tools we have used throughout the thesis so far all have motor equivalence, despite the change in ratio, they all function in a similar manner to the finger and thumb. We have shown using our three tools that this is plausible. Participants have consistently demonstrated scaling of peak end-effector aperture with object size when using all three tools, something which is reliably seen when grasping with the hand (Jeannerod, 1981; 1984; 1997; Wing et al., 1986). In every experiment, peak velocity has also been shown to scale with object distance whilst using all three of the tools, just as it does with the hand (Jeannerod, 1984; 1988). In all but one experiment participants have produced the same peak end-effector apertures with the hand and the blue tool. They have also demonstrated some level of compensation for both the red and yellows tools throughout the thesis. Finally, participants adjusted their movements in the same manner in reaction to visual uncertainty when using the hand, the blue tool and the red tool. All of this supports the idea that properties of the tools that we use are learnt and likely stored in the form of an internal model. It also supports the concept that the brain could be encoding movements in terms of end-effector units (Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Umiltà et al., 2008) and using these models and what it knows about the motor programmes of the hand to carry out these movements. This all makes sense when a tool has motor equivalence, however this process becomes less applicable when this is not the case. If the tool does not have motor equivalence, then arguably it does not make sense for the brain to apply the motor programmes of the hand in this situation, as they do not apply. It could still be that the brain is encoding movement in end-effector units, but it cannot use what it knows about the arm and hand to achieve this. Therefore, an entirely new model would likely be needed, not one adopted from that of the hand.

7.1.1 Grasping with a tool without direct motor equivalence

Having looked at the differences between grasping with the hand and with a 1:1 tool (that preserves the relationship between the hand and the world) and then the addition of how ratio change affected tool kinematics, the next logical step is to look at a tool that does not have motor equivalence. Our previous theories have revolved around the idea of using existing motor programmes known for the hand to develop internal tool models that can be used in the same predictive manner. This idea begins to break down somewhat when applied to a tool without motor equivalence because how can information derived from knowledge of the hand and arm be applied in this situation? It has been pointed out in past research that the concept of embodying a tool only really makes sense when that tool does something similar to the hand (Arbib et al., 2009). For example, would it really make sense to incorporate a tool into the body schema that has no relation to your hand movement whatsoever? The example that Arbib et al. (2009) used was that of a mechanical digger. Embodying the digger seems to make little sense in helping you to control it, as it works in a completely different way to the body. Whilst the arm of a digger may conceptually move in a similar way to your own arm, you are controlling it with levers that have no relationship with typical hand and arm movements whatsoever. There are also for example, robot arms with hands that can rotate through 360^{o}, a movement that is not possible for a human. Embodiment of this type of tool does not seem to make sense, and it is hard to see how an existing motor programme could be utilised to help us control this type of tool. Therefore, an internal model for this type of tool could not be developed by using our knowledge about the movement and control of our own body and instead an entirely new model would need to be learnt.

As it would seem that an entirely new model would need to be developed to use a tool that does not have motor equivalence then it would be interesting to see if the end-effectors are still controlled in a similar manner to normal reaching and grasping. In previous experiments people seemed to be able to learn to use our other three tools quickly and could pick up an object with them successfully on the first trial even though they had never used the tools before. This is likely to be at least partially down to the fact that most people will have used a pair of tongs in their lifetime and they are likely to already have an internal model for this type of tool that only needs to be adapted for the properties of that specific tool. In this experiment, we wanted to know whether individuals would be able to learn to use an unfamiliar type of tool that does not have motor equivalence, in the same manner. We were interested in investigating this through our method of kinematic analysis. In this case using a pair of tongs that reverses the movement of the finger and thumb, now referred to as a reverse tool.

For this experiment, we will look at the kinematics of grasping with a reverse tool, where opening the hand causes the tips of the tool to close. This is a less common transformation of tool and whilst it is likely that participants will have experienced it at some point in their life (clothes pegs, test tube holders) they are unlikely to be particularly familiar with this type of tool and familiarity has been shown to play a part in successful tool use (Itaguchi & Fukuzawa, 2014). It will be interesting to see if participants are still able to show the hallmark features of a reaching and grasping movement (such as scaling of peak end-effector aperture for object size (Jeannerod, 1981; 1984; 1997; Smeets & Brenner, 1999, Wing et al., 1986) and peak velocity for object distance (Jeannerod, 1984; 1988)) when using this different type of tool or not. It will also be interesting to see whether participants are able to control the tips of a reverse tool in the same manner as those of a normal one. The idea of end-effector control is challenged here. Whilst a simple adaptation to ratio was required with the other tools used in our previous experiments, here a very different motor programme is needed. It is no longer the case of adapting a standard model, but instead creating a new one. Whilst mechanically the reverse tool is no more complex than the normal 1:1 tool, the required control process is less direct and comparable to the hand and is therefore less intuitive.

If the brain truly does encode movements in end-effector units then we should see no difference in performance between a reverse and normal tool (Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Umiltà et al., 2008). Research by Umiltà et al. (2008) showed that neurons in F5 (an area associated with grasping in primates) fired when opening the tips of both normal and reverse pliers. The fact that the neurons in F5 fired when both tools were being opened shows that this is not dependant on the opening of the hand (which moved in opposite directions to open the two tools) and instead these neurons seem to be coding for the end-effector of the tool. Gentilucci et al. (2004) got participants to grasp objects using a tool that opened when the handles were squeezed together using the whole hand. They found that, by the end of the experiment, participants were able to scale their peak end-effector apertures to object size in the same manner as when they were using their hand. However, the peak end-effector apertures produced when using the tool were significantly larger. They also found that there was no significant difference in the speed that people moved when using the tool or the hand. The findings of both Umiltà et al. (2008) and Gentilucci et al. (2004) suggest that the brain may be encoding movements in end-effector units, not in hand units. This could mean that even when using a tool that lacks motor equivalence, participants may still be able to learn to use the tool, and may be able to use it in a way that is similar in most respects to normal grasping.

It has been a strength in our previous experiments to have multiple tools to allow for more of an understanding about the movements made. Therefore, we would like to include a normal 1:1 tool in this experiment as well. The experiment by Gentilucci et al. (2004) only compared the movements of the reverse tool to those of the hand so no comparisons can be made about whether people perform differently with this tool than they would be with any other. By using the normal 1:1 tool as well we can begin to see whether there are differences between tools that do have motor equivalence and those that do not. Kinematics with this new normal 1:1 tool can also then be compared to both the hand and those produced with the old 1:1 tool in previous experiments to ensure replicable results.

7.2 Methods

7.2.1 Participants

Eight participants were recruited through opportunity sampling to take part in this experiment (eight female, no male). One dropped out after the first session due to difficulties completing the task. Participants had normal or corrected to normal vision and no known motor impairments that would affect their ability to make a normal grasp. All participants had taken part in previous experiments with the original three tools, but all were naïve to the tools used in this experiment.

7.2.2 Stimuli and Apparatus

With the exception of the reverse tool, the apparatus was the same as those described in section 2.4, and used in Experiment 1 (See Figure 3.1).

The objects, and distances that they were placed at, were the same as in Experiment 2 and 5 (five objects ranging from 25–45 mm, in 5 mm increments).

Two 3D-printed tools were used during this experiment (See Figure 7.1). The first tool was a replica of the 1:1 tool used in the previous experiments and was painted white. The second tool was a reverse tool, which operated by closing the finger and thumb in order to open the tips of the tool. This tool was painted grey. Because they were 3D printed and made out of a different material, the tools were both lighter and slimmer than our previous wooden ones.

Figure 7.1. The tools used in Experiment 6. The reverse tool is at the top; the tool tips are opened by closing the handles. The normal tool is at the bottom, and works in the same manner as the tools used in the rest of the thesis (opening the handles opens the tool tips).

7.2.3 Procedure

The task was explained to participants and retroreflective markers were then attached as per previous experiments if the participant was happy to continue. In the sessions using the tools, participants were first allowed a minute to open and close the tools so that they knew how each one worked. They then put on the PLATO goggles and were instructed to depress the start button with the tool (or in the hand condition the finger and thumb) in a closed position. This was necessary to ensure that meaningful peak end-effector apertures were obtainable from the data for both of the tools. The procedure for a trial was then the same as that in Experiment 1, with the exception that no calibration object was used.

The experiment was carried out in three sessions, two with the tools and one with the hand. Each session consisted of two blocks of 60 trials (three repetitions of each object size, at each distance, with each tool in the tool blocks and six repetitions of the same in the hand block, giving 12 repetitions of each trial in total). The trial amounts were chosen so that the participants were exposed to each of the tools the same amount as the participants had been in Experiment 1, so that we could make some judgements about how easy it was to learn to use these types of tools.

Whether participants started the experiment grasping with their hand or the tools was counterbalanced. In the tool sessions, the tools were randomly interleaved to make the procedure comparable to that of Experiment 1.

7.3 Results

7.3.1 Comparing performance with the 1:1 tools

Figure 7.2 plots the peak end-effector apertures produced with the normal 1:1 tool in this experiment and those produced with the 1:1 tool used in Experiment 1. This is to ensure that our new 3D printed 1:1 tool still produces predictable data. When comparing the peak end-effector apertures of the 1:1 tools the results are similar to one another in that they both the display the scaling of aperture for object size, however apertures are larger in the current experiment.

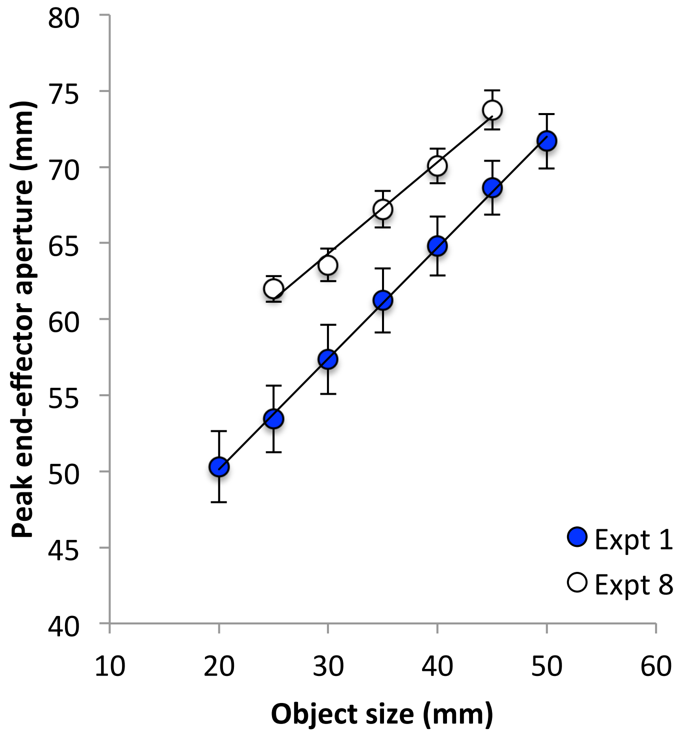


Figure 7.2. Average peak end-effector aperture as a function of object size, collapsed across distance produced with the 1:1 tools in Experiment 1 and Experiment 8. Error bars show +/-1 SEM. Linear regression lines have been fitted through the data. N=8.

As participants in this experiment showed scaling of peak end-effector aperture with object size when using the new 1:1 tool, this suggests that they were able to use the new tool in a manner that is consistent with other reaching and grasping experiments (Jeannerod, 1981; 1984; 1997; Smeets & Brenner, 1999, Wing et al., 1986). The scaling function of the 1:1 tool in Experiment 1 was 0.7 and the scaling function in this experiment is 0.6. So, end-effector aperture scaling with the 1:1 tool in this experiment is slightly lower than that shown in Experiment 1. Whilst performance with the new 1:1 tool is slightly different to that in Experiment 1, it is arguably within reasonable bounds so we can continue with the rest of the analysis.

7.3.2 Peak velocity

Figure 7.3 shows the peak velocities in Experiment 8 with the hand, the normal 1:1 tool, and the reverse tool. It can be seen that participants reached higher peak velocities when grasping with the hand than they did when grasping with the normal 1:1 tool, and that they reached higher peak velocities with the normal tool than they did with the reverse one.

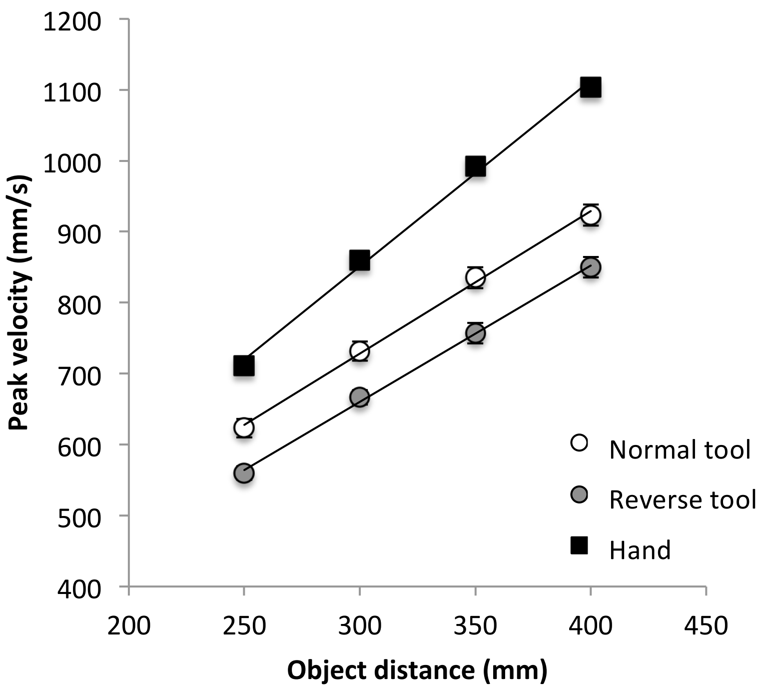


Figure 7.3. Average peak velocity as a function of object distance, collapsed across object size. Errors bars show +/-1 SEM. Linear regression lines have been fitted through the data. N=8.

A 3 x 4 (grasp type x object distance) repeated measures ANOVA revealed a significant main effect of object distance ($F(1.04,6.22)=249.50$, Greenhouse Geisser corrected, $p<.001$) on the average peak velocity reached during the movement, showing that participants scaled their peak velocity for object distance. Planned comparisons on grasp type show that participants reached a significantly higher peak velocity when grasping with their hand than when grasping with the normal tool ($F(1,6)=12.34$, p=.013). This is contrary to what we found in Experiment 1 but supports our finding in Experiment 5. One reason that we could have seen lower peak velocities with the normal 1:1 tool than the hand is that the tool component of this experiment is arguably more difficult than Experiment 1. In the tool condition of Experiment 1 participants were still switching tool trial-by-trial, but the tools all functioned in the same basic way, just with different 'gain' ratios. In this experiment, however, participants swapped trial-by-trial between two tools that worked in a very different manner. This increase in task demand could mean that reaching slower speeds was necessary to allow for online visual feedback. Planned comparisons also show that participants reached a significantly higher peak velocity when grasping with the normal tool than when grasping with the reverse tool ($F(1,6)=7.06$), p=.038). Again, it could be that switching between the 1:1 tool and the reverse tool led to slower movements overall in the tool block compared to the hand block. However, the reverse tool is slower still than the normal one, and this could be suggestive that online feedback is utilised more whilst using this tool. This could be suggestive of an unreliable or noisy internal tool model, that requires online adjustment during the movement for successful movement to be executed.

7.3.3 Peak end-effector aperture

As said previously, it is important to assess kinematic indices in parallel with one another. The faster peak velocities seen with the hand in Experiment 5 were coupled with larger peak end-effector aperture, suggesting a trade-off (Schmidt & Lee, 1999). So, before we can draw conclusions about whether online feedback was utilised with both tools in this experiment the end-effector apertures need to be studied. Figure 7.4 shows the average peak end-effector apertures produced with the two tools and the hand in this experiment. It can be seen that the peak end-effector apertures produced with the normal tool and the hand in this experiment appear to be comparable. This suggests that the reduction in peak velocity when using the normal tool compared to the hand could be suggestive of utilising online visual feedback during the movement as no trade-off in peak end-effector apertures is seen in this experiment.

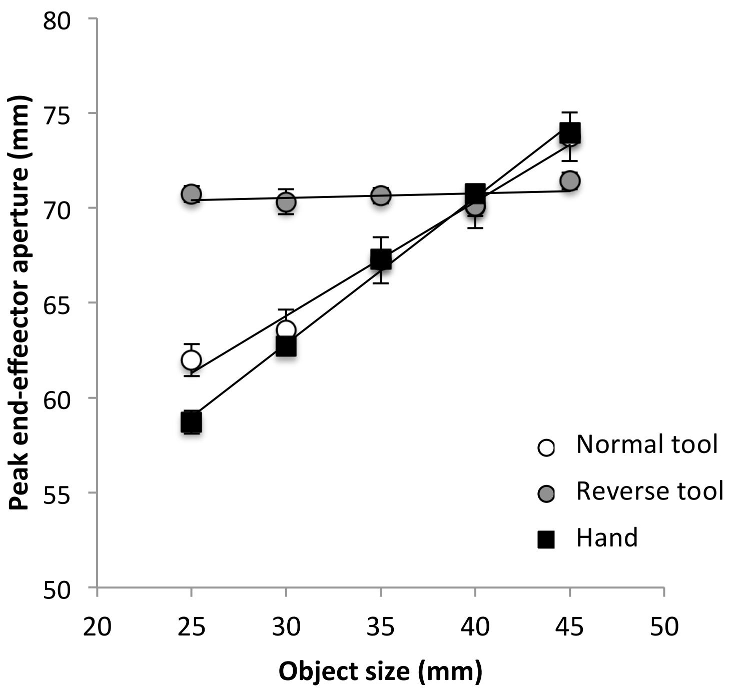


Figure 7.4. Average peak end-effector apertures as a function of object size, collapsed across distance. Error bars show +/-1 SEM. Linear regression lines have been fitted to the data. N=8.

