8-21-2012 12:00 AM

Distinct visual coding strategies mediate grasping and pantomime-grasping of 2D and 3D objects.

Scott A. Holmes
The University of Western Ontario

Supervisor
Dr. Matthew Heath
The University of Western Ontario

Graduate Program in Kinesiology
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science

Recommended Citation

Holmes, Scott A., "Distinct visual coding strategies mediate grasping and pantomime-grasping of 2D and 3D objects." (2012). *Electronic Thesis and Dissertation Repository*. 766.
https://ir.lib.uwo.ca/etd/766

Distinct visual coding strategies mediate grasping and pantomime-grasping of 2D and 3D objects.

(Spine title: Visual coding strategies mediating 2D and 3D grasping)

(Thesis Format: Monograph)

by

Scott A. Holmes

Graduate Program in Kinesiology

A thesis submitted in partial fulfilment
of the requirements for the degree of
Master of Science

The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London Ontario, Canada

THE UNIVERSITY OF WESTERN ONTARIO

School of Graduate and Postdoctoral Studies

CERTIFICATE OF EXAMINATION

Supervisor	Examiners
______________________________	______________________________
Dr. Matthew Heath	Dr. Jody Culham
	______________________________
Supervisory Committee	Dr. James Danckert
______________________________	______________________________
Dr. Matthew Heath	Dr. Tom Jenkyn
______________________________	
Dr. Jody Culham	
______________________________	
Dr. Al Salmoni	

The thesis by

Scott A. Holmes

entitled:

Distinct visual coding strategies mediate grasping and pantomime-grasping of 2D and 3D objects.

is accepted in partial fulfilment of the
requirements for the degree of

Master of Science

Date___________________________

____
Chair of the Thesis Examination Board

Abstract

An issue of current debate in the visuomotor control literature surrounds whether 2D and 3D objects rely on similar or dissociable visual information in supporting goal-directed grasping. Accordingly, in Experiment One I had participants grasp 2D and 3D objects wherein just-noticeable-difference (JND) scores for aperture shaping were computed to determine the extent to which such actions adhere to the psychophysical principles of Weber's law. Results demonstrated that JNDs scaled in accordance with Weber's law in a time-independent and time-dependent manner for 2D and 3D grasping, respectively. In Experiment Two, I sought to further explore the cognitive demands of grasping by having participants pantomime the grasping of 2D and 3D objects. Results showed that grasping 2D objects and pantomime grasping elicited a common time-independent adherence to Weber's law that is distinct from grasping a 3D object. Thus, results demonstrate that 2D and 3D grasping are mediated by distinct visual information.

Keywords: Grasping, pantomime, 2D objects, visual coding, Weber's law

Table of Contents

List of Tables

List of Figures

List of Appendices

List of Abbreviations

JND	Just-noticeable-difference (mm)
GT	Grasping time (ms)
CL	Closed-loop
OL	Open-loop
GA	Grip aperture (mm)
PGA	Peak grip aperture (mm)
tPGA	Time to peak grip aperture (ms)

General Introduction

The ability to generate a successful grasping movement is dependent on extracting task-relevant properties from an intended target object. For example, it is paramount to recognize that a cup of coffee offers the possibility for holding and drinking, whereas a picture of the same cup offers neither of these. Gibson (1986) recognized how the intrinsic (e.g., weight, height) and extrinsic (e.g., orientation, location) nature of an object influences its behavioural affordance and how its act ‘on-able` properties are a product of what actions the object offers the observer. In particular, Gibson noted that “To be graspable, an object must have opposite surfaces separated by a distance less than the span of the hand” (p. 133). It is, however, interesting to note that Gibson’s seminal work does not address the dimensional nature of an object (i.e., 2D vs. 3D). Indeed, this is a particularly far-reaching issue in the visuomotor control literature because several studies have employed a 2D object as a representative proxy for a 3D object (e.g., Vishton, Rea, Cutting & Nunez, 1999; Brown, Halpert & Goodale, 1995; Desanghere & Marotta, 2011; Hu & Goodale, 2000).

On the one hand, some work has reported equivalent visual processes for grasping 2D and 3D objects. For example, Westwood, Danckert, Servos & Goodale (2002) had control participants and a patient with visual agnosia (DF)[1] perform a manual estimation (i.e., a perceptual task) and a grasping task in response to the presentation of differently sized 2D and 3D objects. In terms of control participants, manual estimations and grasping responses (as indexed by peak grip aperture: PGA) to both 2D and 3D objects increased with increasing

---

[1] Prior research has demonstrated that DF has bilateral ventral stream lesions that involve the lateral occipital complex (Goodale,,Milner, Jakobson & Carey, 1991), thus impairing her ability to perceive but not act on objects (for recent review see Goodale, 2011).

object size and produced comparable linear relations. In terms of DF, her performance on the grasping task, but not the manual estimation task, showed a reliable scaling to object size: a finding that was independent of object dimension. Westwood et al. interpreted their results within the theoretical framework of the perception/action model (PAM: Goodale & Milner, 1992). In particular, DF's impaired performance on the manual estimation task was taken as evidence that relative (i.e., scene-based) visual information mediated via the ventral visual pathway is necessary to support top-down and cognitive judgments of object size. In turn, the scaling of PGA to object size observed in both controls and DF was interpreted to reflect that absolute (i.e., Euclidean) visual information mediated via the dorsal visual pathway subserves goal-directed grasping. What is more, Westwood et al's observation that 2D and 3D objects produced comparable linear relations between PGA and object size lead them to conclude that "[T]he dorsal stream grasping system does not discriminate in a fundamental way between 2D and 3D objects" (p. 262). In a similar vein, Kwok and Braddick (2003) showed that PGAs for grasping 2D and 3D objects embedded within a pictorial illusion (i.e., Titchener circles) were refractory to the context-dependent properties of the illusion (i.e., relative visual information), whereas manual estimations of the same objects were reliably 'tricked'. As such, the authors concluded that grasping 2D and 3D objects operates independent of scene-based visual information and that the motor system is restrictively mediated via absolute visual information (but see Conti & Beaubaton, 1980; Coello & Greally, 1997; Krigolson & Heath, 2004; Krigolson, Van Gyn, Tremblay & Heath, 2006).

On the other hand, some evidence suggests that dissociable visual information mediates the grasping of 2D and 3D objects because the former lack fundamental grasping attributes. In particular, grasping a 3D object allows grasp points (i.e., position of the fingers at object contact) to be based on veridical object properties (e.g., Johansson, 1998; Martin, Latash & Zatsiorsky, 2011; for review see Mackenzie & Iberall, 1994; Marteniuk, MacKenzie, Jeannerod, Athenes & Dugas, 1987). In contrast, a 2D object requires that participants integrate a cognitive framework to support the motor response (e.g., Thaler & Goodale, 2011; Neely, Tessmer, Binsted & Heath, 2008) because the grasp points for this action must be perceptually defined. In other words, the participant, and not the physical properties of the object, determines an appropriate and cognitively mediated tolerance for the successful grasping of a 2D object. Moreover, electrophysiological studies of non-human primates have shown that neurons within dorsal and ventral visual processing areas demonstrate selective activation in response to object identification via binocular disparity cues (i.e., 3D objects) (DeAngelis, Cumming & Newsome, 1998; DeAngelis & Newsome, 1999; Maunsell & Van Essen, 1983; Roy, Komatsu & Wurtz, 1992; Shikata, Tanaka, Nakamura, Taira & Sakata, 1996; Taira, Tsutsui, Jiang, Yara & Sakata, 2000; Janssen, Vogels & Orban, 1999; Janssen, Vogels & Orban, 2000a; Janssen, Vogels & Orban, 2000b; Janssen, Vogels, Liu & Orban, 2001; Hinkle & Conner, 2002; Tanaka, Uka, Yoshiyama, Kata & Fujita, 2001; Uka, Tanaka, Yoshiyama, Kata & Fujita, 2000; Watanabe, Tanaka, Uka & Fujita, 2002**)**. As well, a recent human *f*MRI study by Snow et al. (2011) reported that the presentation of 2D and 3D objects engenders dissociable activation within dorsal and ventral visual processing regions (Snow et al. 2011). Thus, an extension drawn from convergent neurophysiological evidence is that distinct neural processes support the *grasping* of 2D and 3D objects.

The goal of the present investigation was to provide a novel adaptation of Weber's law to directly examine the nature of the visual information mediating the aperture shaping trajectories of grasping 2D and 3D objects. In particular, Weber's law states that changes in a stimulus that will be 'just noticeable' is a constant ratio of the original stimulus magnitude and that the sensitivity of detecting a change in any physical continuum is *relative* as opposed to *absolute*. Thus, the just noticeable difference (JND) for weaker stimuli is smaller and the resolution is greater than more robust stimuli in the same sensory continuum. In previous work (Ganel, Chajut & Algom, 2008; Heath, Mulla, Holmes & Smuskowitz 2011; Holmes, Mulla, Binsted & Heath, 2011), within-participant standard deviations of grip aperture (i.e., the JNDs) were computed during manual estimation (i.e., perceptual) and grasping (i.e., motor) conditions to determine participants' sensitivity to detecting changes in the size of 3D target objects. In terms of the perceptual condition, past work has shown that JNDs increase in relation to increasing object size; that is, the trial-to-trial stability of participants estimation of the size difference between their grip aperture (i.e., the comparator stimulus) and the target object decreased as a function of increasing stimulus intensity (i.e., the object size). In contrast, results for the motor condition elicited an increase in JNDs as a function of increasing object size during the early, but not late, stages of grasping (Heath et al., 2011; Holmes et al., 2011). In other words, results for the perceptual condition demonstrate extant adherence to the psychophysical principles of Weber's law and indicate that such a task is mediated via relative visual information. In turn, the time-dependent adherence to Weber's law during the motor condition suggests that the early and late stages of aperture shaping are respectively mediated via relative and absolute visual information. Notably, the findings for the motor task are consistent with the planning/control model's (PCM: Glover, 2004) contention that the early kinematic parameterization of a response is guided by top-down and relative visual information and that absolute visual information gradually assumes command of the unfolding response.

Experiment One

In Experiment One, I sought to determine if 2D grasping exhibits a time-dependent or time-independent adherence to Weber's law. To accomplish my objective, I had participants grasp differently sized objects (20, 30, 40 and 50 mm) in conditions wherein vision was continuously available to the performer (i.e., closed-loop: CL) and when occluded at movement onset (i.e., open-loop: OL). The basis for this visual comparison was to determine whether the presence or absence of online visual feedback differentially influences the nature of visual information mediating 2D and 3D grasping. Importantly, JNDs were computed at decile increments of grasping time in order to provide a temporal analysis of the visual information mediating the grasping of 2D and 3D objects. In terms of research predictions, if the nature of visual information supporting 2D and 3D grasping is equivalent, then responses in both conditions should show an early adherence and late violation to Weber's law. In other words, results would indicate that grasping is mediated by the early use of relative visual information and the later use of absolute visual information. In contrast, if 2D objects render an increased top-down and perception-based processing of object features (i.e., grasp points), then such actions should elicit a continuous adherence to Weber's law; that is, results would evince that grasping a 2D object is mediated by unitary and relative visual information. Importantly, evidence supporting the latter finding would demonstrate that 2D objects do not provide a representative proxy for grasping a 3D object.

