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ORIGINAL ARTICLE

Weber's law in 2D and 3D grasping

Aviad Ozana[1] · **Tzvi Ganel**[1]

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Abstract Visually guided grasping movements directed to real, 3D objects are characterized by a distinguishable trajectory pattern that evades the influence of Weber's law, a basic principle of perception. Conversely, grasping trajectories directed to 2D line drawings of objects adhere to Weber's law. It can be argued, therefore, that during 2D grasping, the visuomotor system fails at operating in analytic mode and is intruded by irrelevant perceptual information. Here, we explored the visual and tactile cues that enable such analytic processing during grasping. In Experiment 1, we compared grasping directed to 3D objects with grasping directed to 2D object photos. Grasping directed to photos adhered to Weber's law, suggesting that richness in visual detail does not contribute to analytic processing. In Experiment 2, we tested whether the visual presentation of 3D objects could support analytic processing even when only partial object-specific tactile information is provided. Surprisingly, grasping could be performed in an analytic fashion, violating Weber's law. In Experiment 3, participants were denied of any haptic feedback at the end of the movement and grasping trajectories again showed adherence to Weber's law. Taken together, the findings suggest that the presentation of real objects combined with indirect haptic information at the end of the movement is sufficient to allow analytic processing during grasp.

Introduction

According to the two visual systems hypothesis (Goodale & Milner, 1992; Ungerleider & Mishkin, 1982), the dorsal visual stream, which mediates vision-for-action, is subserved by distinct neural computations compared to those mediating visual perception in the ventral pathway. Indeed, it has been proposed that actions performed toward real, three-dimensional (3D) objects are subserved by different representations compared to those that mediate visual perception (for discussion, see Goodale & Ganel, 2015).

Recent technological advancements have led to the emergence of a new form of goal-directed actions, performed toward two-dimensional (2D) virtual objects presented on touchscreens. On the one hand, such actions are preformed toward distinct and recognizable visual targets, but on the other hand, these targets lack the basic properties of real objects, such as information on depth and haptic feedback from the surface of the target object. Hence, it is relevant to ask whether or not the computations that mediate action execution toward real objects also characterize actions directed at 2D virtual objects.

Visual cues in 2D grasping

Only a few studies have examined the kinematics of actions directed to 2D objects. These studies mainly compared real-object grasping movements with grasping movements toward 2D objects drawn on a paper. For example, Westwood, Danckert, Servos, and Goodale (2002) proposed that grasping movements toward 2D objects are not fundamentally different than movements during normal grasping of real objects. Their conclusion relied on the performance of a patient with visual-form agnosia (DF) who exhibited intact size sensitivity to both

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✉ Tzvi Ganel
tganel@bgu.ac.il

[1] Department of Psychology, Ben-Gurion University of the Negev, 8410500 Beer Sheva, Israel

2D and real objects during grasping, but not during perceptual estimations. In line with these findings, Kwok and Braddick (2003) found that the Ebbinghaus illusion did not influence grasping movements for both 2D and 3D objects.

More recent evidence, however, suggests that the visual processes that mediate actions performed toward 2D objects are qualitatively different than those that mediate actions directed at real 3D objects (Freud & Ganel, 2015; Holmes & Heath, 2013; Hosang, Chan, Jazi, & Heath, 2015). Specifically, unlike grasping trajectories directed to real object that were shown to be performed in an analytic fashion, evading the influence of Weber's law (Ganel, 2015; Ganel, Chajut, & Algom, 2008), grasping trajectories toward 2D line drawings are subjected to this fundamental principle of perception (Holmes & Heath, 2013, but see Christiansen, Christensen, Grünbaum, & Kyllingsbæk, 2014, for a different pattern of results). Recently, Freud and his colleagues used fMRI to show dissociable patterns of brain activation in 2D and 3D grasping, which supports the idea that the visual dorsal stream is sensitive to the "realness" of the target object (Freud et al., 2017). Overall, these findings suggest that movements toward 3D objects are different than movements toward 2D objects, which in turn could be affected by perceptual processing that intrudes into action (Freud & Ganel, 2015; Gonzalez, Ganel, Whitwell, Morrissey, & Goodale, 2008; Holmes & Heath, 2013).