It can also be seen in Figure 7.4 that the scaling of peak end-effector aperture with object size is present in both the hand-alone and the normal 1:1 tool condition. The scaling function of the hand is 0.8 and the scaling function of the normal tool is 0.6 suggesting that scaling is slightly reduced with this tool. However, it can be seen that there is no scaling for object size at all when using the reverse tool, which had a function of 0.02. Instead participants seemed to adopt large peak end-effector apertures throughout the experiment regardless of the size of the object that they were grasping. The peak end-effector aperture produced throughout with the reverse tool is the same as that with the hand and the normal tool for the 45 mm object. This could suggest that participants are closing their hand on every trial with the reverse tool; causing the tool tips to be as wide open as possible. This is the first time that we have seen a complete lack of scaling with a tool in this thesis. If the brain really is encoding movements in end-effector units (Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Umiltà et al., 2008) then this suggests a fundamental lack of a functioning internal tool model for this tool. However, as stated previously, another possibility is that as this tool does not have motor equivalence, maybe we cannot expect it to be used in a similar way to the 1:1 tool. It could be that tools that do not have motor equivalence do not show the kinematic hallmarks of reaching and grasping with the hand. In a way this would make sense: if the way the hand works has no relevance towards how the tool tips are controlled then why would we expect the tools tips to be controlled in a way that is similar to the hand? To make more concrete inferences about the role of motor equivalence in aperture scaling when grasping with tools more information would need to be collected using many different types of tool. Our reverse tool still arguably functions in a similar manner to the hand, whilst it's function is reversed, it still displays the normal pinch grip function of the hand and the rest of our tools. There are other tools that differ from the hand far more and studying these could help to probe this question further.

It should also be considered that Gentilucci et al. (2004) used a reverse tool that therefore did not have direct motor equivalence and they saw scaling of end-effector apertures in their experiment. There could therefore be other things responsible for the lack of scaling seen in our experiment and a lack of motor equivalence may not be the cause. The experiment by Gentilucci et al. (2004) was very different to our experiment: they ran two blocks of trials, one using the hand, and the other using the reverse tool. This meant that when participants were using the tool they were able to use it over an extended period of time with no interruption. In our experiment, trials with the normal and reverse tool were randomly interleaved. We ran our experiment in this manner to be consistent with our previous experiments. Moreover, there has been a suggestion by research in the past that the switching of internal tool models is a rapid process so we did not foresee an issue with interleaving the tools in this way (Imamizu et al., 2003; Takahashi & Watt, 2017). The other difference between our experiment and the one by Gentilucci et al. (2004) is that they also blocked their object sizes, meaning that participants would pick up the same object 15 times in a row before moving onto the next one. In our experiment, objects were also randomly interleaved, so the same object was rarely grasped with the same tool twice in a row. Because of these task designs, in Gentilucci et al.'s (2004) experiment participants were able to learn a specific motor programme during a block of 15 trials. We on the other hand, deliberately varied demand trial-by-trial to allow us to probe people's ability to programme new movements effectively on each trial. Therefore, the current experiment is arguably better at probing the underlying model of the tool. We found no evidence of an underlying model for the reverse tool and possibly Gentilucci et al. (2004) only did because they were not measuring motor programmes specifically.

7.3.4 Differences across experimental blocks

By comparing the average peak velocities and peak end-effector apertures in different experimental blocks, we can see whether performance with the two tools changed over the course of the experiment. It could be that the lack of end-effector aperture scaling seen overall with the reverse tool may be more pronounced earlier on in the experiment and participants could start to alter the end-effector aperture based on object size as they learn to use the tool.

Figure 7.5 plots the average peak velocities in the four experimental blocks with (a) the normal tool and (b) the reverse tool. Peak velocity with both the normal and reverse tools appears to increase slightly in each block of the experiment. This could suggest that participants are learning to use the tools and need to rely less on visual feedback as they develop an internal tool model.

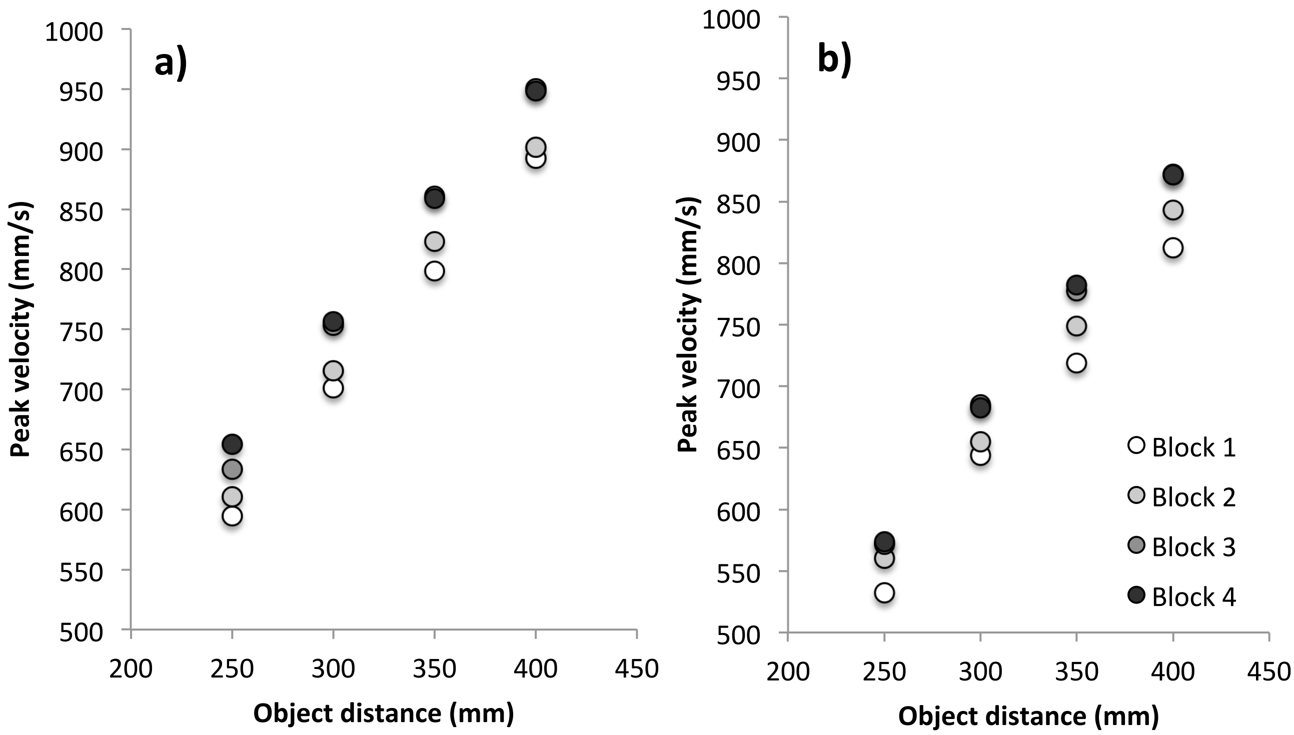


Figure 7.5. Average peak velocities in each block of the experiment, for (a) the normal tool and (b) the reverse tool, as a function of object distance, collapsed across size. Error bars show +/-1 SEM but they are small enough to be obscured by the data points. N=8.

A 4 x 3 x 4 (block number x grasp type x object distance) repeated measures ANOVA revealed a significant main effect of block number on peak velocity ($F(3,18)=7.71$, p=.002). There was no significant block number x grasp type interaction ($F(2.91,17.46)=1.74$, Greenhouse Geisser corrected, p=.225) so peak velocity increased at a similar rate for both tools.

Figure 7.6 plots the average peak end-effector apertures produced in the four blocks with (a) the normal tool and (b) the reverse tool. When using the normal 1:1 tool peak end-effector aperture decreased marginally with each block of the experiment. Whereas when using the reverse tool peak end-effector apertures appear to remain the same and no scaling appears to occur, even later in the experiment.

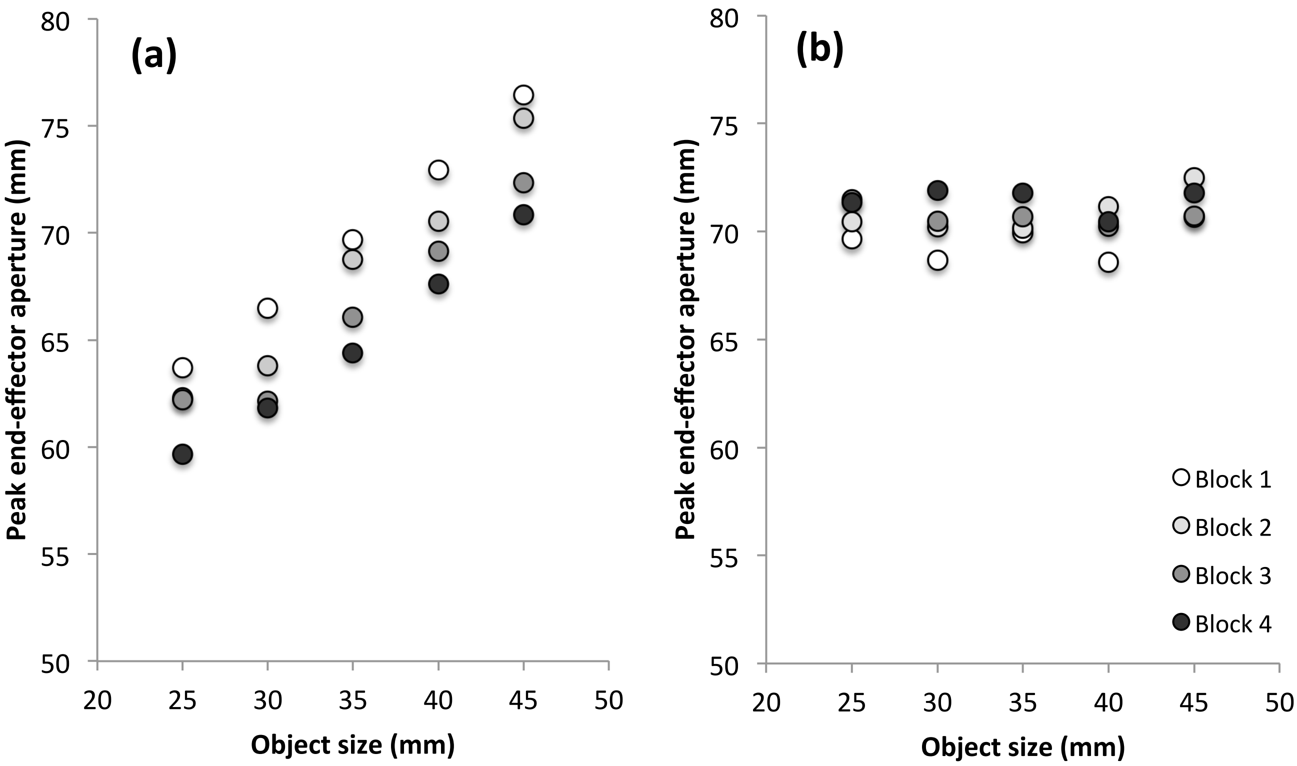


Figure 7.6. Average peak end-effector apertures in each block of the experiment, for (a) the normal tool and (b) the reverse tool, as a function of object size, collapsed across distance. Error bars show +/-1 SEM. N=8.

This can be investigated quantitively by fitting linear regression lines to the data and assessing the slopes of the functions. Arguably learning with the reverse tool in this experiment could manifest as an increase in scaling of peak end-effector aperture with object size. By fitting regression lines to the block-by-block data in Figure 7.6 we can see if the slope is increasing, which would show that scaling was improving. The scaling functions for each block are presented in Table 7.1. It is clear that scaling did not improve throughout the experiment; in fact it went down overall. However, the range of the values is so small that it is unlikely to have significantly reduced. It can therefore be said that scaling did not improve for the reverse tool as the experiment went on. Suggesting that whilst participants were improving their performance, and therefore potentially fine-tuning their internal model of the normal tool, that this did not occur with the reverse tool.

Table 7.1. Scaling functions for the reverse tool in each block of the experiment.

Block number	1	2	3	4
Scaling function	0.04	0.10	-0.03	-0.01

7.3.5 Grasping errors

By looking at the number of errors made when making a grasp with the hand and the two tools, we can see whether more errors were made using the reverse tool than the hand or the normal tool. It could be that the lack of peak end-effector aperture scaling seen with the reverse tool reflects an unreliable internal model of this tool. This would lead to poor performance with this tool in general. This could manifest in both the lack of peak end-effector aperture scaling seen earlier, but also in more mistakes being made during the grasps. By measuring the number of grasping errors made we can investigate this idea further. It was judged that an error was made when a participant had to adjust their grip during the movement in order to be able to pick up the object successfully. This is called an online correction, if participants made an online correction during a trial, then this was counted as an error. Participants could make more than one error on a trial.

Figure 7.7 shows the number of errors made with the hand, the normal tool and the reverse tool during this experiment. When comparing the number of errors made with the normal tool with the number made with the hand it can be seen that twice as many errors were made with the normal tool. As stated many times previously, using any type of tool – even one that has motor equivalence and preserves the ratio between the hand and the world – requires calculations and transformations to take place. Grasping with the hand is something that we have a well-established, reliable model for. Whilst it has been shown that grasping with a normal 1:1 tool also seems to utilise a relatively robust model, transformations regarding the spatial offset of the hand and the end-effector still have to take place, arguably making this a more complex process. When participants used the reverse tool, they produced more than three times as many grasping errors when compared to those made with the 1:1 tool. This, coupled with the lack of aperture scaling seen, supports the conclusion that participants do not have a reliable internal model of the reverse tool. Whilst errors were higher with the normal tool than they were with the hand, they are considerably higher again with the reverse tool, suggesting a difficulty in producing the correct movement on a given trial. The number of errors suggests that participants frequently had to re-adjust their peak end-effector apertures during the movement to be able to successfully grasp an object with the reverse tool.

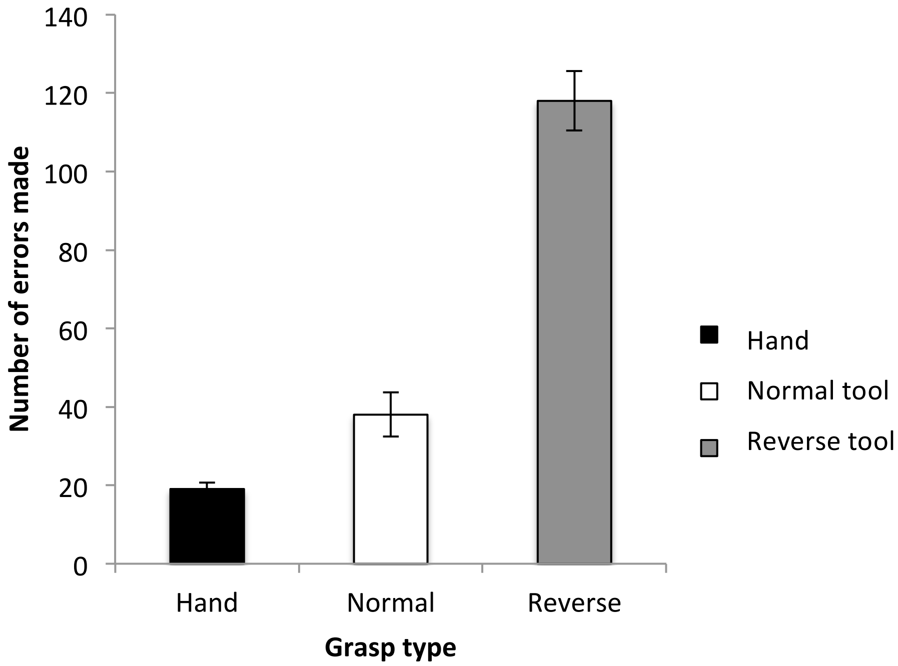


Figure 7.7. The total number of errors made by all participants throughout the experiment with the hand, the normal tool and the reverse tool. Error bars show +/-1 SD. N=8.

By running a one-way repeated measures ANOVA it can be seen that there was a significant main effect of grasp type on the number of errors made ($F(2,12)=16.74$, $p<.001$). Planned comparisons show that there was actually no significant difference in the number of errors made with the 1:1 tool and the hand ($F(1,6)=1.62$, $p=.251$). However, participants made significantly more errors when using the reverse tool than the normal one ($F(1,6)=24.74$, $p=.003$).

Again, it is interesting to look at the number of errors made on a block-by-block basis. This is because there could be evidence that participants were developing an internal model of the reverse tool throughout the experiment. If errors stay consistent throughout then it would suggest that this was not the case. Figure 7.8 shows the average number of errors made in each block of the experiment with each of the tools and the hand. When grasping with the hand or the normal tool errors stay at a relatively constant low level throughout the experiment. With the reverse tool however, there is a clear drop in the number of errors made as the experiment progresses, with the number of errors made in Block 4 being comparable to those made with the normal tool and the hand-alone throughout the experiment.

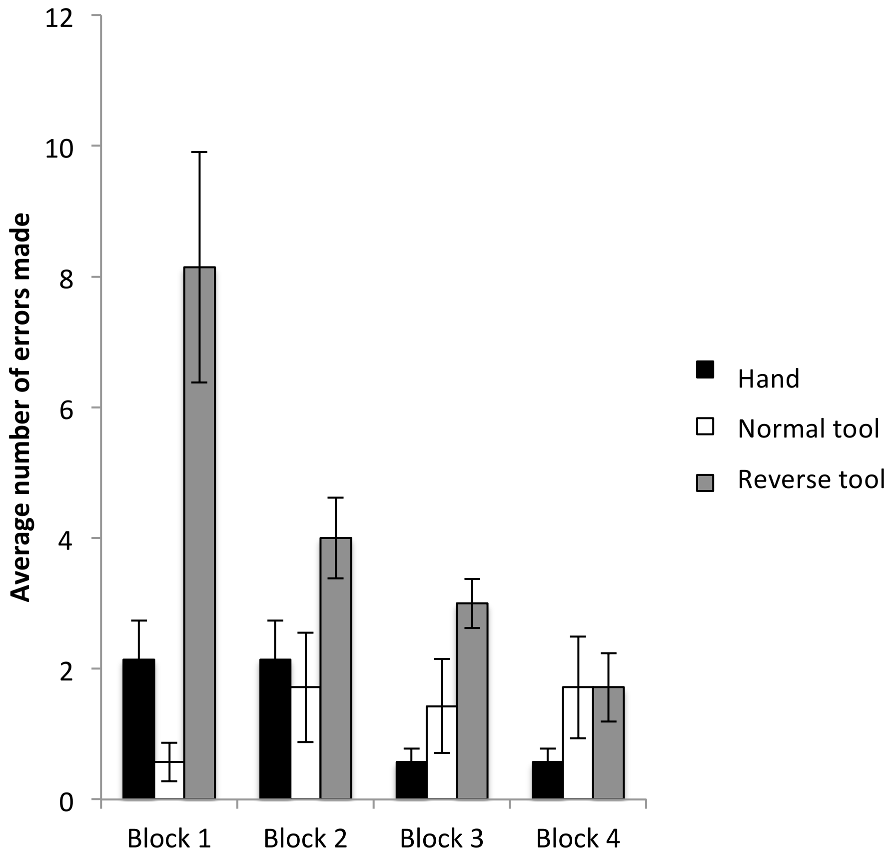


Figure 7.8. The average number of errors made for each grasp type during each block of the experiment. Data for Blocks 1 and 2 and Blocks 3 and 4 are repeated with the hand as only two blocks were completed. Errors bars show +/-1 SEM. N=8.