Methods

Participants

Twelve (3 males, 9 females: age range 18-24) self-declared right hand dominant participants with normal or corrected-to-normal vision were recruited from the University of Western Ontario community. Participants provided written informed consent prior to their participation and this project was approved by the Office of Research Ethics, the University of Western Ontario, and was carried out according to the Declaration of Helsinki.

Apparatus and Procedures

Participants stood in front of a table-top (880 mm high: depth and width of 740 and 1040 mm, respectively) and manually estimated the size (i.e., the perceptual condition) or grasped (i.e., the grasping condition) 2D and 3D objects (see details below) using the thumb and forefinger of their right hand (so-called precision grasp). 2D objects were printed stimuli presented against a neutral white background and were 10 mm in depth and 20, 30, 40, and 50 mm in width. 3D objects were acrylic blocks presented against the same background as the 2D objects and were the same depth (i.e., 10 mm) and width (i.e., 20, 30, 40 and 50 mm) as the 2D objects but involved a height of 10 mm. All target objects were printed/coloured as a matching flat black. Target objects were presented at a common midline location 450 mm from the front edge of the table-top (i.e., in the depth plane) and were oriented with their long-axis perpendicular to the observer. Vision of the grasping environment was controlled via liquid crystal occlusion goggles (PLATO Translucent Technologies, Toronto, ON, Canada) and all visual and auditory events were controlled via MatLab (7.6: The MathWorks, Natick, MA, USA) and the Psychophysics Toolbox extensions (ver 3.0; see Brainard, 1997).

Participants began each trial by resting their right (i.e., grasping) limb on a pressure sensitive switch (henceforth referred to as the start location) positioned at their midline and 50 mm from the front edge of the tabletop. A second pressure sensitive switch was placed 200 mm to the left of participant's midline (and 50 mm from the front edge of the table-top) and was used only during the perceptual condition. In advance of both perceptual and grasping trials the goggles were set to their translucent state while the experimenter positioned the appropriate target object on the table-top. Following placement of the target object in the perceptual condition, participants were instructed to depress and hold the switch located by their left hand. Subsequently, the goggles were set to their transparent state for a randomized preview period (2000-3000 ms) after which time an auditory tone signalled participants to estimate the size of the presented object by separating the distance between the thumb and forefinger of their right hand. Participants' limb remained at the start location and continuous visual feedback was provided during the perceptual condition. Once an accurate (and participant-determined) estimation of the target object was achieved, participants were instructed to release the switch located at their left hand.

For the grasping condition, participants were provided with the same pre-movement cues as the perceptual condition. In this condition however, a precision grasp was initiated in response to the onset of the auditory tone in each of two visual conditions (CL and OL). In the CL condition, the goggles remained in their transparent state throughout a response thereby providing visual feedback during movement planning and execution. In the OL condition, the goggles reverted to their translucent state following release of pressure from the start location. As such, participants were provided visual feedback during movement planning but not during movement execution. Participants were instructed to perform their responses with a grasping time criterion of between 600 and 800 ms and verbal feedback of results ("too fast" or "too slow") was provided after each trial. Any trial falling outside of the grasping time criterion was discarded and re-entered into the trial matrix. The grasping time criterion was employed to avoid possible confounds between movement durations for grasping 2D and 3D target objects. Upon completion of their grasping response, participants were directed to return to the start position. Notably, in both 2D and 3D conditions participants were simply instructed to 'grasp' the target object. This basic instruction set was used to prevent any bias relating to condition goals.

Perceptual and motor conditions were performed in separate and pseudo-randomised sessions. For the motor condition, four separate and randomly ordered blocks reflecting factorial arrangements of visual condition and dimension (i.e., 2D-CL, 2D-OL, 3D-CL, 3D-OL) were completed across two experimental sessions (2 blocks/day). In total, participants completed three sessions over the span of three days, each separated by 24-hours. For all blocks, 20 trials were completed to each target object (which were randomly ordered) resulting in 80 perceptual and 320 motor trials.

Data Analysis

Displacement of the grasping limb was tracked via infrared emitting diodes (IREDs) placed on the medial surface of the distal phalanx of the thumb, the lateral surface of the distal phalanx of the forefinger, and the styloid process of the radius. IRED displacement data were sampled at 400 Hz via an OPTOTRAK Certus (Northern Digital Inc., Waterloo, ON, Canada). In both the perceptual and grasping conditions, IRED sampling occurred for 1500 ms following the auditory tone. Displacement data were filtered offline using a second-order dual-pass Butterworth filter using a low-pass cutoff frequency of 15 Hz. Instantaneous velocities were computed from displacement data via a five-point central finite difference algorithm. In the perceptual condition, grip aperture size was calculated when participants indicated that they had achieved an accurate estimation of object size (i.e., release of pressure from the left hand switch: see above). In the grasping condition, movement onset was marked as the time wherein participants released pressure from the start position and movement offset was defined as the time wherein wrist velocity fell below 50 mm/s for 20 consecutive frames (i.e., 50 ms).

Dependent Variables and Statistical Analyses

In line with previous research, I computed JNDs as the within-participant standard deviations of grip aperture (Ganel, et al., 2008; Heath et al., 2011; Holmes et al., 2011).

According to Ganel et al., the basis for this technique is drawn from the classic method of adjustment in which variance provides a measure of visuomotor uncertainty "…for which the observer is unable to tell the difference between the size of the comparison and the target object" (p. 600). Such an approach supports Fechnerian principles of Weber functions (see Marks and Algom, 1998), and I interpret linear scaling of JNDs to increasing object size (i.e., the Weber function) as adherence to the psychophysical properties of Weber's law.

In the perceptual condition, I computed grip aperture (GA: i.e., resultant distance between thumb and forefinger) and corollary JNDs and examined those data via 2 (dimension: 2D and 3D) by 4 (object size: 20, 30, 40, 50 mm) fully repeated measures ANOVAs. In the grasping condition, I calculated grasping time (GT: time from movement onset to movement offset), peak grip aperture (PGA: maximum resultant distance between thumb and forefinger), and its associated JNDs, as well as the time to peak grip aperture (tPGA: time from movement onset to PGA), and submitted those data to 2 (dimension: 2D and 3D) by 2 (vision: CL and OL) by 4 (object size: 20, 30, 40, 50 mm) fully repeated measures ANOVAs. In addition, I computed GA and associated JNDs at decile increments (i.e., 10, 20,..., 80, 90%) of GT time and added the variable time (10, 20,...,80, 90% of GT) to my ANOVA model. Where appropriate, F-statistics were corrected for violations of sphericity using the appropriate Huynh-Feldt correction (corrected degrees of freedom reported to one decimal place). Main effects and/or interactions were decomposed via simple effects and/or power polynomials (Pedhazur, 1997).

Results

Perceptual condition

As presented in Figure 1, GA and associated JNDs in the perceptual condition produced main effects of object size, Fs(3,33) = 190.99 and 28.96 respectively for GA and JNDs, ps<0.001, such that each increased linearly with increasing object size (only linear effects significant: Fs(1,11) = 228.38 and 61.33, respectively for GA and JNDs, ps<0.001). In turn, GA and JNDs yielded null effects of dimension, Fs(1,11)=0.48 and 1.06 respectively for GA and JNDs, ps=ns, and null dimension by object size interactions, Fs(3,33)=1.87 and 0.83 respectively for GA and JNDs, ps=ns[2].

---

[2] By convention we do not report all non-significant effects or interactions; however, we elected to outline F-ratios for some non-significant effects to demonstrate that our manipulation of object dimension did not reliably influence behaviour in the perceptual condition. Further, the magnitude of the F-ratios indicates that the null findings are not attributed to an inadequate replication sample size (see Keppel, 1991).

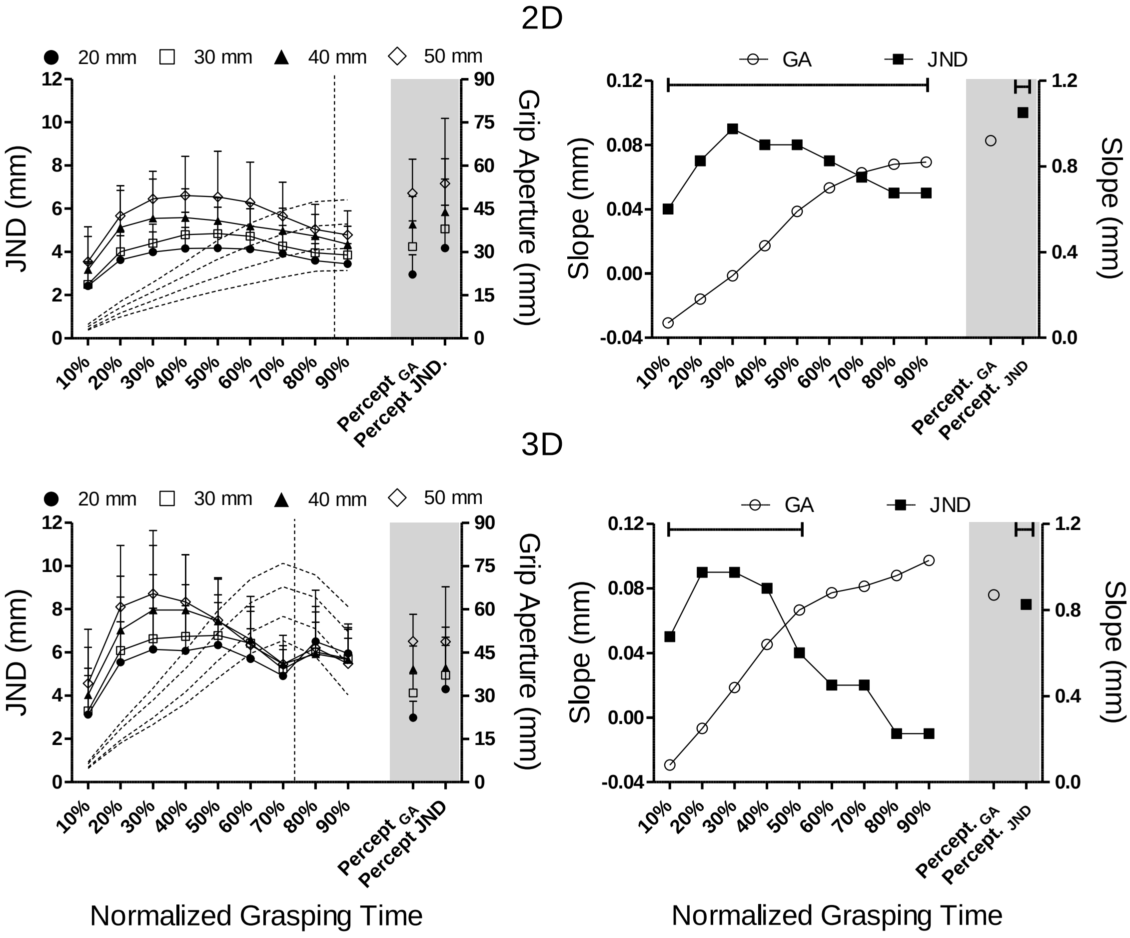


Figure 1. The top and bottom panels represent results from **2D** and **3D** grasping respectively. For the left panels, GA (dotted lines) and JND (solid lines with symbols) magnitudes are presented at decile increments of grasping time as a function of object size. The vertical hatched line denotes the time of PGA. Error bars for JNDs represent one between-participant standard deviation. In the right panels, slope values are presented as a function of object size for JNDs (left axis) and GA (right axis). The capped horizontal lines in these figures denote a significant linear increase in JNDs with increasing object size. For each panel, GA and its associated JNDs for the perceptual condition are presented in the grey boxes.