Holmes and Heath (2013) compared grasping and perceptual estimations of real different-sized blocks to grasping performed toward a set of 2D simple line drawings of objects of similar sizes. Participants were asked to either grasp or estimate the size of each object. The results showed that JNDs during grasping toward real objects (calculated at the point of the maximum grip aperture, MGA) did not vary with object size, evading the influence of Weber's law. However, JNDs during 2D grasping increased in a linear fashion with object size, in line with Weber's law. These findings were recently replicated by Hosang and her colleagues that examined the effects of tactile feedback on 2D grasping (Hosang et al., 2015).

These recent studies provide initial support for the idea that grasping movements toward 2D objects are affected by perceptual processes. Moreover, the pattern of results that show adherence to Weber's law under 2D grasping but not under controlled conditions in which grasping is performed toward 3D objects suggests that the adherence to Weber's law during visuomotor control can be used as an effective tool for probing the nature of the performed action. We note, however, that all the previous studies in this domain were limited by the fact that the target objects were simple 2D line drawings, lacking fine visual details, or a reference to pictorial depth. Therefore, the previous findings do not allow drawing a clear conclusion as to whether or not the adherence to Weber's law is a general property of 2D grasping. It can be argued, therefore, that the observed differences between real and 2D grasping stem, at least in part, from differences along the visual displays. One purpose of the current study was to test whether the adherence to Weber's law is a general property of 2D grasping and would extend to situations in which more realistic displays of objects are presented. Later on, we continued to explore the role of the type of visual objects presented in view and the role of the tactile cues provided at the end of the movement. Overall, the current study was designed to explore the contributions of pictorial and tactile cues for 2D and 3D grasping.

Tactile cues in 2D grasping

A potential reason for the failure in selective processing during 2D grasping is the lack of haptic feedback obtained from the edges of the target object at the end of the grasping movement. Real objects provide distinguishable haptic feedback when the fingers contact their physical surface. According to Johansson and Flanagan (2009), this information can be later used by the visuomotor stream to calibrate and refine the movement toward the object on subsequent trials. In agreement with this idea, removal of haptic feedback from 3D objects has been shown to affect movement trajectories. Bingham, Coats, and Mon-Williams (2007) used a unique L-shaped mirror box to create the illusion that the objects placed in front of a mirror are perceived beyond its surface and within the participant's reach. This design was used to compare grasping movements with and without tactile feedback from the objects which was administrated in 100% or 50% of the trials. Results showed that actions in the partial feedback condition highly resembled simple-grasping movement trajectories for which tactile feedback is allowed. However, actions performed without any tactile feedback led to unnatural prehension movements and to a decrease in movement precision.

Similar results were reported in a more recent study conducted with patient DF, who suffers from extensive lesions in her ventral cortex (Goodale, Milner, Jakobson, & Carey, 1991). Patient DF is severely impaired in her perceptual processing, which also results in very poor performance during perceptual estimations of object size. Interestingly, however, her ability to compute the size of target objects prior to grasp is intact. We note, however, that while more recent investigations of DF's performance during grasping have consistently replicated her normal sensitivity to object size during grasping (Schenk, 2012, Whitwell, Milner, Cavina-Pratesi, Byrne, & Goodale, 2014), there are recent indications that DF's performance along some other aspects of motor control such as her sensitivity to orientation or efficiency in posture selection is impaired, at least to a certain degree (Hesse, Ball & Schenk, 2012; Himmelbach, Boehme, & Karnath, 2012; Rossit et al., 2017; Wood, Chouinard, Major, & Goodale, 2016). Importantly, during grasping, when tactile feedback is completely denied (i.e., grasping at thin air), DF loses her normal sensitivity to size (Schenk, 2012). This could suggest that when haptic feedback is denied, size computations are mediated by ventral stream computations, which are subjected to relative processing style (Goodale, Jakobson, & Keillor, 1994; Whitwell, Ganel, Byrne, & Goodale, 2015).