A 3 x 4 (grasp type x block number) repeated measures ANOVA shows that there was a main effect of block number on the number of errors made ($F(3,18)=14.15$, $p<.001$). There was also a significant block number x grasp type interaction ($F(1.86,11.14)=7.20$, Greenhouse Geisser corrected, $p=.011$), which likely shows that block number had a larger effect on the number of errors made with the reverse tool than the normal tool or the hand. This significant decrease in errors as the experiment went on suggests that participants were learning to use the reverse tool. Whilst the overall high level of errors made with the reverse tool and the lack of aperture scaling for object size could be indicative of an unreliable internal tool model, this reduction of errors as the experiment went on suggests that a model could be present and that it was developing as participants were learning to use this tool.

7.3.6 Learning the tools

This study was designed to give participants the same exposure to both of these tools as participants had to the tools in Experiment 1. This was to allow a comparison of how long it took people to learn to use the different types of tools. In Experiment 1 scaling of peak end-effector aperture for object size was seen in all of the tools after the first block of trials and overall throughout the experiment. If we take this as a measure of having learnt to use the tools then it would suggest that simply changing the ratio of a tool does not make it harder to learn to use a tool, at least in a rudimentarily sensible way. However, in the current experiment people were not able to learn to use the reverse tool 'correctly' in the same amount of time as they still made significantly more errors up until the final block and did not scale their peak end-effector aperture with object size at all. This suggests that when different transformations of tools are used, particularly those tools that do not have motor equivalence, much more time is needed to develop a reliable internal tool model and become a fluent user.

7.4 Discussion

Looking at the results of this experiment it can be argued that participants learnt to use the normal tool relatively quickly and were optimising their performance with it throughout the task. This is illustrated by the fact that peak end-effector apertures reduced slightly block-by-block when using the normal tool and peak velocity significantly increased as well. Both of these could be taken as signs of learning occurring and the internal tool model being refined based on feedback from previous movements. As the experiment went on, more precise peak end-effector apertures could be formed at a higher speed. This, coupled with the low error rate seen throughout the experiment with the normal tool, suggests that participants were able to understand and use this tool efficiently from the beginning, perfecting their movements throughout.

When looking at the data for the reverse tool however, no significant scaling of end-effector aperture was seen, at any point in the experiment. This could suggest a lack of an internal model for this tool or one that is flawed to the point that movements are not produced correctly. If the brain were trying to program movements in terms of end-effector units (Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Umiltà et al., 2008), then we predicted that performance with the two tools would be similar in this experiment. Due to the lack of scaling this obviously was not the case, but whether this was because the movements were being programmed inherently differently or whether the attempted movement was the same but it was being put through a flawed internal model is unclear.

If participants were unable to develop any kind of internal model for the reverse tool then one method to deal with this would be to adopt a large peak end-effector aperture throughout the experiment rather than working to alter their aperture based on object size. If you have no internal tool model, or one that is demonstrably unreliable, then this is a sensible strategy as it will avoid colliding with the object that you are trying to grasp. It would take less mental effort and would be far more successful to adopt this approach than it would to try and calculate the appropriate end-effector aperture on every trial using a flawed model. This may be what is seen in this experiment as participants opt for a relatively large aperture throughout the whole experiment and do not deviate from it, doing the same thing trial-by-trial. It should be noted however that with the reverse tool whilst no change in peak end-effector aperture was seen over the course of the experiment, there was a significant increase in peak velocity block by block. This could suggest an internal model for this tool does indeed exist and that it is improving, increasing the understanding of the tool, but it must be considered that this is not coupled with the same changes in end-effector aperture that were displayed with the normal tool.

As discussed in the introduction a tool that has motor equivalence (Arbib et al., 2009) could be much easier to develop an internal model for because it can be adapted from the pre-existing model of the hand (Telgen, Parvin & Diedrichsen, 2014). However, this would not be the case for a tool that did not have motor equivalence, here an entirely new model would need to be developed. Participants did demonstrate a large reduction in the number of errors made with the reverse tool as the experiment progressed, eventually falling to the level of the normal tool in block 4. This coupled with the increase in peak velocity seen throughout the experiment could suggest that an internal tool model was being developed and improved for the reverse tool as the experiment went on. It could just be that because the reverse tool did not have motor equivalence, and therefore needed an entirely new internal model, that the experiment was not long enough to see performance comparable to the normal tool or the hand. It could be that if a longer experiment was run, with more time to develop an internal model of the reverse tool, or if the tools were blocked, that scaling of peak end-effector aperture may in fact occur if the brain is encoding the movements in end-effector units (Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Umiltà et al., 2008).

Participants were always able to explain to the experimenter what they needed to do to with the reverse tool to be able to grasp an object, so they understood the tool in theory. However, when it came to making the grasp they often moved the tool in the wrong direction when trying to make small online adjustments, suggesting that this understanding was not deep enough to allow proper use of the tool. It can be argued that it is not too surprising that people struggled more with the reverse tool than the normal one, as it is not a transformation that most people would use in day-to-day life whereas the normal tongs arguably are. This increases the likelihood that participants were having to build an internal model of the reverse tool from scratch in this experiment, whereas they could build on existing models and experience for the normal tool. It is also worth considering that other reverse tools that participants are likely to have used in the past, such as spring-loaded clothes pegs and test tube holders, do not necessarily require a precise grip. When using these types of tools in the past the task is simply to open the tool and close it again around the object and there is little gain from having a precisely sized grip. However, when using normal tongs, something which people are more likely to be well trained in and do on a more regular basis, it would be a waste of time and energy to fully open the tongs every time you wanted to grasp something. Therefore, this aperture scaling behaviour is likely to already be built into an internal model for the normal tool.

7.4.1 Further Research

As said earlier, it would be interesting to run a longer version of this experiment to investigate whether individuals ever performed in a similar manner with the normal and reverse tools. If participants did begin to perform in this manner with the reverse tool then it would be possible to look at how long the internal model took to develop to the point that the tool could be used in a similar manner to the hand. Also, if aperture scaling was eventually seen in the reverse tool and we were confident that a relatively robust internal model had been developed, then we could test participant's abilities with these tools further. We could investigate whether users were able to control the end-effectors in a sensible manner when sudden changes are made to the object they were grasping. For example, if the object grew in size during the grasp would individuals be able to take the appropriate action of opening the tool tips wider or would they simply open their hand wider and therefore do the incorrect thing with the end-effector of the reverse tool? This task would not be achievable if the user did not have a robust internal model of the reverse tool, however it cannot be run unless people alter their end-effector aperture according to size. Another experiment that could be run to further probe participants' models of the reverse tool would be to swap the task demands trial by trial. For example, using normal objects where you have to close the tool tips around the object to lift it and also reverse objects where you have to place the tips into a gap in the object and open the tips to lift the object. This would further test whether participants have developed as much of a robust model with the reverse tool as they did with the normal tool as again this task could not be completed if the participants did not have a reliable internal model on which to base calculations. Both of the experiments can only be run however if participants can demonstrably learn to use the reverse tool, so a longer experiment that demonstrated a solid internal model of the reverse tool would be needed first before those participants could then be tested on any of these other experiments.

Chapter 8: General Discussion

8.1 Aim of our research

In this thesis, we were interested in using kinematic analyses and variations in tools' geometrical properties, to further our understanding of tool use. We wanted to investigate whether there were similarities in the way people picked up objects with their hand and with a tool, and whether these remained when we manipulated the ratio of the tool. This was because we wanted to investigate the concepts of end-effector control and internal tool models, and similar performance across the hand and our tools would help to support these theories.

8.2 The adaptation of existing internal models

Movement of the body is planned and implemented using a predictive forward model (Wolpert & Flanagan, 2001). For reaching and grasping this involves using a model of the arm and hand to predict how a given motor programme will play out and making adjustments online if needed. If participants can alter their behaviour appropriately when switching tool trial-by-trial then this would indicate that the properties of tools were stored in the brain, possibly in the cerebellum (Imamizu et al., 2000; 2003; 2007). This would be consistent with the idea of internal tool models, possibly adapted from the predictive forward model of the hand.

We found that many of the hallmarks of typical movements made with the hand when reaching and grasping are still present when using tools. We ran five experiments with our original set of three wooden tools. In all of these experiments the peak velocities that participants reached scaled with the distance of the object being grasped when using the tools. The peak end-effector apertures produced also scaled with the size of the object in all experiments using these tools. Scaling of peak velocity with object distance and peak grip aperture with object size are both typical findings when grasping objects with the hand (Jeannerod, 1981; 1984; 1988; 1997; Smeets & Brenner, 1999, Wing et al., 1986). To find that both effects occurred consistently when grasping objects with our tools, each of which had different ratios, was an interesting finding. This suggests some fundamental understanding of the tools being used as being able to use each of them in a sensible manner that is comparable to the hand supports the concept of internalisation of tool properties. The fact that the movements followed the same basic principles, regardless of the end-effector being used is supportive of the concept that the brain encodes movement information in end-effector units and not in terms of hand opening (Gentilucci et al., 2004; Itaguchi & Fukuzawa, 2014; Umiltà et al., 2008).

8.3 Building in a margin-for-error

Whilst we have produced a lot of evidence in this thesis that the brain encodes movements in end-effectors units and utilises internal tool models, there are obviously differences in movements made with and without tools. This is not surprising. The concept of using the model of the hand to develop and refine an internal model of a tool does not mean that these two models will necessarily function in an identical manner. Using a tool is not the same as using your hand.

In Experiment 1, we analysed the average grasp profiles of the hand and the three tools. This was to attempt to analyse the movement as a whole rather than only investigating it as a sum of its parts. Here a difference between the control of the end-effector when using the hand compared to the tools was evident. The peak end-effector aperture was visibly flattened when using the tools. This has been identified in multiple other experiments and referred to as a plateau (Bongers, 2010; Gentilucci et al., 2014; Itaguchi & Fukuzawa, 2014). This suggests that there is a difference in the way in which the peak end-effector aperture is formed when grasping with a tool and the hand, even if the aperture reached is ultimately the same. As stated previously, there is inherent uncertainty present when using a tool. This is because an internal tool model arguably has to be noisier or less certain than the model of the hand. This plateau around peak end-effector aperture is indicative of uncertainty in the internal tool model. The system is building in a margin-for-error to account for the added noise in the model of the tool. By having a plateau around the peak end-effector aperture the system allows time for any necessary online adjustments.

We also saw in two out of the three experiments that compared peak velocities reached with the tools and the hand that participants were significantly faster when using the hand to grasp an object, an effect that has also been demonstrated in past research (Zheng & Mackenzie, 2007). In Experiment 1, participants spent almost twice as long in the slow phase of the movement when using the tools compared to the hand. Because the internal models of the tools are not as accurate or reliable as that of the hand, then normal motor control mechanisms are compromised. Moving more slowly, particularly in the final precise phases of the movement, allows vision to be utilised and online corrections to be made to ensure a successful grasp (Morgan, 1989; Previc, 1990; Servos, Goodale & Jakobson, 1992; Sheedy, Bailey, Buri & Bass, 1986; Volcic & Domini, 2016).

8.4 An internal tool model or an update of the body schema?

The concept of an internal tool model is possibly another way of looking at the body schema (Head & Holmes, 1911). It has been repeatedly pointed out in the literature that the idea of a body schema is poorly defined (Berlucchi & Aglioti, 2010; Cardinali, Brozzoli & Farnè, 2009b; Critchley, 1979, as cited in Berlucchi & Aglioti, 2010;

de Vignemont, 2010; Maravita, Spence, & Driver, 2003; Poeck & Orgass, 1971; Vallar & Rode, 2009). However, there is a lot of overlap between body schema research and that of internal tool models. Taking the motor programmes that you have developed for your own arm and hand and using these to develop new ones for a given tool that you are using, is arguably comparable to extending your concept of your arm to include a tool and using it as an extension of your own body. Both ideas involve taking the known information about the body and applying this to a tool in order to be able to use it. Internal tool models are arguably just a more mechanistic concept of incorporation into the body schema. Our experiments did not address whether we maintain our perception of our hand during tool use or not (Arbib et al., 2009; Bonifazi et al., 2007; Povinelli et al., 2010), however our findings do complement a lot of the research that shows that tools could be incorporated in the body schema.

As discussed previously, this concept of tool embodiment and the adaptation of the model of the hand begins to break down when the tool does not have motor equivalence (Arbib et al., 2009). As we touched upon in Chapter 5, the concept of motor equivalence is not binary, instead tools differ in the degree of how similar they are—in terms of the control process required—to the hand. There are some tools such as the 360^{o} rotational arm mentioned previously that definitively have no motor equivalence to the hand as this is a movement that the arm and hand cannot physically make. However, there are other tools that do not function in the same manner as the hand, but still have some level of motor equivalence. For example, our reverse tool used in Experiment 6 still utilised a pinch grip, it just did this in the opposite manner to the hand. Mechanically, the reverse tool had an equal level of complexity to the normal 1:1 tool. However, it is unlikely that participants would have had an existing internal model for reverse grasping as this is not something that the body can do, making it less motorically equivalent than a normal pair of tongs. Participants did still scale their peak velocity with object distance when using the reverse tool, and their error rate dramatically reduced during the course of the experiment. This is suggestive of an internal model being developed, and the presence of velocity scaling could suggest that this model is still being based on the knowledge of how the hand works. Research by Umiltà et al. (2008) showed that there are neurons in the monkey brain that appear to code for the end-effector of the tool, firing for the opening of the end-effector of both normal and reverse pliers. Their findings indicate that, given enough time, an internal tool model of a reverse tool could be developed. Taken alongside the learning that seemed to be occurring in Experiment 6 with our reverse tool, this suggests that even tools that are not directly motorically equivalent could utilise internal tool models, and these could still be based, to some extent, on the motor programmes of the hand. However, this model would likely take longer to develop as it cannot be directly adapted from the model of the hand (Telgen, Parvin & Diedrichsen, 2014). Therefore, it seems that internal models can be developed relatively quickly for tools that are similar in function to the hand, but as motor equivalence reduces, models of those that are controlled differently to the hand cannot be developed in the same timeframe.

8.5 Developing and utilising internal tools models

Five of the six experiments that we ran directly compared the kinematics of reaching and grasping with the hand to those produced when using a 1:1 tool. In all but one of these experiments we found no significant differences between the peak end-effector apertures produced with the hand and those produced with the blue 1:1 tool, suggesting a common underlying motor programme. This is contradictory to what has been found by the few studies that have investigated the kinematics of tool use in the past. Bongers (2010), Gentilucci et al. (2004) and Zheng and Mackenzie (2007) all found that participants produced significantly larger peak end-effector apertures when grasping with a tool than they did when using the hand; concluding that tool use alters the aperture kinematics of a grasp. We have consistently shown throughout the thesis that this is not necessarily the case, and that it depends on the type of tool that the participant is using. When the tool that is being used does not alter the mapping between the hand and the world, in the case of our 1:1 tool, then there is less chance of error in the model as less calculations need to be made. Other than taking account of the spatial offset caused by using the tool, the basic motor programme is the same as that of the hand. In this case, we demonstrated that aperture kinematics do not differ between the tool and the hand. When using tools that alter the mapping between the hand and the world however, things become more complex. When the ratio of the tool has been altered, whilst it works in the same basic manner as the 1:1 tool, an extra gain transformation has been added that must be accounted for before the tool can be used accurately.

By using tools that had three different ratios throughout the thesis we could investigate the concept of internal tool models further. In every experiment that we ran with these wooden tools participants produced significantly different peak end-effector apertures. This could initially suggest that the concept of end-effector programming is not correct, as the end-effectors were used in different manners with these three tools. However, when you also look at the peak hand apertures that were produced it can be seen that in all five experiments participants produced significantly different peak hand apertures with the blue 1:1 tool and the red 1.4:1 tool. This shows that with these two tools, whilst the end-effectors were not controlled in the same manner, there was some attempt to adjust the movement to account for tool ratio. This is indicative of a common motor representation. It would appear that the brain is applying information from motor programmes of the hand and utilising this during tool use. This was still the case to some extent with the yellow 0.7:1 tool, however we only saw a significant adjustment for tool ratio in two out of five of the experiments.

In Experiment 2 we aimed to investigate how this apparent selection and utilisation of an appropriate tool model was possible. We used a variety of different cues to the tool that would be used on an upcoming trial to assess what information was needed to prompt an appropriate tool model and allow a sensible reaching and grasping movement to be executed. We found that even an arbitrary identity cue of colour was enough to allow participants to use the red tool no differently to the blue one. This suggests that simply recognising a tool that you already have an internal model for is enough to allow you to access this model and utilise it immediately. This must have been the case in this experiment as participants never saw the tool that they would use and grasped without vision. So, unless information about the tool and how it worked was being pulled up from memory then this result would not have been possible. It has been suggested in past research that these internal tool models can be switched rapidly, possibly on a trial-by-trial basis (Imamizu et al., 2003; Takahashi & Watt, 2017), and it seems that a simple recognition cue is enough to enable this process.

8.6 Noisy and biased internal tool models

By assessing how accurately participants could perceive object size with the hand and the three tools we hoped to further understand the partial compensation seen for the yellow 0.7:1 tool and the red 1.4:1 tool seen throughout the thesis. The ability to accurately perceive object size when using the tool should indicate any systematic biases in the internal tool model. We found that participants judged the size of objects to be essentially the same when using the hand, the blue tool or the red tool, despite the different intervening 'mechanisms', and in the case of the red tool different hand openings, involved in holding the object. However, we found that participants significantly overestimated object size when using the yellow tool. This suggested that they felt that the end-effectors of this tool were open wider than they actually were, which is indicative of a systematic bias in the internal tool model. The hand is open wider for the yellow tool than the blue tool when grasping the same object. If participants had an unreliable internal model of the yellow tool then it is reasonable that they could adjust their tool model towards the known model of the hand. This bias towards the 1:1 mapping would result in a systematic under-opening of the end-effectors (based on the false belief that they are open wider than they are), and would result in lower compensation factor for this tool.