Grasping condition

In line with earlier work (Heath et al. 2011; Holmes et al. 2011), I found that JNDs for CL and OL grasping were not differentially influenced by object size (Fs < 2). Moreover, JNDs for CL and OL grasping did not vary across 2- and 3D grasping (Fs < 1). For that reason, visual condition is included as a collapsed factor in the analyses presented below.

The average grasping time response was 700 ms (SD = 48) and this variable did not elicit any manipulation-related effects. In terms of PGA, results revealed significant main effects for dimension, F(1,11)=120.00, p<0.001, object size, F(3,33)=642.13, p<0.001, and their interaction, F(3,33)=5.04, p<0.05. PGA increased linearly as a function of increasing object size in both 2D and 3D conditions (only linear effects significant: Fs(1,11) = 269.39 and 1875.80 respectively for 2D and 3D conditions, ps<0.001). However, and as shown in Figure 2, the slope relating PGA to object size in the 2D condition (0.82 mm SD=0.17) was shallower than the 3D condition (0.92 mm SD=0.08) (t(11)=2.61, p<0.05). Results for tPGA showed a main effect of dimension, F(1,11) = 53.81, p<0.001, such that PGA occurred later for the 2D (598 ms SD = 75) as compared to the 3D (510 ms SD=53) condition. In terms of JNDs at PGA, results yielded a main effect for object size, F(3,33) = 11.23, p<0.001, and a dimension by object size interaction, F(3,33) = 6.44, p<0.005. Figure 2 shows that JNDs in the 2D condition increased linearly with increasing object size (only linear effect significant: F(1,11)=23.13, p<0.001), whereas JNDs in the 3D condition were refractory to object size (F(1,11)=1.33, p=ns).

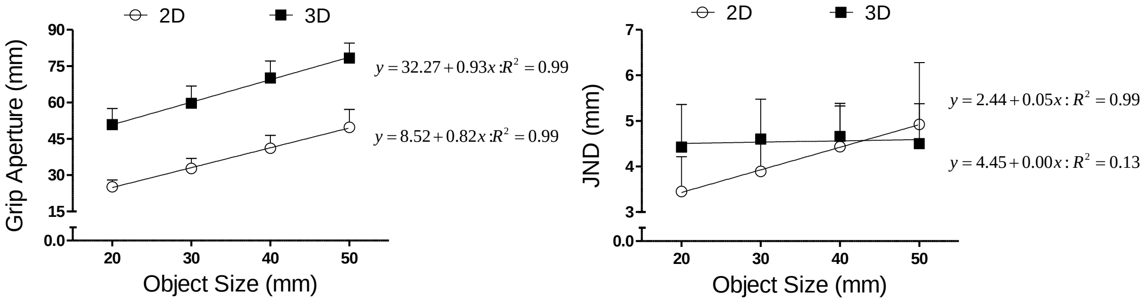


Figure 2. Mean values depicting peak grip aperture (left panel) and corresponding JNDs (right panel) in the **2D** and **3D** grasping tasks. Error bars represent one between-participant standard deviation. Regression lines and equations are depicted for mean peak grip aperture values and JNDs in the **2D** and **3D** grasping conditions.

Results for GA at deciles increments of GT produced main effects for time, $F(2.4,25.9) = 139.80$, $p<0.005$, dimension, $F(1,11) = 119.22$, $p<0.001$, and object size, $F(3,33) = 546.90$, $p<0.001$, as well as a highest-order interaction involving each variable, $F(3.9,43.7) = 3.94$, $p<0.01$. The 2D and 3D conditions elicited a linear increase in GA with increasing object size at each decile of GT ($ps< 0.005$: see Figure 1 and Table 1); however, a contrast of the slopes relating GA to object size showed that slopes were shallower in the 2D as compared to the 3D condition at each decile of GT (see Table 1 for linear regressions).

Grasping Time	Grip Aperture (GA)		Just-noticeable-difference (JND)	
	2D	3D	2D	3D
10%	$y = 1.29 + 0.07x$: $R^2 = 0.97$	$y = 3.14 + 0.08x$: $R^2 = 0.96$	$y = 1.49 + 0.04x$: $R^2 = 0.92$	$y = 1.99 + 0.05x$: $R^2 = 0.95$
20%	$y = 3.54 + 0.18x$: $R^2 = 0.99$	$y = 7.94 + 0.25x$: $R^2 = 0.96$	$y = 2.07 + 0.07x$: $R^2 = 0.96$	$y = 3.67 + 0.09x$: $R^2 = 0.98$
30%	$y = 4.58 + 0.29x$: $R^2= 0.99$	$y = 10.41 + 0.44x$: $R^2 = 0.97$	$y = 2.12 + 0.09x$: $R^2 = 0.97$	$y = 4.20 + 0.09x$: $R^2 = 0.97$
40%	$y = 4.76 + 0.43x$: $R^2 = 0.99$	$y = 13.52 + 0.64x$: $R^2 = 0.99$	$y = 2.44 + 0.08x$: $R^2 = 0.99$	$y = 4.49 + 0.08x$: $R^2 = 0.96$
50%	$y = 4.20 + 0.59x$: $R^2 = 0.99$	$y = 19.44 + 0.80x$: $R^2 = 0.99$	$y = 2.55 + 0.08x$: $R^2 = 0.98$	$y = 5.59 + 0.04x$: $R^2 = 0.91$
60%	$y = 4.32 + 0.70x$: $R^2 = 0.99$	$y = 26.65 + 0.88x$: $R^2 = 0.99$	$y = 2.65 + 0.07x$: $R^2 = 0.96$	$y = 5.54 + 0.02x$: $R^2 = 0.48$
70%	$y = 5.40 + 0.77x$: $R^2 = 0.99$	$y = 30.78 + 0.91x$: $R^2 = 0.99$	$y = 2.63 + 0.06x$: $R^2 = 0.98$	$y = 4.61 + 0.02x$: $R^2 = 0.86$
80%	$y = 6.78 + 0.81x$: $R^2 = 0.99$	$y = 24.66 + 0.96x$: $R^2 = 0.99$	$y = 2.54 + 0.05x$: $R^2 = 0.97$	$y = 6.50 - 0.01x$: $R^2 = 0.23$
90%	$y = 6.86 + 0.82x$: $R^2 = 0.99$	$y = 10.01 + 0.96x$: $R^2 = 0.99$	$y = 2.53 + 0.05x$: $R^2 = 0.99$	$y = 6.23 - 0.01x$: $R^2 = 0.95$
PGA	$y = 8.52 + 0.82x$: $R^2 = 0.99$	$y = 32.27 + 0.93x$: $R^2 = 0.99$	$y = 2.44 + 0.05x$: $R^2 = 0.99$	$y = 4.45 + 0.00x$: $R^2 = 0.13$
Percept.	$y = 3.71 + 0.92x$: $R^2 = 0.99$	$y = 4.63 + 0.87x$: $R^2 = 0.99$	$y = 2.15 + 0.10x$: $R^2 = 0.99$	$y = 2.84 + 0.07x$: $R^2 = 0.94$

Note: PGA = peak grip aperture; Percept. = perceptual condition.

Table 1. Experiment One linear regression equations and proportion of explained variance (R^2) relating grip aperture (GA) magnitudes and just-noticeable-difference (JND) scores to object size (20, 30, 40, and 50 mm) at decile increments of normalized grasping time for **2D** and **3D** conditions. In addition, regression equations and R^2 values are presented at the time of peak grip aperture (PGA) and for the manual estimation task (i.e., Percept.).

Analysis of JNDs revealed main effects for time, $F(3.1,34.6) = 7.30$, $p<0.001$, dimension $F(1,11) = 34.10$, $p<0.001$, and object size, $F(3,33) = 45.62$, $p<0.001$, as well as a highest-order interaction involving each variable, $F(8.4,92.0) = 2.61$, $p<0.001$. Figure 1 shows that JNDs in the 2D condition increased linearly with increasing object size from 10% through 90% of GT ($ps < 0.05$). In contrast, the 3D condition elicited a time-dependent scaling to object size such that JNDs increased linearly with increasing object size from 10- through 50% of GT ($ps<0.05$), but not from 60 through 90% of GT (ps=ns) (see Table 1 for linear regressions).

Discussion

Perceptual Condition

GA and JNDs increased as a function of increasing object size for 2D and 3D conditions. These results demonstrate two important elements. First, the equivalent scaling of GA to object size in the 2- and 3D conditions indicates that participants reliably discriminated between the different object sizes used here and that the accuracy of this perceptual judgment was not modulated as a function of object dimension. Second, the scaling of JNDs to object size in 2D and 3D conditions indicates that manual estimations of object size adhere to the psychophysical principles of Weber's law. In accord with previous work (Ganel et al. 2008; Heath et al. 2011; Holmes et al. 2011), I interpret this result as direct evidence that relative visual information mediates perceptual judgments of object size. As such, the GA and JND findings suggest that the *precision* and relative nature of the visual information mediating perceptual judgments is refractory to the dimensional properties of a target object.

Grasping Condition

GA for 2D and 3D objects scaled continuously to object size (i.e., from 10% through 90% of GT); however, the slopes relating GA to object size were steeper in the latter condition. This finding indicates that participants adopted larger apertures for the grasping of 3D objects. Notably, participants' aperture shaping for 2D grasping reflects an underestimation in object size and is comparable with results from 2D and 3D estimation conditions. In contrast, results from the 3D condition indicate that grasping a 'real' object requires that the thumb and forefinger approach the object more orthogonally to achieve the veridical grasp points necessary for a successful response (see Smeets and Brenner, 1999).

Results for JND analyses showed that grasping a 3D object produced a scaling of JNDs to object size from 10 through 50% of GT, but not from 60 through 90% of GT (and including PGA). This result is consistent with previous work (Heath et al., 2011; Holmes et al., 2011) demonstrating an early adherence, and late violation, to Weber's law and suggests that the early and late stages of aperture shaping are mediated by relative and absolute visual information, respectively. In contrast, the 2D condition showed a continuous scaling of JNDs to object size throughout the trajectory. In other words, the 2D condition demonstrated a time-independent adherence to Weber's law. Such a finding suggests that the top-down demands of grasping a 2D object render the processing of object features via unitary and relative visual information. Thus, I propose that a 2D object cannot be adopted as a representative proxy for a 3D object in understanding the nature of visual information mediating grasping control.