The present investigation

The goal of the current study was to examine the role of visual and tactile cues in 2D and 3D grasping. Adherence to Weber's law was used as a diagnostic tool to probe the nature of the underlying computations that guide actions. In Experiment 1, visually guided grasping movements toward real objects were compared with grasping directed at high-resolution photos of the same objects. Experiment 2 examined the specific contribution of the presentation of real objects when a partial haptic feedback was provided, similar to the feedback provided during 2D grasping. To this purpose, we examined grasping trajectories toward real 3D objects presented beyond a transparent glass surface. Experiment 3 explored the overall contribution of tactile feedback to grasping, using a similar design to the one used in Experiment 2, but now with the total removal of tactile feedback at the end of the movement.

Experiment 1

In the first experiment, grasping trajectories toward 3D rectangular objects were compared with grasping trajectories made toward high-resolution photos of the same objects. Would 2D grasping escape the influence of Weber's law in the presence of such potent visual cues?

Methods

Participants

Sixteen right-handed students (six males, average age 23.5, SD 3.2) participated in the experiment. They all provided informed consent to participate in the experiment and received the equivalent of $10 for their participation. All experimental procedures were approved by the ethics committee of the Psychology department at Ben-Gurion University of the Negev.

Apparatus

Participants sat in front of a black tabletop on which a 19 in. screen was placed horizontally on the table surface (Fig. 1). Computer-controlled PLATO goggles (Translucent Technologies, Toronto, ON) with liquid–crystal shutter lenses were used to control stimulus exposure time. Grip scaling was recorded by an Optotrak Certus device (Northern Digital, Waterloo, ON). The apparatus tracked the 3D position of three active infra-red light emitting diodes attached separately to the participant's index finger, thumb, and wrist (200 Hz sampling rate). The objects were presented at a 30 cm distance from the movement starting point in all experiments. Chinrest was not used in the current set of experiments, so viewing angle was dependent on the height of the participant (when sitting).

Stimuli

3D objects: Three sizes of rectangular-shaped wooden blocks were used (20/40/60 mm long, 10 mm wide, and 10 mm high; object weights were 1.5/3/4.5 g, respectively). The objects were placed on the center surface of the monitor, against a black background (see Fig. 1). 2D objects: High-resolution photos of the 3D objects were used. The objects were displayed on the 1366 × 768 resolution LCD display (50 Hz) against a black background. The photos were those of the same objects in the 3D condition, and were photographed from an average-height participant's point of view using an 8 MP camera. They were later cropped and modified using Adobe Photoshop to be similar in terms of appearance and dimensions to those of the 3D objects (Fig. 1).

Experimental procedure

Prior to each trial, participants placed their index finger and thumb pinched together against a start button, while the goggles were set to the translucent state. Participants were instructed to touch the upper and lower edges of the target object without lifting it up. They were told to initiate their movement upon hearing a "go" auditory tone and to complete their movement prior to the presentation of a second tone. They were then asked to keep their fingers still at the endpoint for an additional 1 s prior to returning to the start position. Each trial began with an opening of the goggles, which remained open for 3000 ms allowing full visual feedback during the trial. The "go" tone was presented 1000 ms after the initial opening of the goggles. The second tone was presented 1250 ms following the presentation of the go tone.