The idea of a bias in the internal model of the yellow tool was supported further in the size discrimination task performed in Experiment 4. Sensitivity to object size in hand units was measured using JNDs. JNDs for the yellow 0.7:1 tool were twice the size of those for the other tools and the hand, suggesting that participants were much poorer at size discrimination with the yellow tool. Size discrimination using a tool relies on the multiplication of hand posture and position by tool gain to accurately judge the size of the objects being felt. We already saw in Experiment 3 that size judgement with the yellow tool was poor. The fact that we also see poor performance in the size discrimination task suggests incorrect calculations are being implemented, likely due to a biased internal model. These findings, coupled with the asymmetric compensation seen for the yellow tool throughout the thesis all support this concept. When this biased model is combined with knowledge of the normal motor programmes of the hand this leads to an error in the planned movement. Participants also took longer to lift the object up and spent more time in the slow phase of the movement in Experiment 1 when using the yellow 0.7:1 tool compared to the blue 1:1 tool. As stated earlier, this is indicative of the internal model not being as accurate or reliable and normal motor control mechanisms being compromised. This is because moving more slowly allows for visual feedback that can be used online to adjust the position of the finger and thumb with respect to the object (Morgan, 1989; Previc, 1990; Servos et al., 1992; Sheedy et al., 1986; Volcic & Domini, 2016).

The yellow tool seems to have a systematic bias towards the opening of the hand, being heavily weighted towards a 1:1 mapping. It is also possible that on top of this, both the yellow and red internal tool models are noisy as well. Noise caused by uncertainty about the tool model can also contribute to the lack of compensation seen in these two tools. Making calculations based on a noisy internal tool model will reduce the accuracy of the movements produced. Tool models are likely to be inherently noisy, so this could account for the overall reduction in compensation for both tools throughout the thesis. Performance with the yellow tool is then further hampered by a more systematic bias towards hand opening as well, resulting in the asymmetry when compared to the red tool. This means that the brain could still be programming movements in end-effector units, however noisy and biased internal models prevent the movement from actually occurring in this manner.

8.7 Adapting a model based on external cues

When visual uncertainty about an object's properties is introduced, participants increase their peak hand apertures to adapt to this (Keefe et al., 2011; Schlicht & Schrater, 2007; Sivak & Mackenzie, 1990; Wing et al., 1986). This reduces the chance that they will collide with the object during the grasp based on an error in the movement calculation due to this increase in uncertainty. When we degraded the vision of participants in Experiment 5 we found that a similar adaptive mechanism was utilised with both the blue 1:1 tool and the red 1.4:1 tool. Internal models of the tools therefore appear to be adjusted on a similar basis as the model of the hand when visual uncertainty is introduced. This supports the concept of a common underlying motor representation being utilised both when grasping with the hand and with tools.

This adaptive mechanism was not seen however for the yellow 0.7:1 tool. No adjustment of peak end-effector aperture was made when using this tool under visually uncertain conditions. We have already established that the internal model of the yellow tool appears to be biased. It could be that when an internal model is biased or flawed in this fashion that adaptive mechanisms cannot be applied. Whether the brain attempts to adjust in this manner when using this tool and the calculation is so flawed that the effect is not seen or whether the adjustment simply cannot be made due to a fundamental misunderstanding of how the tool works is unclear.

8.8 Future directions and implications

Even with three very similar tools, differences in the ability to use them were apparent. More studies utilising multiple tools in the future would be interesting, as it does allow more in-depth investigation than using one tool alone. Our initial thought was that if you could learn to use one of the three wooden tools then the others would be just as easy to use, because they all functioned in the same basic manner. However, both the red and the yellow tool arguably do not have the same level of motoric equivalence to the hand as the blue tool does, as they include a gain transformation. This could mean that internal models for these tools are not as well established, as the extra gain transformation cannot be solved using the model of the hand. However, throughout the thesis performance with the red tool was usually comparable to that of the blue tool whereas it was clear that performance was hampered when using the yellow tool. When asked about this, participants knew that they needed to open their hands wider than they originally thought, but even armed with this knowledge they still fell short of the performance seen with the red tool. It is comparable to what we saw in the experiment with the reverse tool. Participants knew what they *should* be doing to solve the problem, but somehow were unable to take advantage of this information during the grasp. As stated previously, it could be that the transformation of the yellow tool is not encountered as regularly as the red tool's transformation in day-to-day life. It could be that the speed in which an internal tool model can be developed is modulated both by past experience with that transformation and the level of motor equivalence to the hand (and therefore how much the model of the hand can be utilised in the development of the model of the tool). It would therefore be interesting to investigate whether all tools that minimise the grip are generally harder to use or whether there was something specific about our yellow tool that prevented participants from developing a reliable internal tool model. We tried to probe this further in the experiments described in Appendix 1 but were not able to answer our questions, so future research in this area would be interesting.

There has been a lot of work carried out in the past on tool use that has utilised very simple tools like rakes and sticks (Brown et al., 2011; de Grave & Brenner, 2011; Farnè et al., 2005a; Osiurak et al., 2012; Witt et al., 2005 to name a few). Whilst this is likely to be because their questions were very different to those that we had in mind, it must be argued that further study into the types of tools that we use more regularly in our day-to-day lives can only be a worthwhile pursuit. Overall, it is very interesting to me that such seemingly small changes to a tool's mechanics (such as altering its ratio) may actually make quite large differences in people's ability to precisely use the tool. It seems logical that different classes of tools may be harder or easier to use than others, but to see that such small differences in the same types of tools may also matter is interesting. All of our original tools arguably had some level of motor equivalence with the hand, although this was most direct with the blue 1:1 tool. The main difference between the tools was the location of the pivot – and therefore the tool ratio. If more can be learnt about what transformations of tools can be used with little learning and in an intuitive manner and what changes to a tool's mechanics require a lot more time to develop a robust internal model, then tools could be designed in the future with this in mind.

As mentioned previously, we all rely on simple tools in our day-to-day lives to help us to complete tasks. However, there is now also an increasing reliance in more specialised robotic tools in many fields. For example, remote robotic tools are now used in bomb disposal and in surgery, where the user uses a separate interface to control the tools. If we knew more about what kinds of ratio changes and rotational changes the brain could easily understand, then these types of robotics could be built with this in mind in the future, making them more intuitive and arguably safer to use. If a surgeon is able to swap between surgical tools with the press of a button when using a new surgical system then the system needs to be designed to limit the possibility of mistakes being made. We demonstrated in Experiment 2 that colour alone was an informative enough cue to allow participants to use the red 1.4:1 tool as well as if they had all of the information about the tool present. However, more experiments need to be carried out to see whether these findings are applicable to other types of tools as we were not able to interpret our results with the yellow 0.7:1 tool. Further research into cues to tool models could help with the design of these complex robotic tool systems. By finding out exactly what it is about a tool that allows the user to understand and use it, these cues could be built into the robotic systems to act as an extra level of safety, prompting the surgeon as to what tool they are currently using for example. If further research found that colour was a robust cue then something as simple as colour coding the tools in these systems could improve safety. It is likely that with technological advances we may become even more reliant on these more complex tools in the future, so it seems sensible to find out as much information as possible about them so that next generation tools can be designed with these things in mind.

Another application of our research would be in the field of prosthetics; if tools really are incorporated into the body schema then arguably prosthetics should be able to be as well. This should be the ultimate goal when designing prostheses; making something that the user is able to feel is an extension of their own body. By knowing what transformations and movements come intuitively to a user when using a tool and what cues and information are important for precise tool use to be achievable, it might be possible to build prostheses that are more readily accepted by patients. The process of losing a limb and having to adapt to a life with a prosthetic one is already a traumatic and difficult process. Now that prostheses are becoming more lifelike and technology is developing hugely we should be using tool use research to help make them even better.

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Appendix A

A.1 Experiment 7: Was a limit of hand opening responsible for the lack of compensation seen with the yellow tool?

In Experiment 1 we found that participants did not fully compensate for the geometry of either the yellow 0.7:1 tool, or the red 1.4:1 tool. However, they compensated more for the red tool than they did for the yellow one and this pattern of 'asymmetric' compensation was seen for 11 of our 12 participants. One reason for this may have been that the yellow tool requires larger hand openings than the blue or the red one when grasping the same objects. In Experiment 1 we saw that time to peak end-effector aperture increased for larger objects with the yellow tool and that peak velocity was slower for the largest object in our set compared to the other two tools. It is therefore possible that participants were reaching the upper limit of their hand opening and this could be responsible for the significantly lower level of compensation seen when using the yellow tool. To test this, we ran an experiment where the hand openings required to grasp an object were the same for the three tools. This was achieved by using a different set of objects for each tool, such that they caused the same set of hand openings when held. We reasoned that, if an upper limit on grip aperture caused the low compensation for the yellow tool this should be absent when required hand openings were matched. However, if it was not participants reaching their upper hand limit that was the cause then the asymmetry previously seen would still be present. Based on the fact that the lack of compensation is seen at all object sizes for the yellow tool in Experiment 1 (i.e. the grip scaling function is linear, rather than having a 'knee' or plateau) a ceiling effect of hand opening seems unlikely. However, this experiment was intended to serve as a control to answer the question either way.

A.2 Methods

A.2.1 Participants

Five right-handed participants were recruited through opportunity sampling to take part in the experiment (three female and two male). None had taken part in Experiment 1. All participants had either normal or corrected to normal vision and no known motor impairments that would affect their ability to make a normal grasp. Participants gave their fully informed consent at the start of the study. Financial compensation and ethical approval was the same as in Experiment 1.

A.2.2 Stimuli and apparatus

The apparatus was the same as in Experiment 1 except for the different-sized objects in each tool condition. In the yellow 0.7:1 tool condition the object sizes were 24, 28, 31.5, and 35 mm. In the blue 1:1 tool condition the sizes were 35, 40, 45, and 50 mm. And for the red 1.4:1 tool the sizes were 49, 56, 63, and 70 mm. When held with their respective tools these resulted in 35, 40, 45, and 50 mm hand openings for each of the three tools. Object distances were 200, 250, 300, 350, and 400 mm. More distances were used in this experiment to vary the demand on the participant more, to hopefully compensate for the much-reduced range of required peak end-effector apertures. We were concerned that if there was not enough demand to alter motor performance trial by trial then the movements might be memory-based, or generic across different trials.

A.2.3 Procedure

The wrist marker was attached over the radius bone of the participant’s right wrist (to avoid the problems with missing markers that occurred in Experiment 1). No data was collected using the hand in this experiment.

The experiment was run in four separate sessions. Each session consisted of one block of 180 trials, which took participants roughly an hour to complete. Each block consisted of 60 trials with each of the three tools, with 3 repetitions being completed for each object size/distance combination, giving 12 repetitions of each trial type over the complete experiment. Trials were randomised in each block, so that object size, object distance and tool were all randomised. The procedure for this experiment was the same as the tool sessions in Experiment 1, except the calibration object was not used in this experiment.

A.3 Results and discussion

A.3.1 Peak velocity

Figure A.1 shows the average peak velocity (a) as function of object size collapsed across object distance and (b) as a function of object distance collapsed across object size. Both figures show that there seems to be no difference between the peak velocities produced with the three tools in this experiment. It can be seen in Figure A.1b that the farther the object was from the participant the higher the peak velocity was. However, Figure A.1a shows that object size seemed to have little effect. A 3 x 4 x 5 (tool type x matched hand size x distance) repeated measures ANOVA revealed no main effect of tool type ($F(2,8)=1.326$, $p=.318$) meaning that there was no significant difference in the peak velocities reached with the three tools. There was also no main effect of object size ($F(1.24,4.94)=0.62$, Greenhouse Geisser corrected, $p=.503$). There was however a significant main effect of object distance on peak velocity ($F(1.01,4.03)=87.38$, Greenhouse Geisser corrected, $p<.001$). It can clearly be seen in Figure A.1b that as the object distance increased the peak velocity increased as well, looking at planned comparisons it can be seen that peak velocity was significantly higher for each object distance than it was for the previous one.

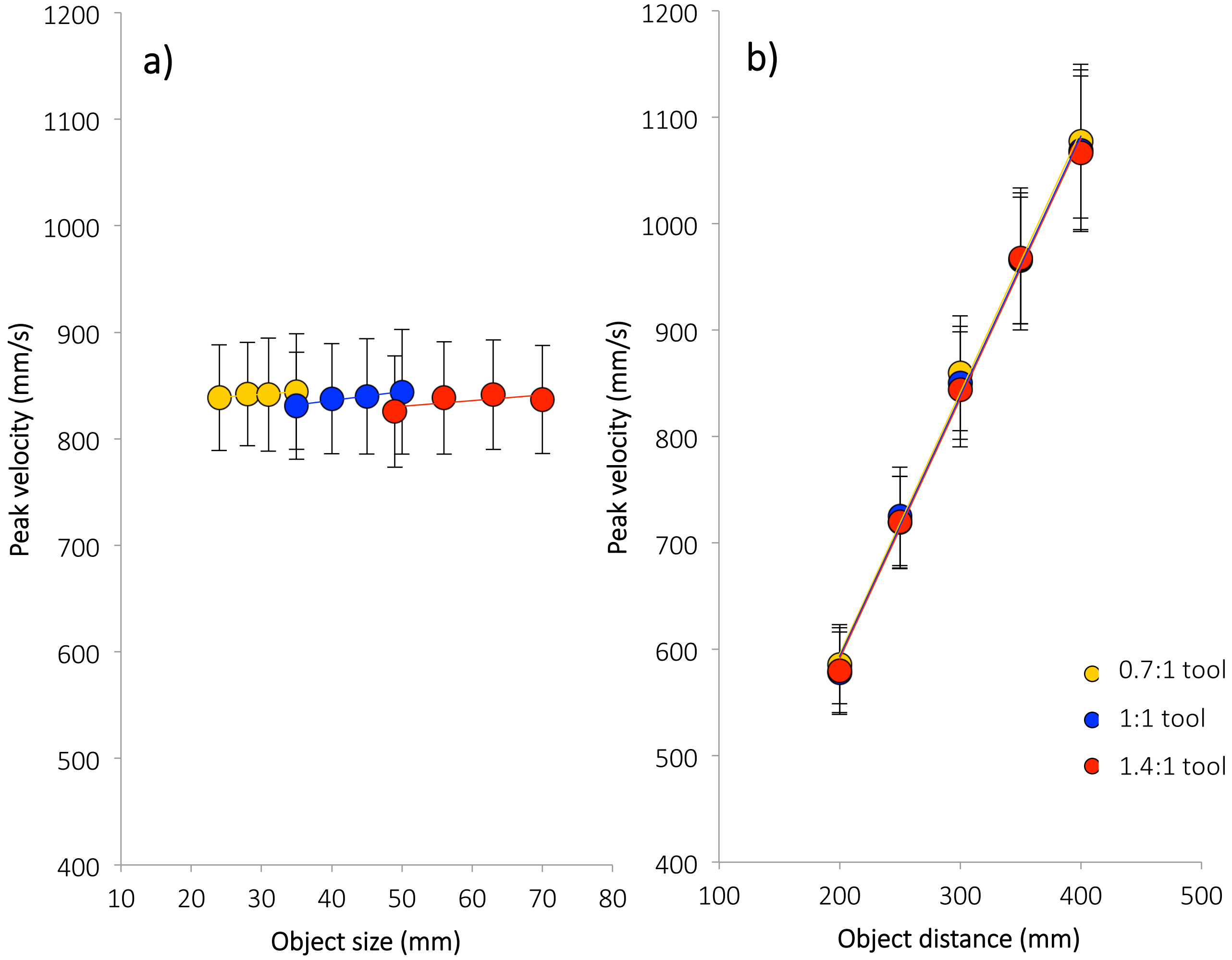

Figure A.1. Peak velocity data. (a) Average time to peak velocity as a function of object size, collapsed across distance. (b) The same data as a function of object distance, collapsed across size. Error bars show +/-1 SEM. Linear regression lines have been fitted through the data. N=5.

These findings support what was found in Experiment 1, this strengthens the idea that using a tool does not necessarily influence the velocity of a movement (Gentilucci et al., 2004).

A.3.2 Scaling of peak end-effector aperture with object size

Figure A.2 plots (a) the average peak end-effector apertures and (b) the average peak hand apertures produced with the hand and the three tools. It can be seen by looking at Figure A.2 that scaling of apertures with object size seems to be less pronounced in this experiment than it was in Experiment 1 across the three tools.

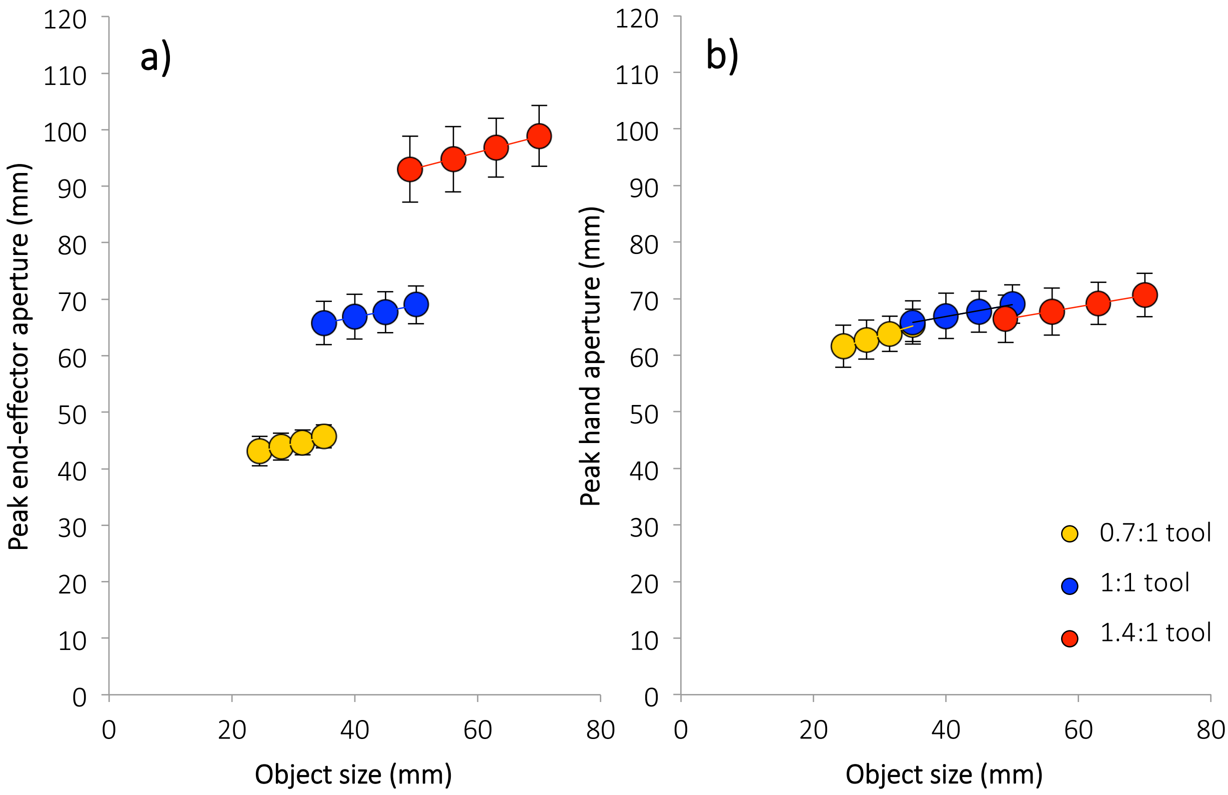

Figure A.2. Aperture data, as a function of object size, collapsed across distance (a) In end-effector units. (b) The same data plotted in units of hand aperture. Error bars show +/-1 SEM. Linear regression lines have been fitted through the data. N=5.