Experiment Two

Experiment One demonstrated that 2D and 3D grasping elicit a time-independent and time-dependent adherence to Weber's law, respectively. As such, I proposed that grasping a 2D object is a top-down and cognitive task that is mediated via unitary and relative visual information. The goal of Experiment Two was to further explore the cognitive demands of grasping a 2D object via a comparison with a pantomime-grasp task. Indeed, in a pantomime-grasp task participants are presented with a visual target object and are instructed to 'mime' a grasping response to a location other than the target. As such the pantomime-grasp task requires that participants evoke the top-down and cognitive process of decoupling the normally direct spatial relations between stimulus and response (so-called non-standard task: Neely & Heath, 2010; Moon et al., 2007; Ford, Goltz, Brown & Everling, 2005; Heath, Bell, Holroyd & Krigolson, 2012; Zhang & Barash, 2000). For example, patient DF is readily able to scale her PGA to the veridical size of a target object during a standard grasping response; however, when asked to perform a pantomime-grasp to that same object she is unable to appropriately scale her grip aperture (Goodale, Jakobson & Keillor, 1994). According to Goodale et al., such a finding is attributed to the fact that DF's bilateral ventral steam lesions impair her ability to access the relative visual information necessary to support the cognitive demands of performing a pantomime-grasp. Furthermore, Westwood, Chapman and Roy (2000) reported that PGAs for grasping an object embedded within a pictorial illusion (i.e., Műller-Lyer figures) are refractory to the context-dependent properties of the visual array, whereas a pantomime-grasp response is reliably tricked by the same illusion. Thus, it has been proposed that pantomime-grasp responses are mediated via unitary and relative visual information.

The goal of the present study was to determine whether a pantomime-grasp response exhibits the same time-independent adherence to Weber's law as grasping a 2D object. I believe this to represent an important question as it provides a basis for determining whether unitary and relative visual information mediate cognitively oriented actions. To accomplish my objectives, participants grasped and pantomime-grasped 2D and 3D objects and I measured the GA and JNDs associated with such responses at decile increments of GT. In terms of research predictions, if cognitively mediated actions are represented by unitary and relative visual information then grasping a 2D object as well as performing a pantomime-grasp response should show a time-independent adherence to Weber's law. In turn, if cognitively mediated actions are not characterized by unitary and relative visual information then grasping a 2D object and the pantomime-grasp condition should demonstrate distinct relations between JNDs and object size.

Methods

Participants

Fourteen (4 male, 10 female: age range 18 to 24) self-declared right hand dominant participants with normal or corrected-to-normal vision were recruited from the University of Western Ontario community. Participants provided written informed consent prior to participation and this project was approved by the Office of Research Ethics, University of Western Ontario, and was carried out according to the Declaration of Helsinki.

Apparatus and Procedures

The general procedures, target objects, grasping time criterion and experimental equipment used in Experiment One were used here. As such, 2D and 3D midline target objects were presented 450 mm from the start location and participants were instructed to grasp the presented object (i.e., grasp condition). Additionally, participants were instructed to pantomime the grasping of 2D and 3D objects (i.e., pantomime-grasp condition). Specifically, an object was presented 150 mm to the left of the object location used in the grasping condition and participants were instructed to pantomime a grasping response to the same endpoint location as used during grasping trials (see Figure 3). In other words, the pantomime-grasp condition required that participants decouple the normally direct spatial relations between stimulus and response. The pantomime-grasp condition entailed the same pre-movement cues as the grasping condition and participants were encouraged to maintain their fixation on the target object during each trial. Notably, although the location of the target object differed between grasp and pantomime-grasp conditions, both entailed a common start and end location. This was done in order to equate grasp trajectories between conditions.

Figure 3. Reaching environment for grasping (left panel) and pantomime-grasp (right panel) trials for both **2D** and **3D** objects. Notably, both the grasp and pantomime-grasp conditions involved a common movement start and endpoint location.

The dimensional nature of target stimuli (2D vs. 3D) and grasping condition (grasping vs. pantomime-grasp) were factorially arranged in separate blocks (i.e., 2D grasp, 2D pantomime-grasp, 3D grasp, 3D pantomime-grasp). The presentation of 2D and 3D target objects was counterbalanced across two experimental sessions separated by 24-hours (2 blocks/day) whereas grasping condition was randomized within each experimental session. For all blocks, 20 trials were completed to each object size (which were randomly ordered) resulting in 320 trials.

Dependent Variables and Statistical Analysis

The same dependent variables used to assess the grasping condition in Experiment One were used here. Notably, I sought to provide *planned* contrasts between grasp and pantomime-grasp conditions separately for the 2D and 3D objects. For that reason, results for GT, PGA, tPGA and associated JNDs for 2D and 3D objects were subjected to independent 2 (condition: grasping, pantomime-grasp) by 4 (object size: 20, 30, 40, and 50 mm) repeated measures ANOVAs. As well, I examined GA and corollary JNDs at decile increments of grasping time by adding the variable time (10, 20,...,80, 90% of GT) to my ANOVA models for 2D and 3D objects.

Results

Grasp and Pantomime-Grasp of 2D Objects

An average GT of 701 ms ($SD = 41$) was found. Results for GT, PGA and tPGA yielded main effects of object size, $Fs(3,39)=2.87$, 639.57 and 5.66 respectively for GT, PGA and tPGA, $ps<0.05$, such that movement durations as well as the size and timing of PGA increased linearly as a function of increasing object size (only linear effects significant: $Fs(1,13)=7.32$, 755.19 and 7.32 for GT, PGA, and tPGA, respectively, $ps<0.05$). As shown in Figure 4, for JNDs at PGA, main effects of condition, $F(1,13)=29.68$, $p<0.001$, and object size, $F(3,39)=6.89$, $p<0.001$, indicated larger values for the pantomime-grasp (4.8 mm $SD=1.5$) than the grasp (3.0 mm $SD=1.0$) condition and showed that values increased in relation to increasing object size (only linear effect significant: $F(1,13)=18.99$, $p<0.05$).

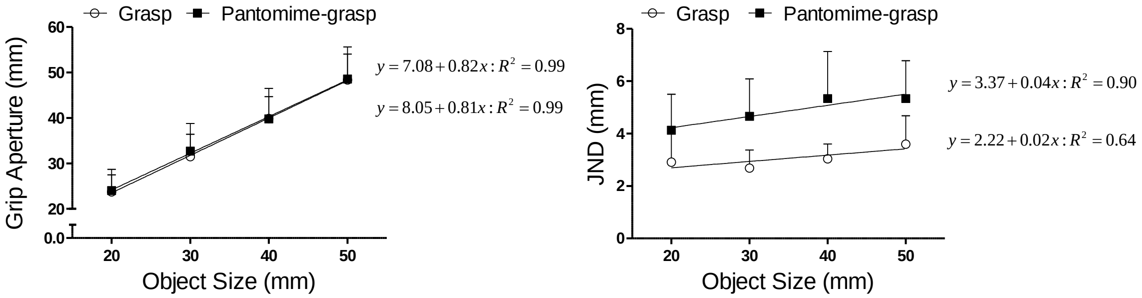


Figure 4. Mean values depicting peak grip aperture (left panel) and corresponding JNDs (right panel) in the grasp and pantomime-grasp conditions for **2D** objects in Experiment Two. Error bars represent one between-participant standard deviation. Regression lines and equations are depicted for mean peak grip aperture values and JNDs in the grasp and pantomime-grasp conditions.

Analysis of GA at decile increments of GT produced main effects of time, $F(1.8,23.5)=76.32$, $p<0.001$, object size, $F(1.2,15.9)=242.90$, $p<0.001$, and their interaction, $F(2.8,35.9)=111.73$, $p<0.001$. Figure 5 shows that GA increased linearly with increasing object size at each decile of GT, and that slopes relating GA to object size increased with increasing GT ($ps<0.05$, see Table 2 for linear regressions).

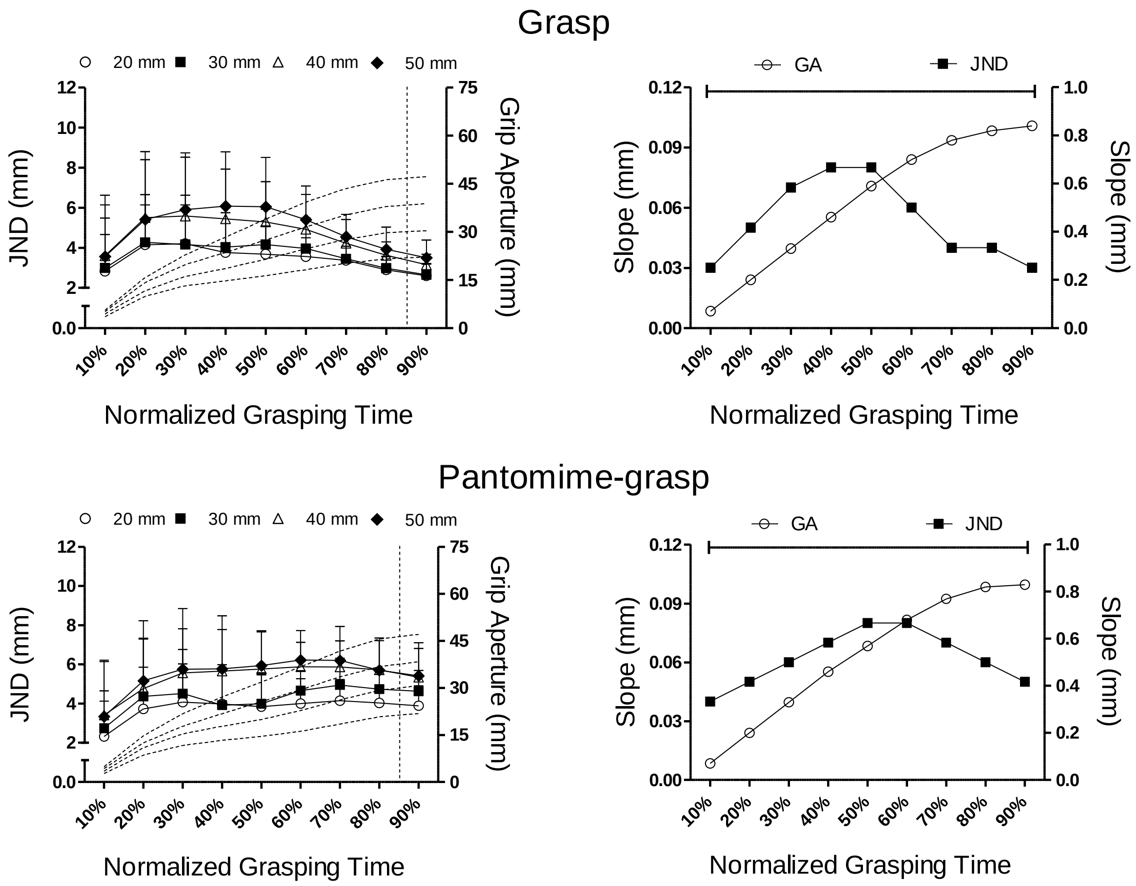


Figure 5: Left panels denote GA (dotted lines) and JND (solid lines) magnitudes at decile increments of grasping time for **2D** grasping and pantomime-grasping. The vertical hatched line denotes the time of peak grip aperture. Right panels demonstrate corresponding slope values for GA and JND scaling as a function of object size. The capped horizontal lines denote when JNDs elicited a linear increase as a function of object size.