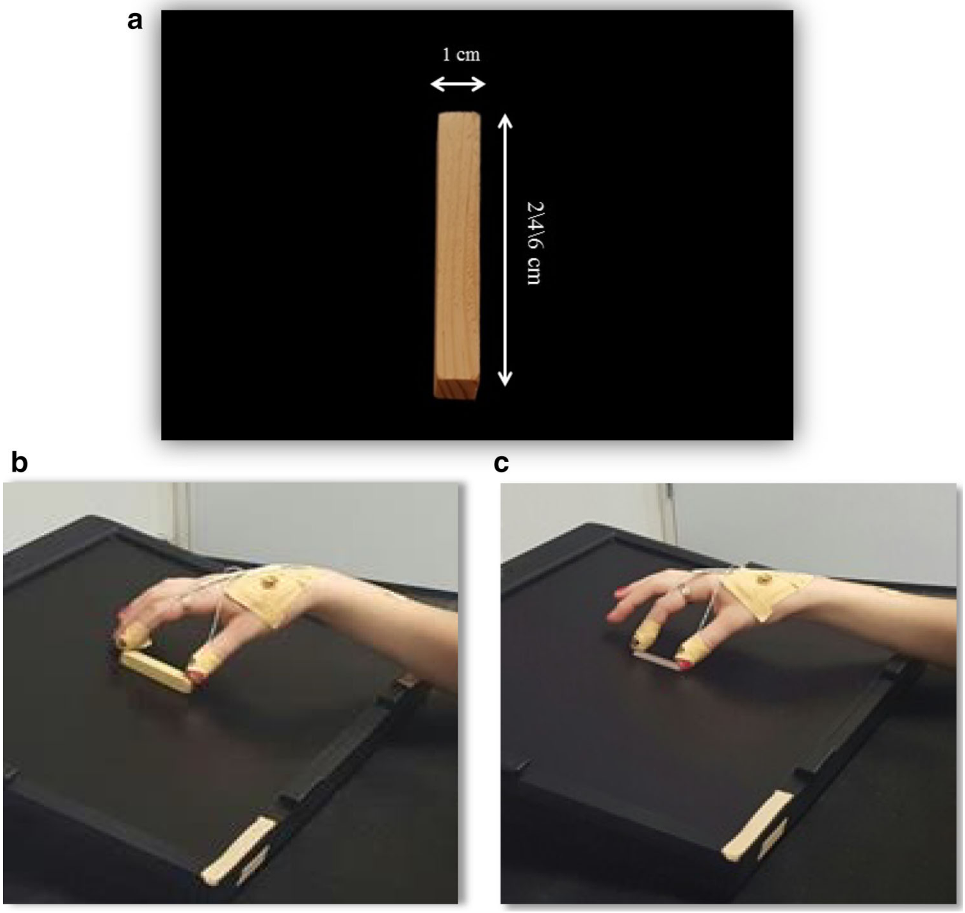

Fig. 1 Illustration of the experimental setup used in Experiment 1. **a** Example of one of the 2D objects. **b** Illustration of the 3D grasping condition. **c** Illustration of the 2D grasping condition

Following a few practice trials and equipment calibration, each participant performed one experimental block containing 3D objects (3D condition) and one containing 2D objects (2D condition). Each block contained 60 pseudo-randomized experimental trials (20 repetitions of each object size). Block order was counterbalanced across participants.

Data analysis

The 3D trajectories of the fingers were recorded in each trial. Movement onset was determined as the point in time at which the aperture between index finger and thumb increased by more than 0.1 mm per frame for at least 50 ms. Movement offset was determined as the point in time at which the aperture between the index finger and thumb changed less than 0.1 mm per frame for at least 125 ms (25 frames), but only after reaching the maximum grip aperture (MGA) between the fingers. The within-subject standard deviations of the apertures at MGA were calculated separately for each object and were used as measures for the JND. We also calculated for each participant the linear slope between the MGA for each object size in relation with the real physical size of that object. To calculate movement trajectory, we divided each trial's trajectory into 11 intervals equal in length (0–100%) and calculated the average aperture in each interval point. Data from the wrist marker were collected to assist in situations in which the aperture data could not be used to conclusively determine movement onset or offset. No such trials were identified, so data from the wrist marker were not further analyzed.

Design and analysis

Object size (three levels) and object type (2D/3D) served as within-subject independent variables. The average aperture between the fingers and the resultant standard deviation (JND) served as the dependent variables. The two dependent measures were sampled at the point of MGA, known to be highly correlated with object size during grasping (Jakobson & Goodale, 1991; Jeannerod, 1984).