The peak end-effector aperture data for the blue tool had a slope of 0.2, the red tool had one of 0.3 and the yellow tool also had one of 0.2. This shows that the peak end-effector aperture produced when grasping the largest object was not much bigger than that produced for the smallest object with any of our three tools in this experiment. In Experiment 1 we saw a slope of 0.7 for the blue 1:1 tool and 0.9 and 0.6 for the red 1.4:1 and yellow 0.7:1 tools, respectively. Scaling in this experiment is therefore very low compared to both Experiment 1 and grasping performance typically seen with the hand in other studies that tends to be 0.8 (Smeets & Brenner, 1999). This lack of scaling is puzzling as scaling of grip aperture with object size is something that reliably occurs in normal grasping and therefore this suggests a problem with this experiment. Because of this, it becomes difficult to draw meaningful conclusions from this experiment. Further than this we ran this experiment to attempt to answer questions raised by Experiment 1, so if the pattern of results for peak end-effector aperture of Experiment 1 have not been replicated in this experiment it does somewhat limit our ability to answer questions about the first experiment. Results of peak velocity were replicated, however. Keeping this in mind some conclusions can be drawn with caution.

It has been shown in the past that familiarly sized objects or a limited stimulus set can affect the reach (McIntosh & Lashley, 2008) and grasp (Keefe & Watt, 2009) aspects of a movement. This means that if a small object set is used in an experiment then performance might not be reflective of a normal grasp. We were concerned about this during this experiment and therefore we tried to vary demand as much as possible. However, the fact that we needed to match hand openings with the three different tools meant that the range of required motor outputs (i.e. with the hand) was in fact very small: only four different hand openings were needed to grasp all the objects throughout the experiment. We speculate therefore that—given relative uncertainty about the tools' properties, combined with learning that similar movements were often required—a reasonable strategy in this study might have been to produce essentially generic movements in all situations, and adopt a similarly wide hand opening for all three tools. This would make sense in some respects, as participants were still able to successfully grasp all the objects in this manner and save energy by not having to calculate appropriate grip apertures on each trial. We had no choice in the present experiment but to use a small object set, as we could not match any more hand openings for the three tools without ending up with objects that were very close in size to one another. We were initially more concerned that having similarly sized objects may lead to strange grasping patterns. We felt that if participants continued seeing very similar objects on every trial that this may lead them to adopt a constant grip aperture throughout the experiment. In the end, this happened anyway and may be unavoidable with our specific tools due to the restrictions they place on the object set using this methodology.

A.3.3 Compensation factors

Figure A.3 plots the compensation factors for the red and yellow tools in this experiment, and shows that no compensation was present for either of the two tools. What is actually seen in the yellow tool is a slight negative compensation factor. This has occurred because participants opened their hand less when using the yellow tool than when using the blue one – the opposite direction to what we would expect with compensation for the tool ratio.

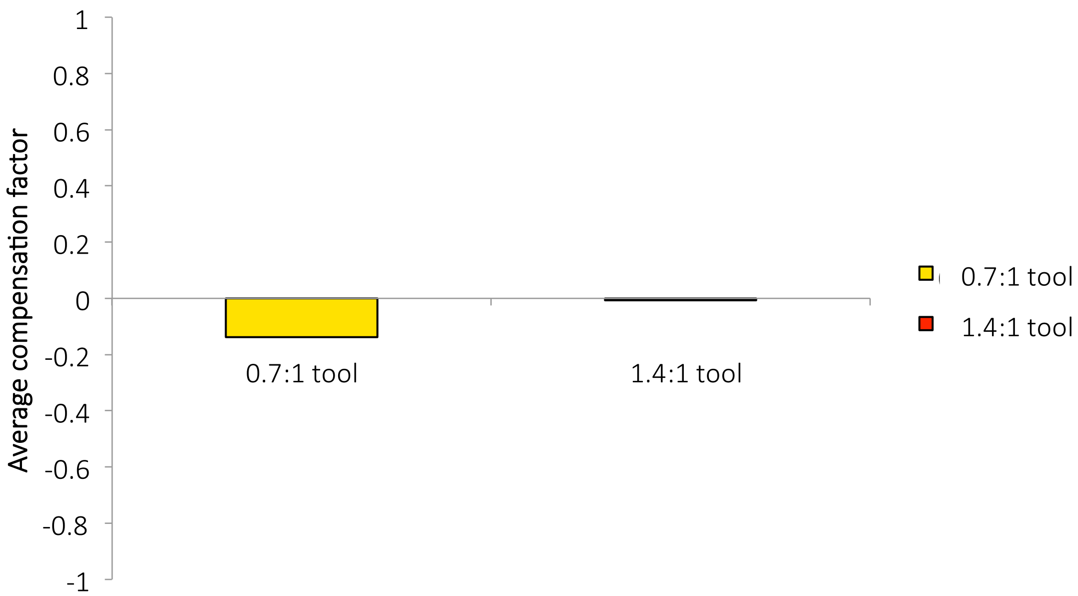

Figure A.3. Average compensation factors for the yellow 0.7:1 tool and the red 1.4:1 tool. Error bars show +/-1 SEM. N=5.

The compensation factors are not as useful in this experiment as they were in the previous one. This is because we are calculating a measure of success in using the red and yellow tools based on non-typical data from the blue one. As very limited scaling of end-effector aperture was seen when using any of the three tools it indicates no sensitivity to object size so it is unlikely that compensation for tool gain would occur. This makes the conclusions that can be drawn from this analysis limited.

As said before, our ability to draw conclusions about whether an upper hand-opening limit was the cause of the low yellow tool compensation is limited by the fact that participants did not perform in an expected manner. However, it can be argued that because the under-opening of the yellow tool is seen across all object sizes in Experiment 1 that this is unlikely to be the case. If a limit in hand opening were truly the cause of the lack of compensation then it would be expected that we would see better compensation and larger peak hand apertures for the yellow tool with smaller object sizes and that this would reach a ceiling when grasping the larger objects. Instead we see an under-opening with the hand for all object sizes when using the yellow tool and because of this it could be argued that a limit in hand opening is unlikely to be the cause. However, further experiments would be needed to confirm this.

A.4 Experiment 8: Does limiting required motor output restrict end-effector aperture scaling?

In Experiment 7 we found a lack of grip aperture scaling for object size with all three of the tools. We speculated that the limited range of motor outputs required to complete the task might have caused this lack of scaling. However, in Experiment 7 it was not possible to isolate this effect from our tool-gain manipulation so here we tested that hypothesis using just the blue 1:1 tool and the hand. We wanted to see whether using a similarly small object set would reduce the peak end-effector aperture scaling seen with the hand and whether the same effect could be replicated when only using one tool (thereby reducing task demands). This is important to look at because it is very unusual not to see scaling of grip apertures with object size with the hand (Jeannerod, 1981; Jakobson & Goodale, 1991). If we can reproduce the effect seen in Experiment 7 when grasping with the hand this would be stronger evidence that the limited variation in required movements was the cause of the issue. By looking at these two conditions we can see whether the small object size might have been responsible for the results seen in Experiment 7 or whether people scale their grip correctly in this experiment and therefore something else was the cause.

A.5 Methods

A.5.1 Participants

9 participants (2 male, 7 female; 8 right-handed, 1 left-handed; 5 naïve and 4 who had taken part in previous experiments) took part in the experiment. They were recruited through opportunity sampling from Bangor and the surrounding areas. Participants had normal or corrected to normal vision and no known motor impairments that would affect the ability to make a normal grasp.

A.5.2 Stimuli and apparatus

The apparatus was the same as in Experiment 1 except for the different-sized objects, and the fact that only the blue 1:1 tool was used. The objects in this experiment were the same as those used with the 1:1 tool in Experiment 7 (30, 35, 40, and 45 mm). The object distances were also the same as in Experiment 7 (200, 250, 300, 350, and 450 mm).

A.5.3 Procedure

The experiment was run in one session and consisted of two blocks, one using the hand and one using the blue 1:1 tool. As in Experiment 1, hand and tool trials were blocked to avoid having to remove and replace the markers every few trials. The experiment was counterbalanced so that half of the participants started on the hand-grasping block and half started on the tool-grasping block. Each block consisted of 60 trials and took 15-20 minutes to complete. The procedure of a trial was the same as in Experiment 7.

A.6 Results and discussion

A.6.1 Peak velocity

Figure A.4 plots the average peak velocity in Experiment 8 (a) as a function of size collapsed across distance and (b) as a function of distance collapsed across size. In the previous experiments peak velocity increased as object distance increased but object size had no effect on it. Looking at Figure A.4 it can be seen that Experiment 8 has the same pattern of data. It can also be seen that there appears to be no difference in peak velocity for the hand and the blue 1:1 tool.

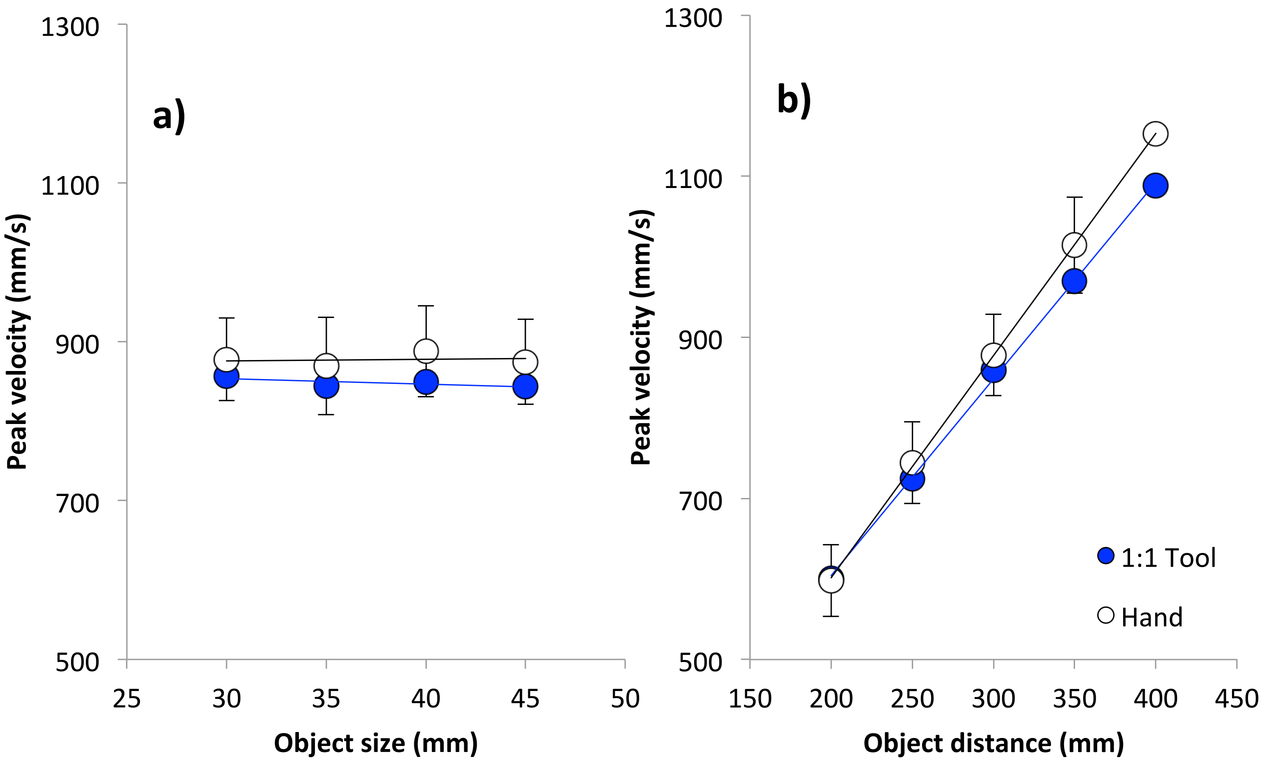

Figure A.4. Peak velocity data. (a) Average peak velocity as a function of object size, collapsed across distance. (b) The same data as a function of object distance, collapsed across size. Error bars show +/-1 SEM. Linear regression lines have been fitted through the data. N=9.

A 2 x 4 x 5 (grasp type x object size x object distance) repeated measures ANOVA revealed no significant main effect of either grasp type ($F(1,8)=0.88$, $p=.375$) or object size ($F(3,24)=1.34$, $p=.286$). There was however a significant main effect of object distance ($F(1.29,10.34)=199.79$, Greenhouse Geisser corrected, $p<.001$). It can be seen using planned comparisons that each distance was associated with a significantly higher peak velocity than the previous one.

A.6.2 Scaling of peak end-effector aperture with object size

Figure A.5 shows the average peak end-effector aperture for the hand and the blue tool as a function of object size (collapsed across distance). For the previous experiments we plotted both peak end-effector aperture and peak hand aperture. However, the different units are redundant with the blue 1:1 tool and the hand so only one plot is presented here. It can be seen that contrary to Experiment 1 participants seem to have different peak end-effector apertures for the hand and the 1:1 tool.

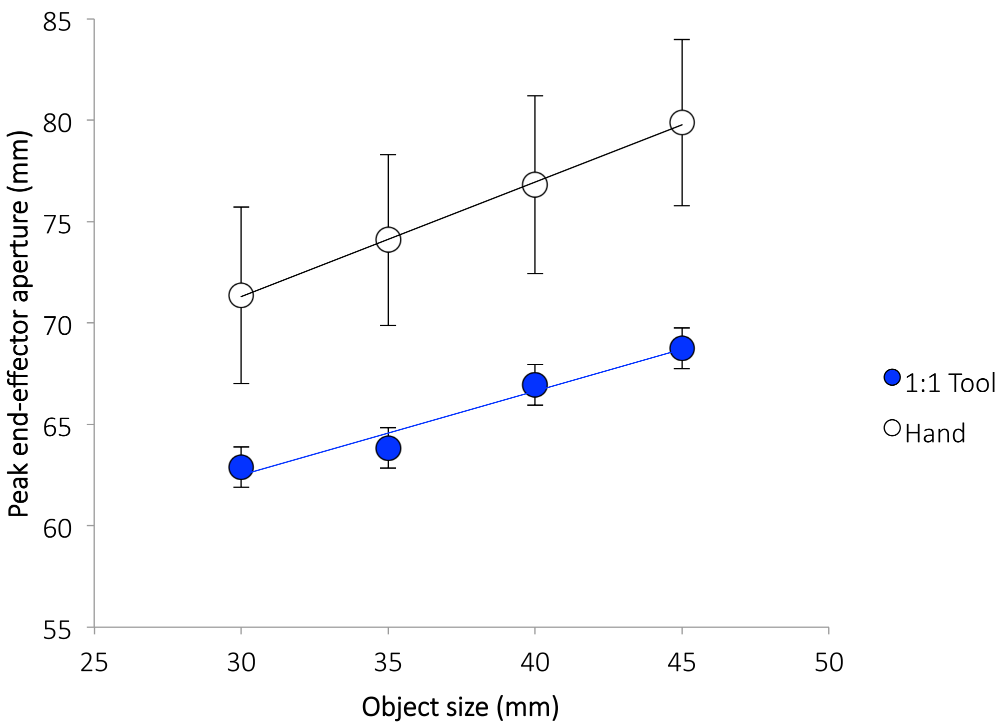

Figure A.5. Average peak end-effector apertures for the hand and the blue 1:1 tool. Error bars show +/-1 SEM, error bars are small enough for the 1:1 tool to be obscured by the data markers. Linear regression lines have been fitted through the data. N=9.

A 2 x 4 (grasp type x object size) repeated measures ANOVA revealed a main effect of both grasp type ($F(1,8)=12.27$, p=.008) and object size ($F(1.45,11.60)=42.96$, Greenhouse Geisser corrected, p<.001). As suspected, this contradicts Experiment 1 where there was no significant difference in peak end-effector aperture with the hand and the blue 1:1 tool. It can be seen here that peak end-effector apertures are significantly larger with the hand than they are with the 1:1 tool. It was also seen in Experiment 7 that there was no significant effect of object size on peak end-effector aperture, again in this experiment the opposite has been shown.

Whilst it is interesting that we have not replicated the peak end-effector aperture effect seen in Experiment 1, this experiment set out to look at whether participants would scale their peak end-effector apertures or not. Figure A.6 plots the scaling functions for the hand and the 1:1 tool in Experiment 1 and Experiment 8. Scaling functions for Experiment 2 are not plotted, as this experiment did not include any hand grasping trials. Looking at Figure A.6 it can be seen that the scaling functions of the peak end-effector apertures were still much lower in the current experiment than they were in Experiment 1. However, the scaling function with the blue 1:1 tool is still far higher in the present experiment than it was in Experiment 7 (where it was 0.2).