Grasping Time	Grip Aperture (GA)		Just-noticeable-difference (JND)	
	Grasp	Pantomime	Grasp	Pantomime
10%	$y = 2.27 + 0.07x$: $R^2 = 0.99$	$y = 1.33 + 0.07x$: $R^2 = 0.99$	$y = 2.27 + 0.03x$: $R^2 = 0.85$	$y = 1.64 + 0.04x$: $R^2 = 0.86$
20%	$y = 5.78 + 0.20x$: $R^2 = 0.99$	$y = 4.65 + 0.20x$: $R^2 = 0.99$	$y = 3.08 + 0.05x$: $R^2 = 0.80$	$y = 2.86 + 0.05x$: $R^2 = 0.98$
30%	$y = 6.59 + 0.33x$: $R^2 = 0.99$	$y = 5.11 + 0.33x$: $R^2 = 0.99$	$y = 2.68 + 0.07x$: $R^2 = 0.86$	$y = 2.83 + 0.06x$: $R^2 = 0.94$
40%	$y = 5.27 + 0.46x$: $R^2 = 0.99$	$y = 4.05 + 0.46x$: $R^2 = 0.99$	$y = 1.92 + 0.08x$: $R^2 = 0.94$	$y = 2.34 + 0.07x$: $R^2 = 0.81$
50%	$y = 4.17 + 0.59x$: $R^2 = 0.99$	$y = 2.86 + 0.57x$: $R^2 = 0.99$	$y = 1.92 + 0.08x$: $R^2 = 0.98$	$y = 2.06 + 0.08x$: $R^2 = 0.86$
60%	$y = 3.88 + 0.70x$: $R^2 = 0.99$	$y = 2.33 + 0.68x$: $R^2 = 0.99$	$y = 2.20 + 0.06x$: $R^2 = 0.97$	$y = 2.43 + 0.08x$: $R^2 = 0.96$
70%	$y = 4.52 + 0.78x$: $R^2 = 0.99$	$y = 2.92 + 0.77x$: $R^2 = 0.99$	$y = 2.40 + 0.04x$: $R^2 = 0.92$	$y = 2.81 + 0.07x$: $R^2 = 0.97$
80%	$y = 5.14 + 0.82x$: $R^2 =0.99$	$y = 4.37 + 0.82x$: $R^2 =0.99$	$y = 2.06 + 0.04x$: $R^2 = 0.93$	$y = 2.94 + 0.06x$: $R^2 = 0.89$
90%	$y = 5.36 + 0.84x$: $R^2 = 0.99$	$y = 5.34 + 0.83x$: $R^2 = 0.99$	$y = 1.86 + 0.03x$: $R^2 = 0.92$	$y = 2.96 + 0.05x$: $R^2 = 0.92$
PGA	$y = 7.08 + 0.82x$: $R^2 = 0.99$	$y = 8.05 + 0.81x$: $R^2 = 0.99$	$y = 2.22 + 0.02x$: $R^2 = 0.64$	$y = 3.37 + 0.04x$: $R^2 = 0.90$

Table 2: Experiment Two linear regression equations and proportion of explained variance (R^2) relating grip aperture (GA) magnitudes and just-noticeable-difference (JND) scores to object size (20, 30, 40, and 50 mm) at decile increments of normalized grasping time for **2D** grasp and pantomime-grasp conditions. In addition, regression equations and R^2 values are presented at the time of peak grip aperture (PGA).

Results for JNDs yielded main effects of time, $F(2.8, 36.4)=3.14$, $p<0.05$, and object size, $F(2.4,30.5)=37.79$, $p<0.001$, and interactions involving time by condition, $F(3.5,45.5)=10.67$, $p<0.001$, and time by object size, $F(10.1,131.7)=2.46$, $p<0.05$. Figure 5 shows that grasp and pantomime-grasp conditions elicited comparable JNDs from 10% through 60% of GT (ps = ns); however, from 70% though 90% of GT, JNDs were larger in the latter condition (see Table 3 for post-hoc contrasts). Results for the time by object size interaction indicated that JNDs increased with increasing object size at each decile of GT with slope values peaking at approximately 50% of GT, $ps<0.05$ (see Table 2 for linear regressions). In other words, JNDs elicited a unitary scaling to object size; however, the magnitude of the slopes relating JNDs to object size varied with time.

Grasping Time	Post hoc contrast - Main effect
10%	F < 1, p = 0.47
20%	F < 1, p = 0.48
30%	F < 1, p = 0.99
40%	F < 1, p = 0.99
50%	F < 1, p = 0.87
60%	F = 3.52, p = 0.08
70%	F = 19.34, p <0.001
80%	F = 37.46, p <0.001
90%	F = 41.80, p <0.001

Table 3. Simple effects contrasts for the time by condition interaction for JNDs found for **2D** objects in Experiment Two.

Grasp and Pantomime-Grasp of 3D Objects

The average GT was 702 ms ($SD = 18$) and this variable produced no manipulation-related effects. In terms of PGA and tPGA, main effects were found for condition, $Fs(1,13)=166.87$ and 6.47 respectively for PGA and tPGA, $ps<0.05$, and object size, $Fs(3,39)=565.10$ and 11.49, $ps<0.001$. PGAs were smaller and occurred later in the pantomime-grasp (PGA: 36 mm $SD=12$, tPGA: 573 ms $SD=98$) than the grasp condition (PGA: 58 mm $SD=12$, tPGA: 511 ms $SD=49$), and both increased linearly with increasing object size (only linear effects significant: $Fs(1,13)=769.28$ and 13.57 respectively for PGA and tPGA, $ps<0.005$). For JNDs at PGA, results yielded main effects of condition, $F(1,13)=12.97$, $p<0.005$, object size, $F(3,39)=9.23$, $p<0.001$, and their interaction, $F(3,39)=4.98$, $p<0.005$. As shown in Table 4 and Figure 6, JNDs in the pantomime-grasp condition increased with increasing object size (only linear effect significant: $F(1,13)=19.67$, $p<0.001$) whereas JNDs in the grasping condition were refractory to object size ($F(1,13)=2.82$, $p=ns$).

Grasping Time	Grip Aperture (GA)		Just-noticeable-difference (JND)	
	Grasp	Pantomime	Grasp	Pantomimed
10%	$y = 5.94 + 0.08x$: $R^2 = 0.90$	$y = 2.66 + 0.08x$: $R^2 = 0.99$	$y = 2.69 + 0.05x$: $R^2 = 0.73$	$y = 2.51 + 0.03x$: $R^2 = 0.64$
20%	$y = 12.08 + 0.27x$: $R^2 = 0.98$	$y = 5.25 + 0.24x$: $R^2 = 0.99$	$y = 3.28 + 0.10x$: $R^2 = 0.93$	$y = 3.24 + 0.07x$: $R^2 = 0.99$
30%	$y = 15.20 + 0.43x$: $R^2 = 0.99$	$y = 5.10 + 0.39x$: $R^2 = 0.99$	$y = 3.15 + 0.10x$: $R^2 = 0.90$	$y = 3.26 + 0.07x$: $R^2 = 0.97$
40%	$y = 16.03 + 0.59x$: $R^2 = 0.99$	$y = 3.89 + 0.52x$: $R^2 = 0.99$	$y = 3.24 + 0.09x$: $R^2 = 0.94$	$y = 3.00 + 0.08x$: $R^2 = 0.97$
50%	$y = 18.19 + 0.73x$: $R^2 = 0.99$	$y = 3.20 + 0.63x$: $R^2 = 0.99$	$y = 3.84 + 0.06x$: $R^2 = 0.97$	$y = 2.69 + 0.08x$: $R^2 = 0.95$
60%	$y = 21.29 + 0.84x$: $R^2 = 0.99$	$y = 3.06 + 0.72x$: $R^2 = 0.99$	$y = 4.11 + 0.04x$: $R^2 = 0.96$	$y = 2.40 + 0.09x$: $R^2 = 0.94$
70%	$y = 23.78 + 0.90x$: $R^2 = 0.99$	$y = 3.22 + 0.80x$: $R^2 = 0.99$	$y = 3.74 + 0.03x$: $R^2 = 0.78$	$y = 2.48 + 0.08x$: $R^2 = 0.88$
80%	$y = 20.45 + 0.94x$: $R^2 = 0.99$	$y = 3.74 + 0.85x$: $R^2 = 0.99$	$y = 4.73 + 0.01x$: $R^2 = 0.31$	$y = 2.30 + 0.07x$: $R^2 = 0.95$
90%	$y = 10.05 + 0.99x$: $R^2 = 0.99$	$y = 3.87 + 0.87x$: $R^2 = 0.99$	$y = 4.24 + 0.01x$: $R^2 = 0.09$	$y = 2.29 + 0.07x$: $R^2 = 0.95$
PGA	$y = 24.88 + 0.94x$: $R^2 = 0.99$	$y = 7.08 + 0.84x$: $R^2 = 0.99$	$y = 3.68 + 0.01x$: $R^2 = 0.39$	$y = 2.40 + 0.07x$: $R^2 = 0.95$

Table 4. Experiment Two linear regression equations and proportion of explained variance (R^2) relating grip aperture (GA) magnitudes and just-noticeable-difference (JND) scores to object size (20, 30, 40, and 50 mm) at decile increments of normalized grasping time for **3D** grasp and pantomime-grasp conditions. In addition, regression equations and R^2 values are presented at the time of peak grip aperture (PGA).

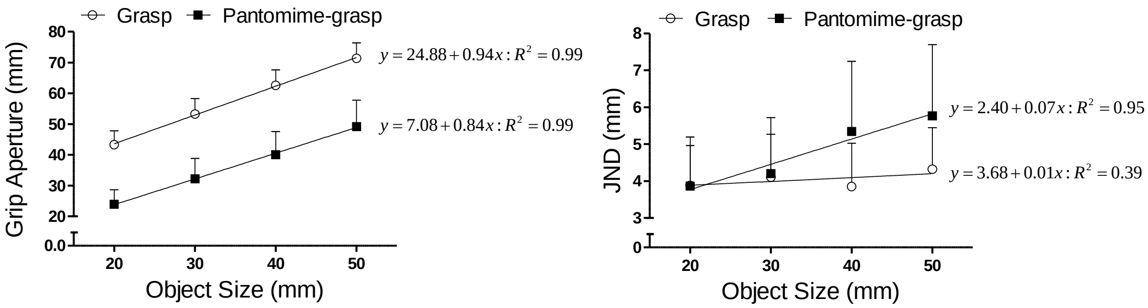


Figure 6: Mean values depicting peak grip aperture (left panel) and corresponding JNDs (right panel) in the grasp and pantomime-grasp conditions for **3D** objects in Experiment Two. Error bars represent one between-participant standard deviation. Regression lines and equations are depicted for mean peak grip aperture values and JNDs in the grasp and pantomime-grasp conditions.

Results for GA at decile increments of GT revealed main effects of time, $F(1.7,22.0)=74.05$, $p<0.001$, condition, $F(1,13)=204.03$, $p<0.001$, and object size, $F(1.2,15.9)=219.99$, $p<0.001$, as well as interactions involving time by condition, $F(1.5,3.2)=21.17$, $p<0.001$, and time by object size, $F(3.2,41.2)=104.23$, $p<0.001$. GAs for the grasp condition were larger than the pantomime-grasp condition at each decile (see Table 5 for post hoc contrasts) and a qualitative examination of Figure 7 indicates that the largest between-condition difference occurred at 70% of GT. In terms of the time by object size interaction, GA increased linearly with increasing object size at each decile of GT, $ps<0.05$ (see Table 5 for linear regression equations). Moreover, Figure 7 shows that nature of the time by object size interaction is rooted in the fact that the slopes relating GA to object size increased with GT.