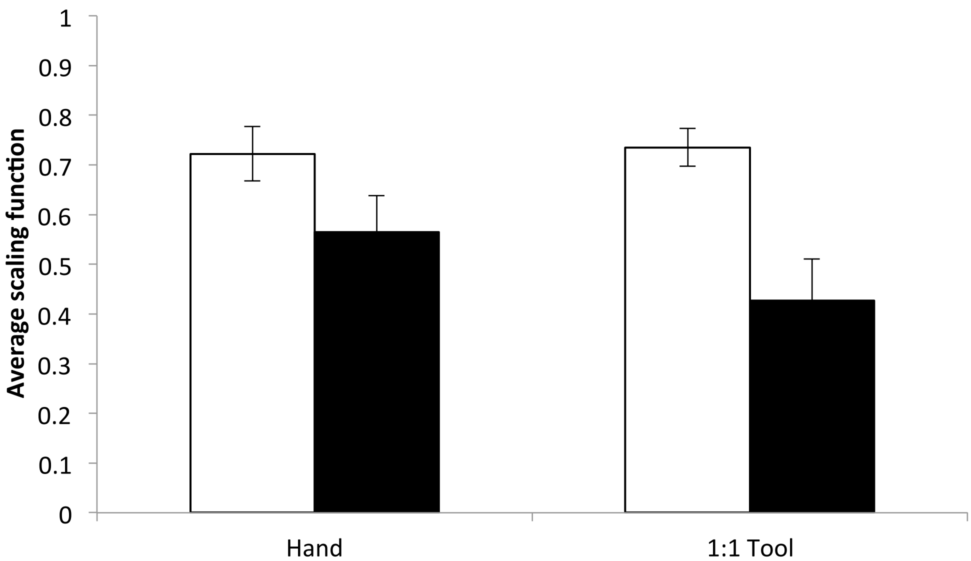

Figure A.6. Average scaling functions for both the hand and the blue 1:1 tool in Experiment 1 (in white) and Experiment 8 (in black). Error bars show +/-1 SEM. N=9.

This suggests that the small range of object sizes used in Experiment 7 may not be entirely responsible for the lack of scaling that was seen. One reason for this could be that because only the hand and one tool were used in this experiment the task demands were far lower than they were in Experiment 7 which used three tools with different ratios. This could mean that if less effort was needed to understand the tool in the current experiment and therefore the strategy of simply adopting a wider peak end-effector aperture was not as necessary. However it is clear that the restricted object range did reduce scaling to some extent, as 0.56 is low scaling for grasping with the hand which would usually be expected to be at around 0.8 (Smeets & Brenner, 1999). To see a reduction in the scaling with the hand as well as with the blue tool does add weight to the argument that the small object size was at least partially to blame for the lack of scaling seen in Experiment 7.

Figure A.7 shows individual and average scaling functions for the 1:1 tool and the hand plotted against each other for Experiment 1 and 8. No data was collected with the hand in Experiment 7 so this experiment is not shown here. It can be seen from both the spread of the data points and the error bars on the average data points that performance in Experiment 8 was much more variable than it was in Experiment 1.

Figure A.7 shows that in this experiment, there were large individual differences in scaling function across participants with some showing expected levels of scaling and some showing very little (or none) when using the blue 1:1 tool. In contrast, in Experiment 1 there was a more consistent performance seen across all participants.

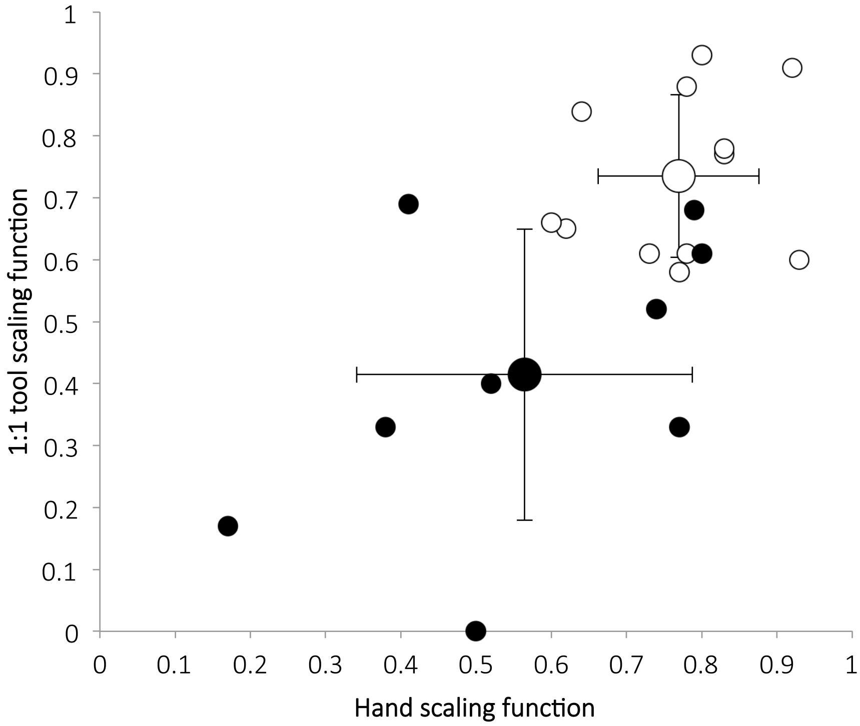

Figure A.7. Individual scaling functions for the hand and the 1:1 tool in Experiment 1 (white dots) and 8 (black dots). The large dot is the average with error bars showing +/- 1 SD. N=9.

A.7 Chapter discussion

It can certainly be argued that the small object set did have an effect on the peak end-effector apertures produced in both Experiment 7 and 8. Whilst the performance in Experiment 8 was not as poor as that seen in Experiment 7, end-effector aperture scaling was reduced for both the hand and the 1:1 tool compared to previously observed values and what was expected based on past research (Smeets & Brenner, 1999). It is possible that because Experiment 7 involved more complicated tools that this compounded the effect and reduced the peak end-effector aperture scaling further but this cannot be confirmed without further investigation.

It would certainly be interesting to investigate the effect of a small object set further using a larger sample size. If the effects seen in Experiment 7 held with a much larger sample of participants then this would be of methodological importance to studies of reaching and grasping.

Appendix B

B.1 Rationale and Sensitivity

B.1.1 Rationale

Throughout the thesis the basic premise of Experiment 1 was run repeatedly as a basis for the other experiments. In most of the other experiments participants still reached and grasped a series of object sizes at a series of distances with the three tools, before further experimental manipulations were applied. Because of this we have 33 unique participants who have completed something methodologically similar to Experiment 1 across the course of the thesis. Throughout data collection we struggled to get adequate sample sizes for the experiments due to the length of the time the participants had to be tested for (and therefore a reluctance of individuals to sign up to the experiments). By combining the data from each of the relevant experiments into one 'meta-analysis' we will be able to see whether the effects found throughout this thesis are robust when a larger sample size is analysed, therefore having more power than our previous experiments will have had.

We also have a smaller subset of participants who took part in multiple experiments throughout the thesis. We can use their data to look at practise effects and the effect that using repeated participants may have had on experimental results. It was noted in Experiment 4 that we saw higher levels of compensation than we had seen in previous experiments. This experiment only included four participants, all of whom had taken part in at least one experiment with the tools previously. It was hypothesised that the higher levels of compensation seen in Experiment 4 could have been caused by these participants retaining information about the tools from previous experiments and therefore being in a better position to use them more accurately from trial one than a naïve participant would be. We have eight participants who took part in two experiments, a further four who took part in three and one who took part in four. We are again going to suffer from a small sample size during this analysis, but by combining these participants together into one group of 13 'experienced' participants, it should give us some indication of whether compensation for the tools improved when participating in multiple experiments.

B.1.2 Considerations on Statistical Sensitivity

Throughout the thesis so far statistics have been reported with no accompanying measure of effect size. This raises an issue because reporting only statistical significance does not provide any indication of the magnitude of the effect and statistical significance can also be confounded by sample size. For example a very large effect found in a very small sample can lead to a statistically significant result, but so can a very small effect in a very large sample. Effect sizes provide a measure of the magnitude of the effect; therefore by reporting effect sizes as well as statistical significance we are also providing information about the size of the effect, making the statistics more meaningful.

The power of a statistical test, the size of an effect and the size of the sample are all related to one another. A small sample size, or a small effect size can both reduce the power of a statistical test making it more likely that the null hypothesis will be accepted when it should in fact be rejected. It is therefore important to make sure that you have a large enough sample size in order to be confident that you have enough power to detect an effect. This is a potential issue with the experiments so far in this thesis – due to the nature of the experiments they all had small sample sizes, reducing the power of our statistical tests. Coupled with the fact that no effect sizes were reported throughout the thesis this makes it difficult to make judgements about the validity of the statistical effects reported throughout.

To illustrate this point further I will present two sensitivity analyses that report the minimum size of effect that could be detected with 0.9 power given a variety of sample sizes. A value of 0.9 power has been selected due to the fact that we would wish to be able to draw meaningful conclusions from null results and therefore we would need to ensure that there is less than a 10% chance of a Type II error occurring. This first sensitivity analysis will be predicted on a paired sample t-test as this is illustrative of comparing the compensation factors of the yellow 0.7:1 tool and the red 1.4:1 tool throughout the thesis. The second sensitivity analysis will be predicted on a repeated measures ANOVA as this is illustrative of the other comparisons made in the thesis for example between peak end-effector apertures or peak velocities for the three tools (and sometimes the hand).

Experiment 1 had a sample size of 12; the minimum effect size that we would have the power to detect with an alpha of 0.05 and power of 0.9 would be d_z=1.03. During the thesis our smallest sample size was seen in Experiment 4 where we only had 4 participants; here the minimum detectable effect size with the same parameters would have been d_z=2.51. These are large effect sizes; and therefore any small effects would likely be undetectable using these small sample sizes. As mentioned in the rationale, throughout the thesis many participants undertook tasks that were similar to Experiment 1, meaning that we have data for 33 participants for something resembling Experiment 1. Here the minimum effect size that we would have the power to detect with an alpha of 0.05 and power of 0.9 would be d_z=0.58. This shows that by increasing the sample size we have improved our ability to identify an effect, as a smaller effect would be detectable in this sample size. We also wish to investigate whether there is an effect of exposure to the tools, with participants who took part in multiple experiments potentially performing better than those who took part in only one. We have data for 13 'experienced' participants who had already taken part in another experiment with the tools, the minimum effect size that we would have the power to detect with an alpha of 0.05 and power of 0.9 would be d_z=1.09.

As discussed above we also carried out many ANOVAs throughout the thesis so I will also present a sensitivity analysis that uses Cohen's f as the effect size measure. Again looking at our sample size of 12 for Experiment 1 the minimum effect size that we would have the power to detect with an alpha of 0.05 and power of 0.9 would be f=0.41. For our smallest sample of four participants the minimum effect size that we would have the power to detect with an alpha of 0.05 and power of 0.9 would be f=0.83. Using all of the participants who took part in some form of Experiment 1 (33 people) the minimum detectable effect size would be 0.24, again this is a much lower value now that the sample size has increased.

B.1.3 Considerations on the reporting of effect sizes

I did a lot of research into effect sizes whilst writing up this appendix and found that there are many different ways to measure an effect size and they all have their advantages and disadvantages. I mostly focused on effect sizes for ANOVAs, as this is what is reported throughout the majority of this thesis. Through this research, I have chosen to use Cohen's d and Cohen's f as my measures of effect size, reporting d when I calculate t-tests and f when I calculate ANOVAs. Cohen's d and f are both standardised effect size measures that indicate the difference between means in units of standard deviation. This means that if the value is larger than one then the difference between the means is more than one standard deviation. Because these effect sizes are standardised it makes them comparable across different units, which is seen as a big advantage for comparing across different measures and different experiments. Often when using ANOVAs eta squared or partial eta squared are reported as these are often readily available in statistical software packages, however they have their limitations. Whilst eta squared can be interpreted in terms of percentage of variance accounted for by the variable, making it an intuitive measure to understand (Levine & Hullett, 2002) it also has an upward bias, which is particularly bad when sample sizes are small (Fisher, 1928, as cited in Levine & Hullett, 2002). This makes it a poor effect size measure for our purposes. Partial eta squared loses many of the advantages of eta squared; it is not equivalent to r^2 in the manner that eta squared is equivalent to *r,* and it is also not understandable as percentage of variance accounted for. It also suffers from the same overestimate issues as eta squared (Levine & Hullett, 2002), which again makes it unsuitable for our purposes. Omega-squared is another effect size measure that can be used with ANOVA that is less biased than eta squared or partial eta squared, so is potentially a better measure of effect size. However, it measures the overall effect of the ANOVA and therefore is hard to interpret in a meaningful way, which is a serious drawback (Field, 2009). Taking these things in to decision, I decided to use Cohen's f, because it is not biased in the same way as eta squared and partial eta squared, but it is still interpretable in a meaningful manner as an effect size.

B.2 Methods

B.2.1 'Meta-analyses' procedures

As discussed briefly in the rationale, we will carry out two separate 'meta-analyses'. The first will look at the 33 naïve participants. This is any participant taking part in Experiment 1, 2, 3, 4 or 5 who has not taken part in a previous experiment with the tools. We will analyse the performance of these individuals together on the basic reaching and grasping procedure from these experiments to investigate how people perform when using the tools for the first time. The second 'meta-analysis' will then more briefly look at those participants who took part in multiple experiments with the original three tools – this will allow us to investigate the effect of repeated and longer exposure to the tools on our various measures.

By comparing the results of these two meta-analyses we should be able to see whether we would have seen different effects if we had run longer experiments, exposing participants to our tools for longer periods of time. We will also be able to see whether including participants in later experiments who were not naïve to our tools had an effect on our results. Finally using the analysis of unique participants, we will be able to see whether the effects that we found throughout this thesis are robust with larger sample sizes or whether a lack of power in our experiments affected our results.

B.2.2 Participants

In the first 'meta-analysis' of naïve participants we have a total of 33 participants who undertook some form of the grasping task seen originally in Experiment 1. This includes all 12 participants who took part in Experiment 1, six participants whose first experiment was Experiment 2, eight participants whose first experiment was Experiment 3 and seven whose first experiment was Experiment 5. No participants were included in this analysis from Experiment 4 as this consisted entirely of non-naïve participants and no participants were included from Experiment 6 as this experiment utilised different tools and is therefore not comparable.

In the second 'meta-analysis' of repeated participants we have a total of eight participants who took part in two experiments, four of whom also completed a third experiment, and one of whom completed a fourth. By looking at these participants in comparison to the naïve participants we should be able to investigate practice effects and see whether compensation for the tool ratios increased with repeated participation in these experiments.

B.2.3 Differences in stimuli, apparatus and procedure

The data for both 'meta-analyses' comes from several different experiments, each of which has small methodological differences:

Experiment 1 used object sizes of 20mm (25mm for the red tool) – 50mm, increasing in 5mm increments, placed at distances of 150mm, 300mm and 450mm. Something unique to this experiment was that participants grasped the calibration object with the tool before they had to make the actual grasp that was recorded. Peak velocity was recorded from a marker on the pisiform bone of the wrist in this experiment, for all future experiments it was recorded from the radius of the wrist. For a full description of the methodology in this experiment see section 3.2.

Experiment 2 used object sizes of 25mm – 45mm, increasing in 5mm increments, placed at random distances between 200-350 mm from the participant. Distances were binned for analysis, 200-249 mm were labelled 200 mm, 250-299 mm were labelled 250 mm and 300-349 mm were labelled 300 mm. This experiment used both closed and open-loop trials, only the data from closed-loop trials will be included in this analysis. The procedure of the closed-loop trials was the same as Experiment 1 with the exception that no calibration object was used. For a full description of the methodology in this experiment see section 4.2.

Experiments 3 and 4 used object sizes of 25mm-50mm, increasing in 5mm increments, placed at either 200mm, 250mm, 300mm, 350mm or 400mm from the participant. Participants did not sit and grasp objects continuously in blocks in this experiment; they would grasp an object with one tool and then report the size of a second hidden object using a different tool. For a full description of the methodology in these experiments see sections 5.3 and 5.6.

Experiment 5 used object sizes of 25mm-45mm, increasing in 5mm increments, placed at random distances between 200-350 mm from the participant. Distances were binned for analysis, 200-249 mm were labelled 200 mm, 250-299 mm were labelled 250 mm and 300-349 mm were labelled 300 mm. Participants completed grasps with both blurred and normal vision in this experiment but only data from the normal vision blocks is included in this analysis. For a full description of the methodology in this experiment see section 7.2.

As can be seen above, each experiment used slightly different object sizes and distances. Because of this we did not have data at every object size and distance for all of the experiments. This was a particular problem when calculating indices like peak velocity that rely on distance data, as this was very mismatched. To solve this regression lines were fitted to the data and using the formula of the line extra data points were calculated to fill in gaps in the data. Using this method gave us data for object sizes of 25mm-50mm in 5mm increments at distances of 150mm-450mm in 50mm increments. Whilst this is not ideal as we are analysing calculated data points in some places rather than actual data it was deemed the best solution in this situation. Whilst ideally you would never run statistical tests on computed data points, this was the only way to maintain a high number of participants with comparable data considering we were running our statistical tests after data collection and the experiments had not been designed for this purpose.

B.3 Results

B.3.1 Peak velocity – naïve participants

Figure B.1 plots the average peak velocity reached by the 33 naïve participants, as a function of object distance, collapsed across object size for the three tools. The data for the hand conditions are not presented here as data with the hand was not collected in every experiment and so is not present for all 33 of our participants. It can be seen that there appears to be no difference in the peak velocity reached with the three different tools.

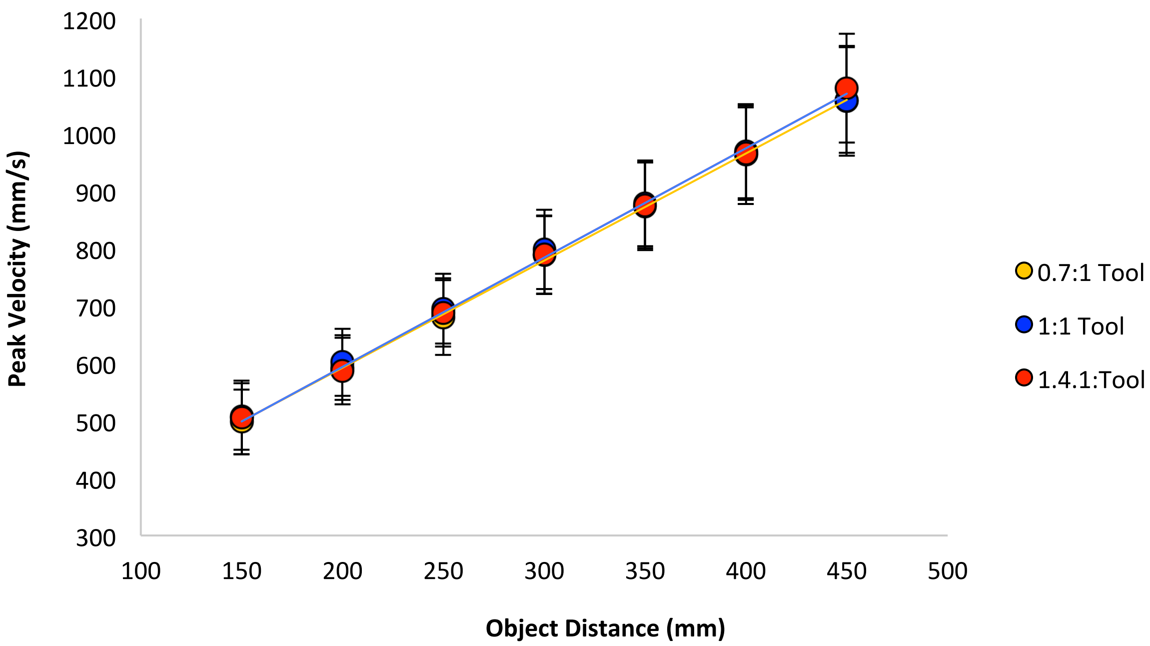

Figure B.1. Peak velocity data as a function of object distance, collapsed across sizes for the three tools. Error bars show 95% CIs. Linear regression lines are fitted through the data. N=33.

A 3 x 7 (tool type x object distance) repeated measures ANOVA revealed no main effect of tool type on peak velocity (F(1.68, 53.65)=.50, Greenhouse Geisser corrected, p=.576). It did show a significant main effect of object distance though (F(1.16, 37.16)=210.98, Greenhouse Geisser corrected, p<.001, f=2.56), showing that as object distance increased so did peak velocity.

Figure B.2 presents the average peak velocity for the 27 naïve participants who took part in an experiment where data was collected with the hand; this is therefore a subset of the participants presented in Figure B.1. By presenting this separately we can assess the differences between the three tools with the maximum possible sample size (33 participants). However, I am still interested in investigating the difference between the hand and the blue 1:1 tool with a larger sample size than we have been able to in the rest of the thesis. so I have looked at this as well, this will continue to be how I investigate effects through this appendix.

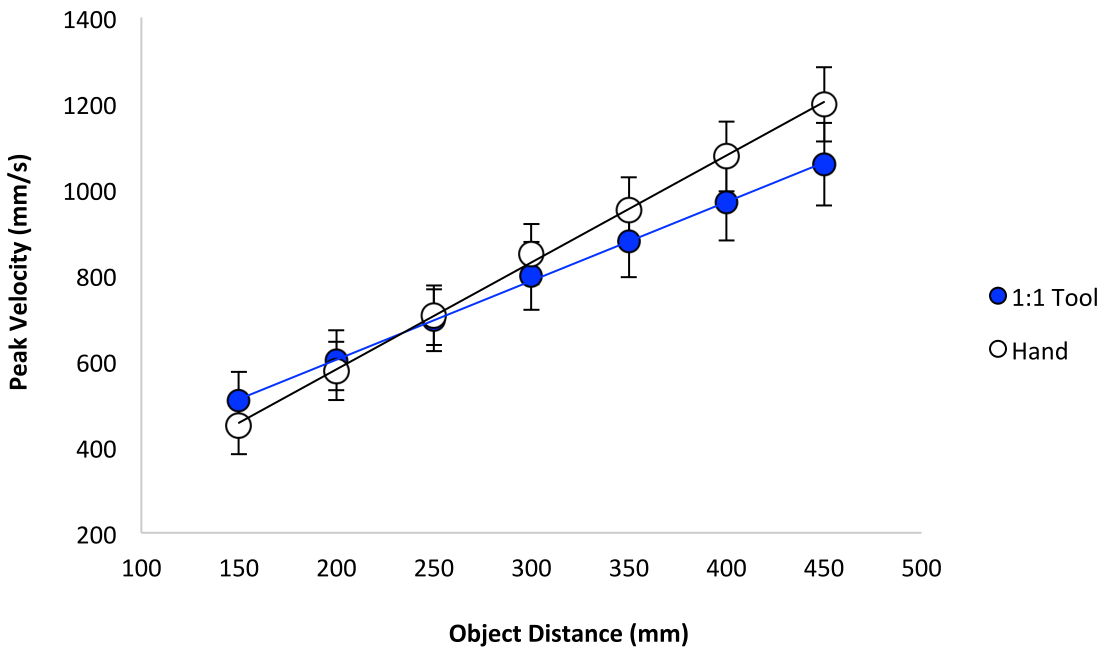

Figure B.2. Peak velocity data as a function of object distance, collapsed across sizes, for the blue 1:1 tool and the hand. Error bars show 95% CIs. Linear regression lines are fitted through the data. N=27.

A 2 x 7 (grasp type x object distance) repeated measures ANOVA revealed no main effect of grasp type on peak velocity (F(1, 26)=.32, p=.578). These analyses confirm what was found quite consistently in the rest of thesis that the peak velocity reached with the hand, the yellow 0.7:1 tool and the red 1.4:1 tool does not significantly differ from that reached with the blue 1:1 tool.

B.3.2 Movement time – naïve participants

An index that has not been measured so far in this thesis is that of movement time, so this will be investigated here with our larger sample size. For our purpose movement time is the time between the releasing of the start button and the lifting of the object. In Experiments 1 and 2 the lifting of the object was recorded automatically when contact between the conductive strips on the bottom of the object and the table was broken (see section 2.4 for further detail). Towards the end of Experiment 2 this system was becoming unreliable with contact between the object and the table breaking before the object was actually lifted (where this was the case at the end of Experiment 2 these trials have been identified and removed). Because of this for Experiments 3, 4 and 5 I have had to measure the object lift in a different way. During these experiments I had fixed a retroreflective marker to the back of each object so that its movements could also be tracked in the future if necessary. I have written and used a piece of Matlab code to identify when this marker starts to move (in a way that is more than just a random jitter) and records the frame number in a text file. I have then computed movement time by calculating the number of frames between the releasing of the start button and the object beginning to move and translating this into seconds.

Figure B.3 plots the average movement time for the 33 naïve participants, as a function of object distance, collapsed across object size for the three tools. It can be seen that movement times appear to be slightly longer for the yellow 0.7:1 tool than the blue 1:1 tool or the red 1.4:1 tool.

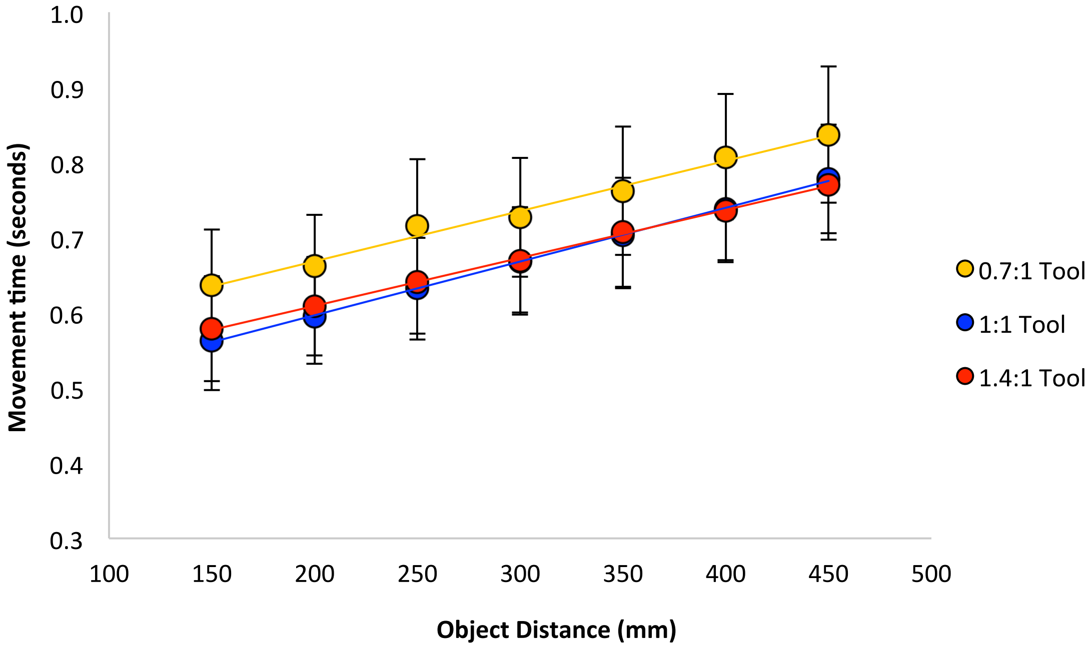

Figure B.3. Movement time data as a function of object distance, collapsed across sizes, for the three tools. Error bars show 95% CIs. Linear regression lines are fitted through the data. N=33.

A 3 x 7 (tool type x object distance) repeated measures ANOVA revealed a significant main effect of tool type on movement time (F(1.16, 37.06)=.25.70 Greenhouse Geisser corrected, p<.001, f=0.90). Planned comparisons show that movement times were significantly longer with the yellow 0.7:1 tool than they were with the blue 1:1 tool (F(1,32)=30.70, p<.001, f=0.98), but there was no difference in movement time between the red 1.4:1 tool and the blue tool (F(1,32)=1.39, p=248). The ANOVA also showed a significant main effect of object distance (F(1.47,47.09)=92.70, Greenhouse Geisser corrected, p<.001, f=1.70), showing that as object distance increased so did movement times.

Figure B.4 presents the average movement time as a function of object size collapsed across object distance for the hand and the blue 1:1 tool. Again this is for the 27 naïve participants who took part in an experiment where data was collected with the hand and is therefore a subset of the participants presented in Figure B.3. It can be seen that movement times appear to be longer when using the blue 1:1 tool than when using the hand alone.

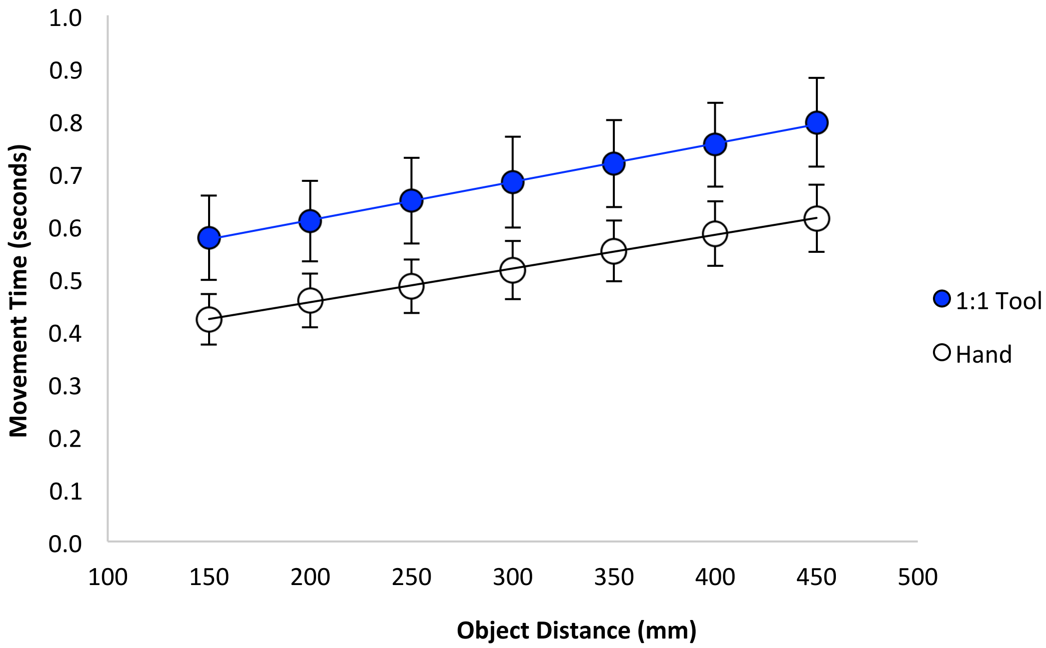

Figure B.4. Movement time data as a function of object distance, collapsed across sizes, for the blue 1:1 tool and the hand. Error bars show 95% CIs. Linear regression lines are fitted through the data. N=27.

A 2 x 7 (grasp type x object distance) repeated measures ANOVA revealed a significant main effect of grasp type on movement time ($F(1, 26)=25.48$, $p=<.001$, $f=0.99$). This shows that movement times were significantly longer when using the blue 1:1 tool than they were when using the hand alone. So despite there being no difference in the peak velocity reached with the blue tool and the hand the movement did take longer overall when using the blue tool.

B.3.3 Peak end-effector aperture – naïve participants

Figure B.5 plots (a) the average peak end-effector apertures and (b) the average peak hand apertures for the 33 naïve participants, as a function of object size, collapsed across object distance for the three tools. It can be seen that there appears to be some level of compensation for both the yellow and red tools, however compensation appears to be asymmetric, with participants compensating more for the ratio of the red 1.4:1 tool than the yellow 0.7:1 one.

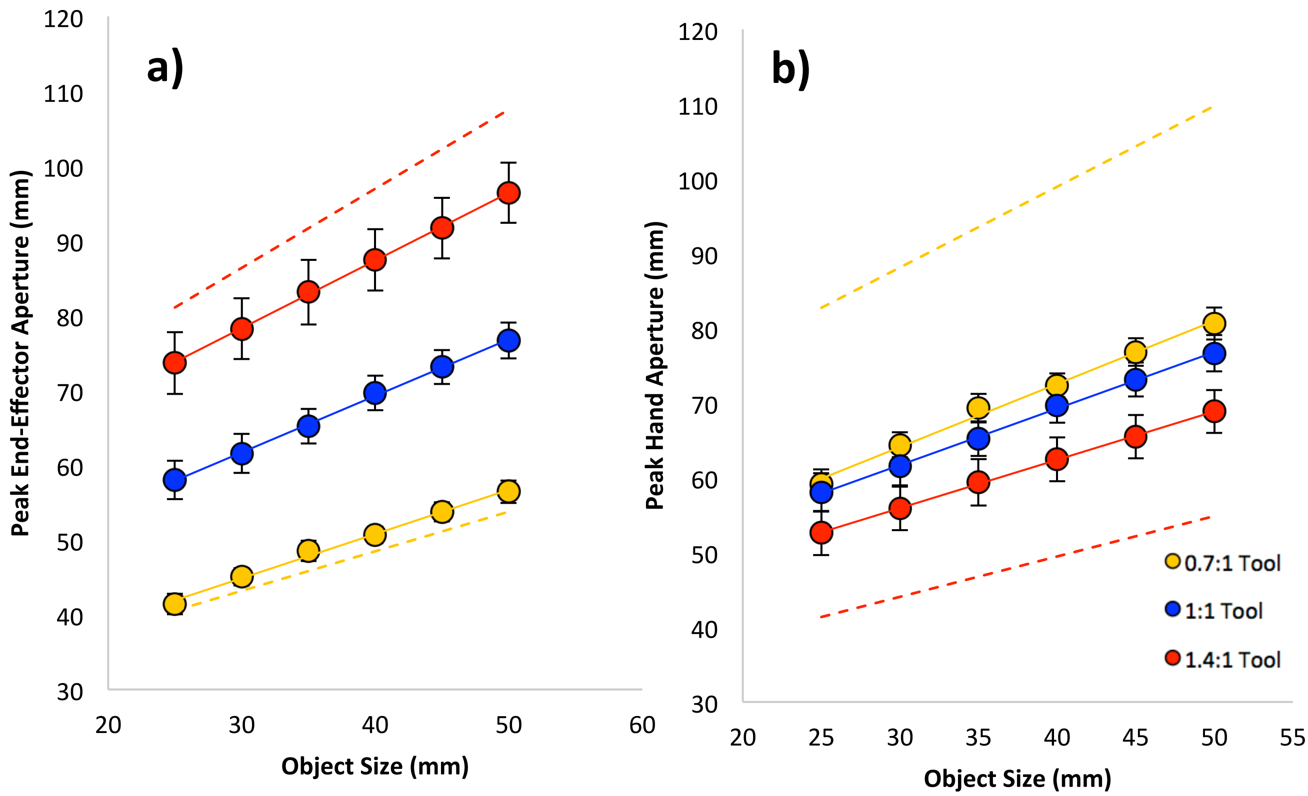

Figure B.5. Aperture data, as a function of object size, collapsed across distance. (a) In end-effector units. The dashed lines show the predictions for the 0.7:1 (yellow) and 1.4:1 (red) tools if there was no compensation for the effect of tool geometry. (b) The same data plotted in hand aperture units. Here the dashed lines show the prediction for perfect compensation for tool geometry. Error bars show 95% CIs. Linear regression lines have been fitted through the data. N=33.

A 3 x 6 (tool type x object size) repeated measures ANOVA revealed a significant main effect of tool type on peak end-effector apertures ($F(1.15,36.78)=398.97$, Greenhouse Geisser corrected, $p<.001$, $f=3.54$). Planned comparisons show there was a significant difference between the peak end-effector apertures produced with the yellow 0.7:1 tool (F(1,32)=469.17, p<.001, f=3.82) and the red 1.4:1 tool (F(1,32)=270.80, p<.001, f=2.90) when compared to the blue 1:1 tool. This shows that compensation for tool ratio was not perfect in either case, as if it were then we would expect to see no significant difference between the peak end-effector apertures produced with the three tools. The ANOVA also showed a significant main effect of object size (F(1.52,48.59)=491.09, Greenhouse Geisser corrected, p<.001, f=3.92), showing that as object size increased so did peak end-effector aperture.

By running a second ANOVA on the peak hand aperture data we can investigate whether participants significantly altered their hand apertures when using the three tools. A 3 x 6 (tool type x object size) repeated measures ANOVA revealed a significant main effect of tool type on peak hand apertures (F(1.31,41.85)=59.35, Greenhouse Geisser corrected, p<.001, f=1.36). Planned comparisons show there was a significant difference between the peak hand apertures produced with the yellow 0.7:1 tool (F(1,32)=14.72, p=.001, f=0.68) and the red 1.4:1 tool (F(1,32)=104.14, p<.001, f=1.80) when compared to the blue 1:1 tool. This shows that there was some level of compensation for the ratios of both the tools, however the effect is larger with the red tool than it is with the yellow one.

Figure B.6 shows the peak end-effector apertures produced with the blue 1:1 tool and the hand for the 27 naïve participants who took part in an experiment where data was collected with the hand and is therefore a subset of the participants presented in Figure B.5. It appears to show that slightly larger peak end-effector apertures were produced with the hand than with the blue 1:1

tool. Only peak end-effector apertures are presented here, as for the hand and the blue 1:1 tool the peak end-effector apertures and the hand apertures are the same.