Grasping Time	Post hoc contrast – Main effect
10%	F = 8.80, $p<0.05$
20%	F = 19.08, $p<0.001$
30%	F = 27.69, $p<0.001$
40%	F= 47.08, $p<0.001$
50%	F = 104.40, $p<0.001$
60%	F = 232.23, $p<0.001$
70%	F = 350.89, $p<0.001$
80%	F = 141.74, $p<0.001$
90%	F = 24.84, $p<0.001$

Table 5. Simple effects contrasts for the time by condition interaction for GA found for **3D** objects in Experiment Two.

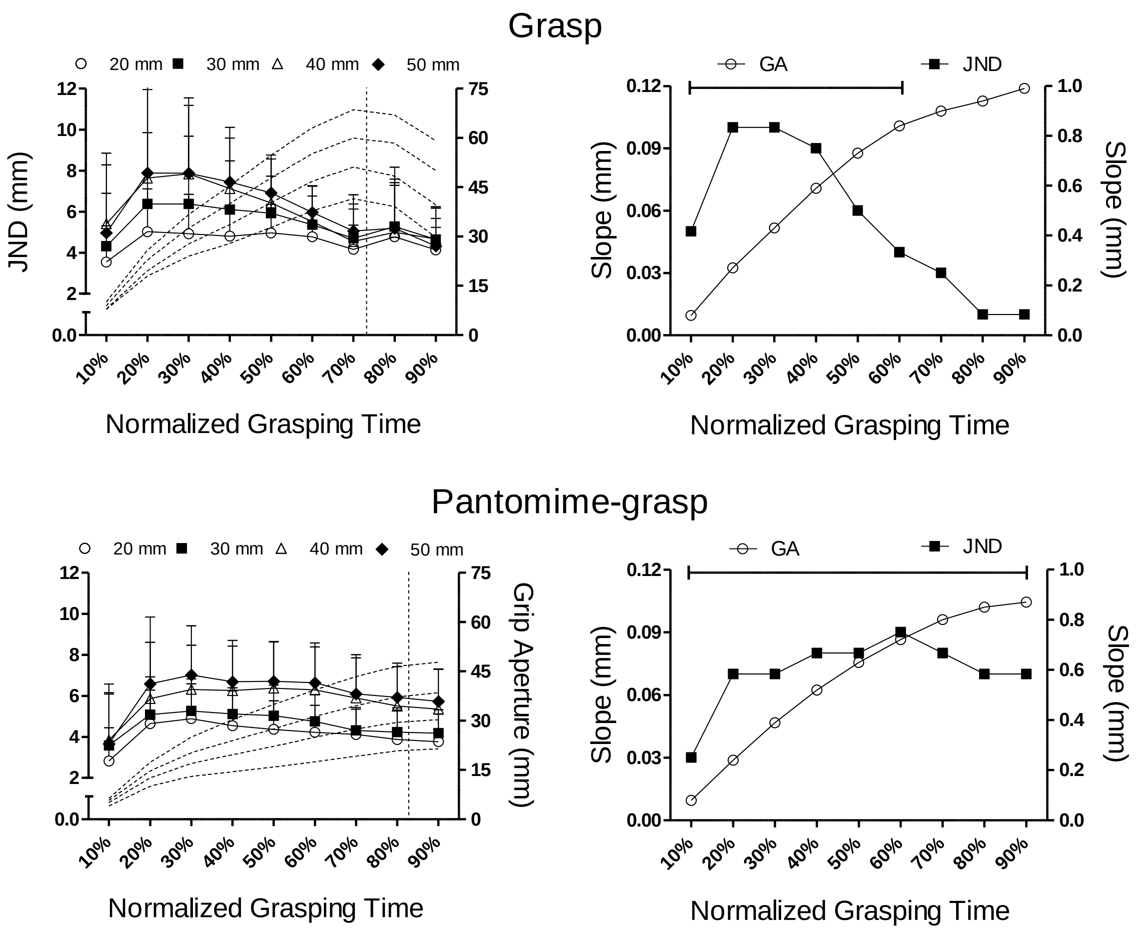


Figure 7. Left panels denote GA (dotted lines) and JND (solid lines) magnitudes at decile increments of grasping time for **3D** grasp and pantomime-grasp. The vertical hatched line denotes the time of PGA. Right panels demonstrate corresponding slope values for GA and JND scaling as a function of object size. The capped horizontal line denotes when JNDs elicited a linear increase a function of object size.

Results for JNDs at deciles of GT revealed main effects for time, $F(2.9,37.8)=6.15$, $p<0.005$, and object size, $F(3,39)=30.23$, $p<0.001$, as well as a highest-order interaction involving time by condition by object size, $F(7.5,97.6)=3.38$, $p<0.005$. Figure 7 shows that JNDs for the grasping condition increased with increasing object size from 10 through 60% of GT ($ps<0.05$), but not from 70% though 90% of GT (ps=ns). In contrast, JNDs in the pantomime-grasp condition scaled throughout the response (i.e., 10% through 90% of GT, $ps<0.05$) (see Table 4 for linear regression equations).

Discussion

Grasp and Pantomime-Grasp of 2D Objects

GA and JND values increased linearly with increasing object size at each decile of GT. These findings indicate that the precision of aperture shaping in grasp and pantomime-grasp conditions were comparable and each condition elicited a time-independent adherence to Weber’s law. In other words, aperture shaping in both conditions was mediated via unitary and visual information. Interestingly, however, JNDs for the pantomime-grasp condition were larger than the grasp condition during the late stages of the response (i.e., >70% of GT). This is a general characteristic of tasks involving a decoupling of the normally direct spatial relations between stimulus and response and is attributed to the fact that actions directed to a veridical target allow for the trial-to-trial reduction of endpoint variability (e.g., Heath, Maraj, Gradkowski & Binsted, 2009; Neely & Heath, 2010).

Grasp and Pantomime-Grasp of 3D Objects

GA for the grasp and pantomime-grasp conditions increased in relation to increasing object size at each decile of GT; however, and as shown in Figure 7, the former produced larger GAs than the latter condition at matched time points. One possible reason for this difference is that grasping a real object mandates that the thumb and forefinger approach the veridical object at a more orthogonal vector than when grasping a cognitively represented object (i.e., the pantomime-grasp condition). Additionally, it may be that grasping a real object results in the specification of a more precise GA than when performing a pantomime-grasp. Support for the latter position stems from the observation that PGA associated with the pantomime-grasp condition was on par to that associated with the manual estimations reported in Experiment One and elsewhere (Ganel et al., 2008; Heath et al., 2011; Holmes et al., 2011). Indeed, because extensive evidence has shown that perceptual judgments reliably underestimate object size (Marks & Algom, 1998) it may be that the GAs associated with the pantomime-grasp condition indicate a similar (and perceptual) underestimation of object size.

In terms of JNDs, the grasping condition showed an early (10 through 60% of GT) but not late (70 through 90% of GT) scaling to object size. As indicated previously (Experiment One; see also Heath et al., 2011; Holmes et al., 2011), such a finding has been interpreted as evidence of a time-dependent adherence to Weber’s law and the early and late specification of grip aperture via relative and absolute visual information, respectively. In contrast, JNDs for the pantomime-grasp condition showed a continuous scaling to object size (i.e., from 10% through 90% of GT). I propose that this time-independent adherence to Weber’s law indicates aperture specification via unitary and relative visual information.

Moreover, these results in combination with the findings for the 2D grasp and pantomime-grasp conditions indicate that the manipulation of the cognitive demands of a task via object properties (i.e., 2D) or via the spatial relations between stimulus and response (i.e., grasp-pantomime) render a comparable form of cognitive control and the mediation of aperture shaping via relative visual information.

General Discussion

The results from the two experiments demonstrate that the dimensional properties of a target object and the underlying goal (grasp vs. pantomime-grasp) of a response influence the nature of the visual information mediating motor output. Concerning my primary research question, results show that participants adopted distinct aperture trajectories and dissociable visual representations of object size as a function of the dimensional properties of an object. In particular, the slopes relating GA to object size at each decile of grasping time were shallower when grasping a 2D as compared to a 3D object. This result suggests that grasping a 2D object results in an underestimation of object size commensurate with perceptual judgments (see Figure 1 and 5). More notably, the JND findings revealed that grasping a 2D object produced a time-independent adherence to Weber's law, whereas grasping a 3D object elicited a time-dependent adherence. In line with earlier work (Heath et al., 2011; Holmes et al., 2011), the time-dependent adherence to Weber's law is taken as evidence that early and later aperture shaping for grasping a 3D object is mediated via relative and absolute visual information, respectively. This interpretation is consistent with Glover's (2004) PCM and suggests that the early stages of aperture shaping are cognitively mediated, whereas the unfolding aperture control operates independent of top-down cognitive processes.

Importantly, the time-independent adherence to Weber's law in the 2D grasping task demonstrates that the absence of volumetric object properties renders *in toto* aperture shaping via relative visual information. I believe this to represent an important finding as it demonstrates that grasping a 2D object is a top-down and cognitively mediated action. In particular, the absence of veridical grasp points precludes the use of absolute visual information. Thus, I propose that grasping a 2D object requires that grasp points are determined perceptually and thereby render an aperture trajectory that elicits a unitary adherence to the psychophysical properties of Weber's law.

In light of the above-mentioned results, it is important to address why some previous work has not identified similar findings from grasping 2D objects. Recall that Westwood et al. (2002) reported that grasping 2D and 3D objects resulted in a reliable scaling of PGA to object size: a result they interpreted as providing evidence for the use of absolute visual information for grasping a 2D object. Interestingly, however, examination of Westwood et al's data shows that PGA for the 2D task was reliably smaller than matched sized 3D objects. This finding is consistent with the present work and suggests that although the motor system is able to discriminate between differently sized 2D objects, such a process results in a size underestimation consistent with well-documented perceptual judgments (Marks and Algom, 1998). As well, recall that Kwok and Braddick (2003) reported that PGAs for grasping 2- and 3D objects were refractory to pictorial illusions. Indeed, the conclusions from the present study would predict that pictorial illusions should trick 2D grasping as such actions are mediated via unitary and relative visual information. Critically, however, and as shown in Figure 1 and 5 of the current study, PGA occurs much later when grasping a 2D as opposed to a 3D object. Therefore, if a similar late onset of PGA occurred in the Kwok and

Braddick study, this may have precluded an accurate determination of the nature of the visual information supporting the grasping of a 2D object.