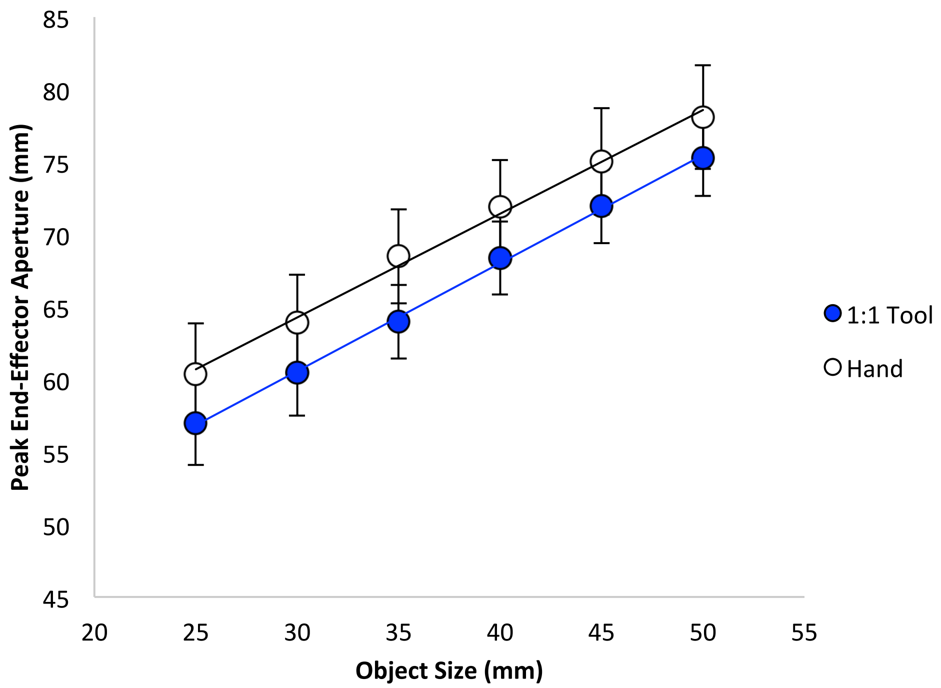

Figure B.6. Aperture data as a function of object size, collapsed across distances, for the blue 1:1 tool and the hand. Error bars show 95% CIs. Linear regression lines are fitted through the data. N=27.

A 2 x 6 (grasp type x object size) repeated measures ANOVA revealed a significant main effect of grasp type on peak end-effector aperture ($F(1,26)=4.50$, $p=.044$, $f=0.42$). Apertures produced with the hand were significantly larger than those for the blue tool (it should be noted that this effect is on the border of significance and is smaller than that seen with the yellow or red tool). This is contrary to the rest of the thesis, so it is possible that we did not have enough power to identify this previously due to our small sample sizes.

B.3.4 Safety margin – naïve participants

Another potentially interesting way to investigate peak-end effector apertures is to calculate a measure that demonstrates the margin-for-error built into the movement. As discussed previously in this thesis, building in a margin error is a sensible behaviour in reaching and grasping as it means slight miscalculations in the movement or the internal model will not necessarily result in failure to grasp the object (Schlicht & Schrater, 2007). By subtracting object size from peak-end effector aperture we get a measure of the margin-for-error, which we will refer to as the safety margin.

Figure B.7 shows the safety margins for the three tools for the 33 naïve participants, as a function of object size, collapsed across object distance. Safety margin clearly differs with the three tools, being largest for the red 1.4:1 tool and smallest for the yellow 0.7:1 one.

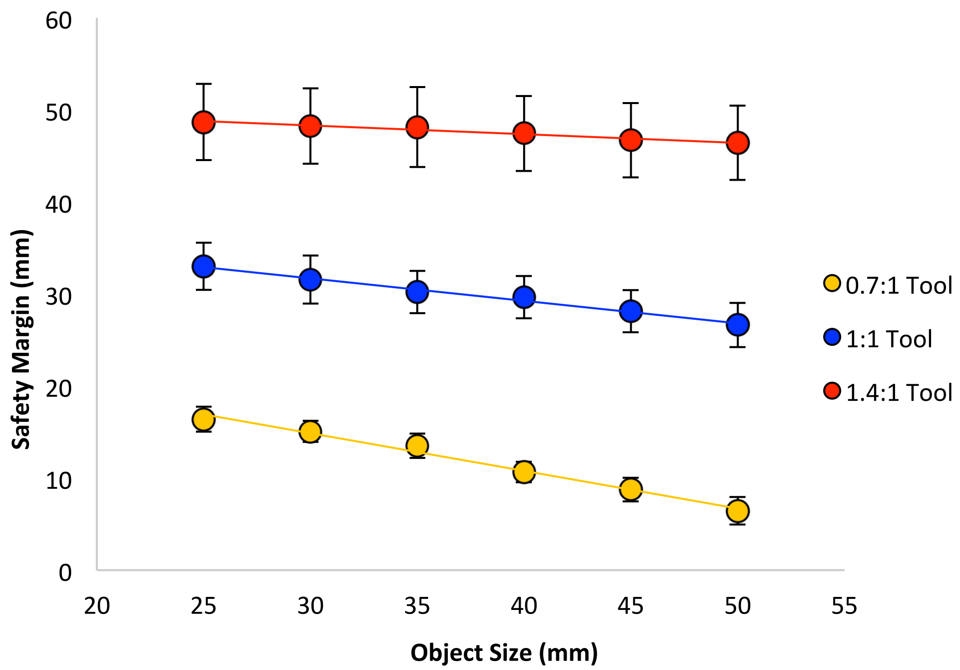

Figure B.7. Safety margin as a function of object size, collapsed across distances, for the three tools. Error bars show 95% CIs. Linear regression lines are fitted through the data. N=33.

Multiplying the safety margin found for the blue 1:1 tool by each of the tool ratios still gives larger values than is actually seen for the yellow tool and smaller values than is actually seen for the red tool. This shows that this is not just a case of building in the same safety margin at the hand each time and this being propagated by the ratio of the tool. Instead safety margins are legitimately larger for the red tool and smaller for the yellow tool. It can also be seen that safety margins decrease as object size increases. This effect is small with the red tool with a difference of just 2.3mm between the safety margins for the 25mm and 50mm objects. The effect is slightly larger for the blue tool with a difference of 6.4mm, and largest for the yellow tool with a difference of 10.0mm. In fact when grasping the largest object participants only had a safety margin of 6.5mm when using the yellow tool, compared to 26.7mm for the blue tool and 46.4m for the red.

A 3 x 7 (tool type x object size) repeated measures ANOVA revealed a significant main effect of tool type on safety margin ($F(1.15,36.78)=398.96$, $p=<.001$, $f=3.54$). Planned comparisons show that participants produced significantly smaller safety margins with the yellow tool ($F(1,32)=14.72$, $p=.001$, $f=0.68$) and significantly larger safety margins with the red tool ($F(1,32)=104.131$, $p<.001$, $f=1.80$) when compared to the blue tool. This shows that the safety margin is affected by the ratio of the tool. There was also a significant main effect of object size ($F(1.50,48.08)=525.18$, $p<.001$, $f=4.07$), which shows that the safety margin got smaller as object size increased.

Figure B.8 shows the average safety margin for the 27 naïve participants who took part in an experiment where data was collected with the hand and is therefore a subset of the participants presented in Figure B.7. It can be seen that the safety margin appears to be smaller for the blue tool than it is for the hand, although this may not be significant as the error bars do cross one another.

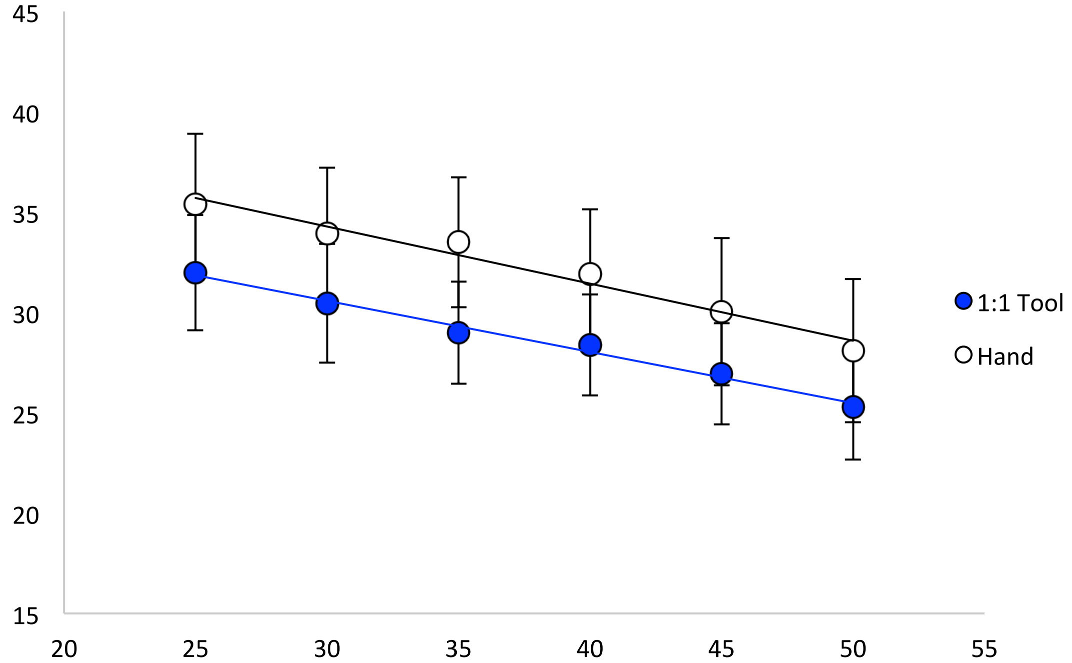

Figure B.8. Safety margin as a function of object size, collapsed across distances, for the blue 1:1 tool and the hand. Error bars show 95% CIs. Linear regression lines are fitted through the data. N=27.

A 2 x 6 (grasp type x object size) repeated measures ANOVA revealed a significant main effect of grasp type on safety margin ($F(1,26)=4.50$, p=.044, f=0.42). Safety margins produced with the hand were significantly larger than those for the blue tool (again, it should be noted that this effect is on the border of significance and is smaller than that seen with the yellow or red tool). This shows that participants built in a larger margin-for-error when using the hand to grasp an object than when using a 1:1 tool. This is contrary to what was expected as the use of a tool arguably adds uncertainty when compared to the hand so a logical course of action would be to increase the safety margin to account for the added uncertainty. It is unclear why safety margins would be larger with the hand , except possibly that the longer movement times with the blue tool allowed a smaller safety margin to be employed, but this would need further experiments to be able to form a more concrete understanding.

B.3.5 Compensation factor – naïve participants

Section B.3.3 showed some compensation for the ratio of both tools, however it did not appear to be perfect in either case. To look at this more quantitatively we can calculate compensation factors for the red and yellow tools (see section 3.3.5 for details on how these are calculated). Figure B.9 shows the compensation factors for the two tools for the 33 naïve participants. It can be seen that participants did compensate somewhat for the ratios of both of the tools, however this compensation was asymmetric with participants compensating more for the ratio of the red tool than the yellow one.

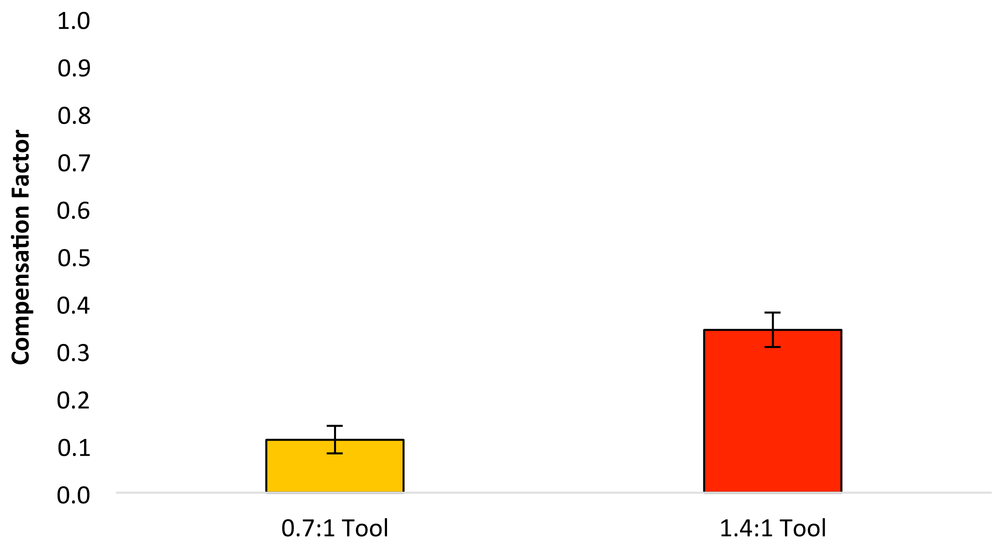

Figure B.9. Average compensation factors for the yellow 0.7:1 tool and the red 1.4:1 tool. Error bars show +/-1 SEM. N=33

A paired samples t-test confirms that participants compensated more for the red tool than they did for the yellow one ($t(32)=6.80$, $p<.001$, $d_z=1.21$). This confirms what was found throughout most of the rest of the thesis.

B.3.6 Compensation factor – the effect of experience

As discussed in the rationale, it would be interesting to see whether participants who took part in more than one experiment, and are therefore more experienced with the tools, perform better than those who only took part in one experiment. We could reassess all of the indices in this manner but it would potentially be difficult to interpret the findings. For example, does leaving a smaller safety margin mean that performance has improved or worsened? Some measures arguably are easier to make sense of - for example a faster peak velocity could indicate more confidence during the movement and therefore a better understanding of the tool. However this could only be argued if it was coupled with no change in the other measures in which trade-offs can be seen, such as peak end-effector aperture and overall movement time. One measure where it is easy to interpret the findings is that of the compensation factor. If the factors were larger for experienced participants than naïve ones then this would show an improvement based on exposure to the tools.

Figure B.10 plots the compensation factors for the red and yellow tools for both the naïve participants (n=33) and the experienced participants (n=13). It can be seen that compensation factors do appear to be higher for the experienced participants than the naïve ones. It also seems that compensation has improved more in the case of the yellow tool than the red tool between these two groups. This means that whilst there is still some asymmetry present in compensation in the experienced group, this is less so than it is in the naïve group.

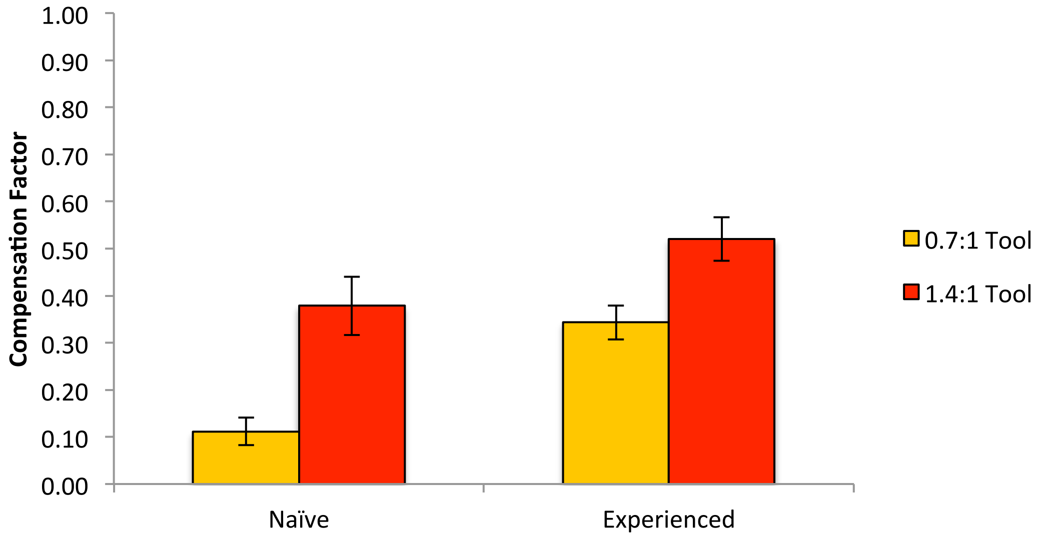

Figure B.10. Average compensation factors for the yellow 0.7:1 tool and the red 1.4:1 tool. Error bars show +/-1 SEM. Naïve N =33, Experienced N = 13.

An independent samples t-test confirms that compensation was higher for the experienced participants than it was for the naïve participants for both the yellow 0.7:1 tool ($t(43)=4.00$, $p<.001$, $d_z=1.27$) and the red 1.4:1 tool ($t(43)=2.56$, $p=.014$, $d_z=0.91$). It can also be seen here that the effect is larger for the yellow tool than the red one, showing that performance improves more with the yellow tool when participants are experienced. This could show why compensation was higher in Experiment 4, where all of our participants were experienced and also why we did not see the same levels of asymmetry later on in the thesis (when we had a larger proportion of experienced participants).

B.4 Discussion

The larger sample size of 33 participants (or in the case of analyses including the hand 27 participants) increased the power of our statistical tests and enabled us to potentially identify smaller effects than when we had smaller sample sizes. We did find some differences in this appendix compared to what we found throughout the thesis and this could potentially be due to the larger sample size and the associated increase in power. For example, we found here that participants produced larger peak end-effector apertures with the hand than they did with the blue 1:1 tool whereas in the majority of the thesis we found no significant differences between the peak end-effector apertures produced with the hand and the blue tool. It is a relatively small effect compared to others in this section and is only marginally statistically significant, so it is possible that this type of effect would not have been picked up using the small sample sizes we had throughout the thesis. Another difference seen was that participants did significantly alter their hand openings when using the yellow 0.7:1 tool. In Experiments 1, 2 and 3 we saw no significant difference in the hand openings for the yellow and blue tools. In Experiments 4 and 5 we did see a significant difference, however these experiments had higher proportions of experienced participants, and experience has been shown here to increase compensation for tool ratio, particularly in the case of the yellow tool. Again, it is possible that we have uncovered this effect in our naïve participants here due to the increase in sample size and power.

There are some things however that have been replicated in this appendix, for example we still see no differences in peak velocity between the three tools, or between the blue tool and the hand and this was typically the pattern of results seen in the thesis as well. We have now investigated movement time as well as peak velocity in this appendix and found that movement times were longer with the blue tool compared to the hand, suggesting that even though similar speeds were reached, the movement took longer to complete when using a tool. There was no significant difference in the movement times with the red and blue tools, however participants took significantly longer to complete the movement when using the yellow tool. Another replication here is the asymmetry between the red and yellow tool that was seen throughout the thesis. Participants compensated less for the ratio of the yellow tool than they did for the red one. Coupled with the longer movement times for the yellow tool and the small safety margins employed whilst using it, this could all still point to a biased or flawed internal model of the yellow tool as was identified in the main body of the thesis. Compensation did improve with experience with the yellow tool, however it was still asymmetric in our experienced participants as well (although to a lesser extent than our naïve participants).