In Experiment Two I sought to contrast the grasping of a 2D target object with a non-standard pantomime-grasp. The inclusion of the pantomime-grasp condition was based on coalescent behavioural, clinical and neuroimaging work showing that decoupling the normally direct spatial relations between stimulus and response is a cognitively mediated act. Indeed, extensive work examining the cost of looking or pointing to a direction other than a cued target (so-called non-standard task) has shown that such actions are associated with more extensive activation of fronto-parietal networks than their standard (i.e., responses entailing spatial overlap between stimulus and response) task counterparts (see Moon et al., 2007; Ford et al., 2005; Heath et al., 2012; Zhang & Barash, 2000). Indeed, the increased cortical activation has been tied to the cognitive demands associated with decoupling the normally direct spatial relations between stimulus and response. As well, a number of behavioural studies have shown that non-standard tasks are mediated by relative visual information (Heath, Maraj, Gradkowski & Binsted, 2009; Heath, Maraj, Maddigan & Binsted, 2009; Maraj & Heath, 2010; Heath, Dunham, Binsted & Godbolt, 2010; Crawford, Kean, Klein & Hamm, 2006). Moreover, Westwood et al. (2000) showed that pictorial illusions tricked pantomime-grasp, but not a standard grasp condition. In other words, the cognitive demands of decoupling stimulus and response renders motor output that is supported by relative visual information. Not surprisingly then, Experiment Two showed that the pantomime-grasp of 3D target objects produced smaller GA values than their standard 3D grasp counterparts. Moreover, the pantomime-grasp of 2D and 3D objects resulted in a time-independent scaling of JNDs to object size on par to that associated with grasping a 2D target object. In other words, the extant adherence of 2D grasping and pantomime-grasping (2- and 3D objects) to Weber's law indicates that actions in both contexts are cognitively mediated. As such, I propose that the cognitive control of action is supported via unitary and relative visual information (see also Rossetti et al. 2005).

Conclusions

The results of Experiment One and Two demonstrate that grasping a 2D object elicits a time-independent adherence to the psychophysical principles of Weber's law. Moreover, I have shown that grasping a 2D object elicits the same adherence to Weber's law as that associated with a pantomime-grasp task. Thus, I conclude that grasping a 2D object is a top-down and cognitively mediated task that is supported via unitary and relative visual information. Most importantly, these results provide a direct demonstration that 2D and 3D objects do not provide representative proxies for one another in understanding the visual information supporting grasping control.

References

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*(4), 433–436.

Brown, L. E., Halpert, B. A, & Goodale, M. A. (2005). Peripheral vision for perception and action. *Experimental Brain Research*, *165*(1), 97-106.

Coello, Y. & Grealy, M.A. (1997). Effect of size and frame of visual field on the accuracy of an aiming movement. *Perception*, 26(3), 287-300.

Conti, P. & Beaubatan, D. (1980). Role of structured visual field and visual reafference in accuracy of pointing movements. *Perceptual and Motor Skills*, 50(1), 239-44.

Crawford, T. J., Kean, M., Klein, R. M., & Hamm, J. P. (2006). The effects of illusory line motion on incongruent saccades: implications for saccadic eye movements and visual attention. *Experimental Brain Research*, *173*(3), 498-506.

DeAngelis, G.C., Cumming, B.G. & Newsome, W.T. (1998). Cortical area MT and the perception of stereoscopic depth. *Nature*, 394, 677-680.

DeAngelis, G.C. & Newsome, W.T. (1999) Organization of disparity-selective neurons in macaque area MT. *Journal of Neuroscience*, 19, 1398-1415.

Desanghere, L., Marotta, J.J. (2011). “Graspability” of objects affects gaze patterns during perception and action tasks. *Experimental Brain Research.* 212(2), 177-87.

Ford, K.A, Goltz, H.C., Brown, M.R.G., & Everling, S. (2005). Neural processes associated with antisaccade task performance investigated with event-related FMRI. *Journal of Neurophysiology*, *94*(1), 429-40.

Ganel, T., Tanzer, M., & Goodale, M. A. (2008). A double dissociation between action and perception in the context of visual illusions: opposite effects of real and illusory size. *Psychological Science*, *19*(3), 221-5.

Gibson, J. (1986). *The ecological approach to visual perception*. London: Lawrence Erlbaum associates.

Glover, S. (2004). Separate visual representations in the planning and control of action. *The Behavioral and Brain Sciences*, *27*(1), 3-24; discussion 24-78.

Goodale, M.A. (2011). Transforming vision into action. *Vision Research*, 51(13), 1567-87.

Goodale, M. A., Jakobson, L. S. & Keillor, J. M. (1994). Differences in the visual control of pantomimed and natural grasping movements. *Neuropsychologia*, *32*(10), 1159-78.

Goodale, M.A., Milner, A.D. (1992). Separate visual pathways for perception and action. *Trends in Neuroscience*, 15(1), 20-5.

Goodale, M.A., Milner, A.D., Jakobson, L.S., Carey, D.P. (1991). A neurological dissociation between perceiving objects and grasping them. *Nature*. 349(6305), 154-6.

Heath, M., Bell, J., Holroyd, C. B., & Krigolson, O. (2012). Electroencephalographic evidence of vector inversion in antipointing. *Experimental Brain Research*, 19-26.

Heath, M., Dunham, K., Binsted, G., Godbold, B. (2010). Antisaccades exhibit diminished online control relative to prosaccades. *Experimental Brain Research.* 203(4), 743-52.

Heath, M., Maraj, A., Gradkowski, A., & Binsted, G. (2009). Anti-pointing is mediated by a perceptual bias of target location in left and right visual space. *Experimental Brain Research*, *192*(2), 275-86.

Heath, M., Maraj, A., Maddigan, M., & Binsted, G. (2009). The antipointing task: vector inversion is supported by a perceptual estimate of visual space. *Journal of Motor Behavior*, *41*(5), 383-92.

Heath, M., Mulla, A., Holmes, S. A, & Smuskowitz, L. R. (2011). The visual coding of grip aperture shows an early but not late adherence to Weber's law. *Neuroscience Letters, 490*(3), 200-4.

Hinkle, D.A. & Conner, C.E. (2002). Three-dimensional orientation tuning in macaque area V4. *Nature Neuroscience*, 5, 665-670.

Holmes, S.A., Mulla, A., Binsted, G. & Heath, M. (2011). Visually and memory-guided grasping: aperture shaping exhibits a time-dependent scaling to Weber's law. *Vision Research*, 51(17), 1941-8.

Hu, Y. & Goodale, M.A. (2000). Grasping after a delay shifts size-scaling from absolute to relative metrics. *Journal of Cognitive Neuroscience.* 12(5), 856-68.

Janssen, P., Vogels, R., Liu, Y. & Orban, G.A. (2001). Macaque inferior temporal neurons are selective for three-dimensional boundaries and surfaces. *Journal of Neuroscience*, 21, 9419-9429.

Janssen, P., Vogels, R. & Orban, G.A. (1999). Macaque inferior temporal neurons are selective for disparity-defined three dimensional shapes. *Proceedings of the National Academy of Science*, 96, 8217-8222.

Janssen, P., Vogels, R. & Orban, G.A. (2000a). Three–dimensional shape coding in inferior temporal cortex. *Neuron*, 27, 385-397.

Janssen, P., Vogels, R. & Orban, G.A. (2000b). Selectivity for 3D shape that reveals distinct areas within macaque inferior temporal cortex. *Science*, 288, 2054-2056.

Johansson, R. S. (1998). Sensory input and control of grip. In *Sensory guidance of movement* (pp.45-63). John Wiley & Sons Ltd.

Keppel, G. (1991). *Design and analysis: A researcher's handbook*. (3rd Edition). New Jersey: Englewood Cliffs.

Krigolson, O. & Heath, M. (2004). Background visual cues and memory-guided reaching. *Human Movement Science*, 23(6), 861-77.

Krigolson, O., Van Gyn, G., Tremblay, L. & Heath, M. (2006). Is there "feedback" during visual imagery? Evidence from a specificity of practice paradigm. *Canadian Journal of Experimental Psychology*, 60(1), 24-32.

Kwok, R. M., & Braddick, O. J. (2003). When does the Titchener Circles illusion exert an effect on grasping? *Neuropsychologia*, 41(8), 932-940.

MacKenzie, C. L., Iberall, T. (1994). *The grasping hand*. The Netherlands: North-Holland.

Maraj, A., Heath, M. (2010). Antipointing: perception-based visual information renders an offline mode of control. *Experimental Brain Research.* 202(1), 55-64.

Marks, L. E., & Algom, D. (1998). Psychophysical scaling. In M. H. Birnbaum (Ed.), *Measurement, judgment, and decision making* (pp. 81-178). San Diego: Academic Press.

Marteniuk, R.G., MacKenzie, C.L., Jeannerod, M., Athenes, S., Dugas, C. (1987). Constraints on human arm movement trajectories. *Canadian Journal of Psychology*. 41(3), 365-78.

Martin, J.R., Latash, M.L., Zatiorsky, V.M. (2011). Coordination of contact forces during multifinger static prehension. *Journal of Applied Biomechanics*, 27(2), 87-98.

Maunsell, J.H. & Van Essen, D.C. (1983). Functional properties of neurons in middle temporal visual area of the macaque monkey. II. Binocular interactions and sensitivity to binocular disparity. *Journal of Neurophysiology*, 49, 1148-1167.

Moon, S.Y., Barton, J.J., Mikulski, S., Polli, F.E., Cain, M.S., Vangel, M., Hamalainen, M.S., Manoach, D.S. (2007). Where left becomes right: a magnetoencephalographyic study of sensorimotor transformation for antisaccades. *NeuroImage*, 36, 1313-23.

Neely, K.A, & Heath, M. (2010). Visuomotor mental rotation: the reaction time advantage for anti-pointing is not influenced by perceptual experience with the cardinal axes. *Experimental Brain Research*, 201(3), 593-8.

Neely, K.A., Tessmer, A., Binsted, G., & Heath, M. (2008). Goal-directed reaching: movement strategies influence the weighting of allocentric and egocentric visual cues. *Experimental Brain Research*, 186(3), 375-84.

Pedhazur, E.J. (1997). Multiple regression in behavioral research: Explanation and prediction (3rd Edition). Orlando: Harcourt Brace College Publishers.

Rossetti, Y., Revol, P., McIntosh, R., Pisella, L., Rode, G., Danckert, J., Tilikete, C., Dijkerman, H.C., Boisson, D., Vighetto, A., Michel, F. & Milner, A. (2005). Visually guided reaching: bilateral posterior parietal lesions cause a switch from fast visuomotor to slow cognitive control. *Neuropsychologia,* 43, 162-177

Roy, J.P., Komatsu, H. & Wurtz, R.H. (1992). Disparity sensitivity of neurons in monkey extrastriate area MST. *Journal of Neuroscience,*12, 2478-2492.

Shikata, E., Tanaka, Y., Nakamura, H., Taira, M. & Sakata, H. (1996). Selectivity of the parietal visual neurons in 3D orientation of surface of stereoscopic stimuli. *Neuroreport,* 7, 2389-2394.

Smeets, J.B., Brenner, E. (1999). A new view on grasping. *Motor Control.* 3(3), 237-71.

Snow, J. C., Pettypiece, C. E., McAdam, T. D., McLean, A. D., Stroman, P. W., Goodale, M. A, & Culham, J. C. (2011). Bringing the real world into the fMRI scanner: Repetition effects for pictures versus real objects. *Scientific Reports*, 1, 130.

Taira, M., Tsutsui, K.I., Jiang, M., Yara, K. & Sakata, H. (2000). Parietal neurons represent surface orientation from the gradient of binocular disparity. *Journal of Neurophysiology.* 83, 3140-3146.

Tanaka, H., Uka, T., Yoshiyama, K., Kata, M. & Fujita, I. (2001). Processing of shape defined by disparity in monkey inferior temporal cortex. *Journal of Neurophysiology.* 85, 735-744.

Thaler, L., & Goodale, M.A. (2011). The role of online visual feedback for the control of target-directed and allocentric hand movements. *Journal of Neurophysiology*, 105(2), 846-59.

Uka, T., Tanaka, ,H., Yoshiyama, K., Kato, M., & Fujita, I. (2000). Disparity selectivity of neurons in monkey inferior temporal cortex. *Journal of Neurophysiology,* 84, 120-132.

Vishton, P. M.; Cutting, J; Nunez, L. (1999). Comparing effects of the horizontal-vertical illusion on grip scaling and judgement: relative versus absolute, not perception versus action. *Journal of Experimental Psychology: Human Perception and Performance. 25*(6), 1659-1672.

Watanabe, M., Tanaka, H., Uka, T. & Fujita, I. (2002). Disparity-selective neurons in area V4 of macaque monkeys. *Journal of Neurophysiology,* 87, 1960-1973.

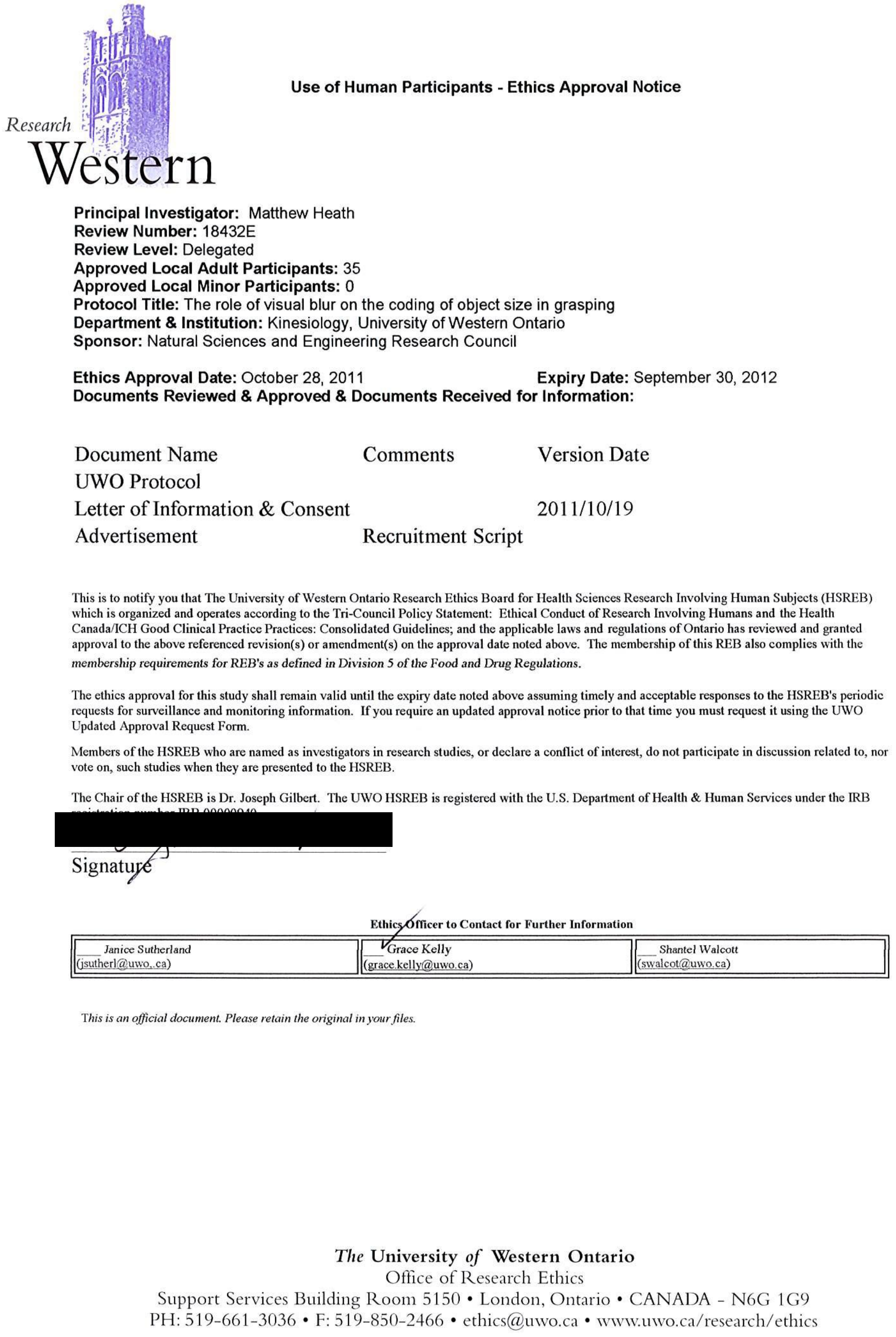
Westwood, D. A, Chapman, C. D., & Roy, E. A. (2000). Pantomimed actions may be controlled by the ventral visual stream. *Experimental Brain Research*, 130(4), 545-8.

Westwood, D. A, Danckert, J., Servos, P., & Goodale, M.A. (2002). Grasping two-dimensional images and three-dimensional objects in visual-form agnosia. *Experimental Brain Research*, 144(2), 262-7.

Zhang, M., & Barash, S. (2000). Neuronal switching of sensorimotor transformations for antisaccades. *Nature*, 408(6815), 971-5.

Appendix A

The University of Western Ontario Research Ethics Board of Approval notice



Research Western

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Matthew Heath
Review Number: 18432E
Review Level: Delegated
Approved Local Adult Participants: 35
Approved Local Minor Participants: 0
Protocol Title: The role of visual blur on the coding of object size in grasping
Department & Institution: Kinesiology, University of Western Ontario
Sponsor: Natural Sciences and Engineering Research Council

Ethics Approval Date: October 28, 2011 **Expiry Date:** September 30, 2012
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
UWO Protocol		
Letter of Information & Consent		2011/10/19
Advertisement	Recruitment Script	

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the *membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.*

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The UWO HSREB is registered with the U.S. Department of Health & Human Services under the IRB [redacted]

Signature

Ethics Officer to Contact for Further Information

___ Janice Sutherland (jsutherl@uwo,.ca)	✓ Grace Kelly (grace.kelly@uwo.ca)	___ Shantel Walcott (swalcot@uwo.ca)

This is an official document. Please retain the original in your files.

The **University** *of* **Western Ontario**
Office of Research Ethics
Support Services Building Room 5150 • London, Ontario • CANADA - N6G 1G9
PH: 519-661-3036 • F: 519-850-2466 • ethics@uwo.ca • www.uwo.ca/research/ethics

Curriculum Vitae

Name: Scott A. Holmes

Address:
School of Kinesiology,
The University of Western Ontario,
London, Ontario, Canada

Post-Secondary Education and Degrees:

The University of Western Ontario, London, ON
Masters of Science Candidate, Kinesiology
2012

McMaster University, Hamilton, ON
B.Sc. Kinesiology. Minor in Biology.
2009

Publications:

Weiler, J., **Holmes, S.A.**, Mulla, A., & Heath, M. (2011). Pro- and antisaccades: dissociating stimulus and response influences the online control of saccade trajectories. Journal of Motor Behavior, 43(5): 375-381.

Holmes, S.A., Mulla, A., Binsted, G., & Heath, M. (2011). Visually and memory-guided grasping: aperture shaping exhibits a time-dependent scaling to Weber's Law. Vision Research, 51(17): 1941-1948.

Heath, M., Mulla, A., **Holmes, S.A.**, & Smuskowitz, L.R. (2011). The visual coding of grip aperture shows an early but not late adherence to Weber's law. Neuroscience Letters, 490(3): 200-204.

Heath, M., **Holmes, S.A.**, Mulla, A., Binsted, G. (Submitted). Grasping time does not influence the early adherence of aperture shaping to Weber's law.

Cusimano, M., **Holmes, S.A.**, Sawicki, C., Topolovec-Vranic, J. (Submitted). Assessing aggression following Traumatic Brain Injury: A systematic review of the validated aggression scales.

Research presentations:

Holmes, S.A., Marriott, K., MacKenzie, A., Sin, M., Heath, M. (2012). Distinct visual metrics support the late stages of aperture shaping for 2D and 3D target objects. [Abstract: Poster]. Annual conference for the Vision Sciences Society.

Marriott, K., **Holmes, S.A.**, Tay, J., Heath, M. (2012). Goal-directed grasping: Vision and haptic percepts of object size influence early but not late aperture shaping. [Abstract: Poster]. Annual conference for the Vision Sciences Society.

Mulla, A., **Holmes, S.A.**, Binsted, G., Dhaliwal, P., & Heath, M. (2011, November). Visually derived and memory guided grasping elicit a temporally dependent adherence to Weber's law [Abstract: Poster]. Annual conference of the Society for Neuroscience: Neuroscience 2011.

Marriott, K., Tay, J., **Holmes, S.A.**, Heath, M. (2011) Goal-drected grasping: Haptic and visual percepts' of object size influence early but not late aperture shaping. [Abstract: Poster]. Annual conference for the Canadian Society for Psychomotor Learning and Sports Psychology.

Holmes, S.A., Mulla, A., McDermid, A., Ethridge, E., Abes, A., & Heath, M. (2011, October). The variability of grip aperture shaping is determined by relative and absolute object properties [Abstract: Oral]. Annual conference of the Canadian Society of Psychomotor Learning and Sport Psychology: SCAPPS 2011.

Holmes, S.A., Mulla, A., & Heath, M. (2011, May). Dynamic early adherence and late violation of Weber's law in goal-directed grasping [Abstract: Poster]. Vision Sciences Society 2011.

Weiler, J., **Holmes, S.A.**, Mulla, A., & Heath, M. (2011, May). Distinct response latencies do not influence pro- and antisaccade trajectories

[Abstract: Poster]. Vision Sciences Society 2011.

Holmes, S.A., Mulla, A., Smuskowitz, L.R., & Heath, M. (2011, January). Goal-directed grasping follows a process-dependent adherence to Weber's law [Abstract: Poster]. 2011 AGRS-FHS Symposium.

Awards and scholarships:

2012 - Kinesiology Travel Award. School of Kinesiology, Faculty of Health Sciences, The University of Western Ontario, $520.

2011 - Faculty of Health Sciences Graduate Student Conference Travel Award. Faculty of Health Sciences, The University of Western Ontario, $500.

2011 - Western Graduate Research Scholarship. School of Kinesiology, Faculty of Health Sciences, The University of Western Ontario, $11,300

2011 - Kinesiology Travel Award. School of Kinesiology, Faculty of Health Sciences, The University of Western Ontario, $700.

2010 - Western Graduate Research Scholarship. School of Kinesiology, Faculty of Health Sciences, The University of Western Ontario. $11,300

2009 – The McMaster Athletic Council Award. McMaster University.

2009 – Sister Christine Gaudet Scholarship Fund and Dr. S. Gordon Ross Memorial Fund Award. St. Michael's Hospital, $500

2008 – Sister Christine Gaudet Scholarship Fund and Dr. S. Gordon Ross Memorial Fund Award. St. Michael's Hospital, $1000

Teaching experience:

Graduate Teaching Assistant, September 2010 – April 2012
School of Kinesiology, The University of Western Ontario
Introduction to Sport Psychology – 1st year

Introduction to Psychomotor Behavior – 1st year
Movement Neuroscience – 3rd year

Professional associations:

Canadian Society for Psychomotor Learning and Sport Psychology
Vision Sciences Society