Results and discussion

Average aperture

Average aperture trajectories throughout the movement in 2D and 3D grasping are presented in Fig. 2. As can be seen

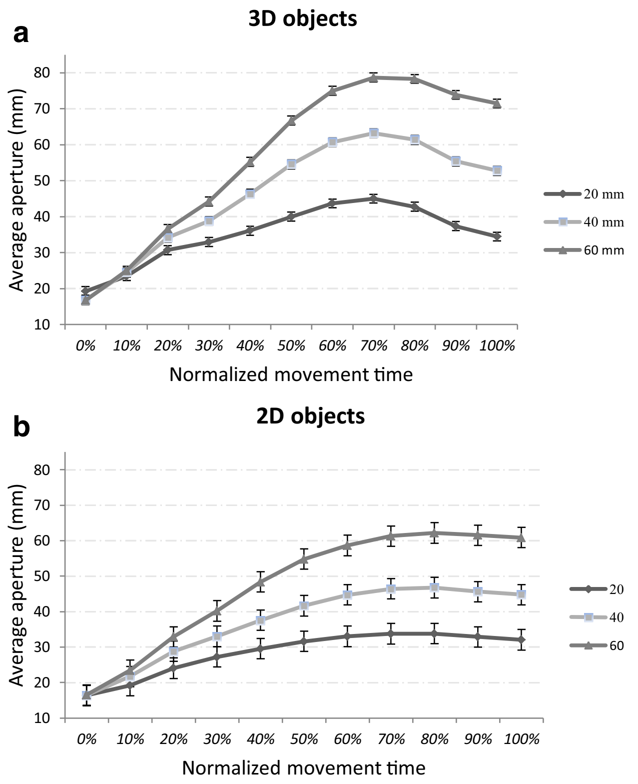

Fig. 2 Average fingers' aperture across the movement trajectory toward 3D objects (**a**) and 2D objects (**b**). Sensitivity to object size was observed in both tasks. *Error bars* represent confidence intervals for the main effect of object size in repeated measures ANOVAs (Jarmasz & Hollands, 2009)

in the figure, grasping apertures were tuned to object size throughout the two types of movements.

A repeated measures ANOVA with Greenhouse–Geisser correction of the aperture between the fingers was conducted on the MGA data and revealed a significant main effect of size [$F_{(1,16.5)} = 297.5$, $p < 0.05$, $\eta_p^2 = 0.95$] and of object type [$F_{(1,30)} = 54.3$, $p < 0.05$, $\eta_p^2 = 0.78$] as well as the interaction between object type and size [$F_{(2,30)} = 7.6$, $p < 0.05$, $\eta_p^2 = 0.34$]. Planned comparisons showed that hand apertures linearly increased with object size for 2D objects [$F_{(1,15)} = 105.2$, $p < 0.05$, $\eta_p^2 = 0.87$] (33, 46, and 61 mm for the small, medium, and big objects, respectively) and for 3D objects [$F_{(1,15)} = 1000.6$, $p < 0.05$, $\eta_p^2 = 0.98$] (40, 58, and 76 mm). A paired sample *t* test was conducted to compare the linear slopes between the 2D and 3D grasping conditions (calculated in relation with the real physical sizes of the objects). The average linear slope was significantly smaller in the 2D condition (0.67) compared to the 3D condition [0.81, $t_{(15)} = 2.77$, $p < 0.05$]. Hence, average fingers aperture showed different trajectory patterns in 2D and 3D grasping.

JNDs

As can be seen in Fig. 3, 2D and 3D grasping trajectories showed a different pattern of adherence to Weber's law. In particular, 3D grasping violated Weber's law, whereas JNDs during 2D grasping increased with object size, in adherence to Weber's law. A repeated measures ANOVA with Greenhouse–Geisser correction of the JNDs did not show a significant effect of object size [$F_{(1.2,27)} = 3.5$, $p > 0.05$]. The main effect of object type was also not significant [$F_{(1,30)} = 0.36$, $p > 0.05$]. The interaction between the linear component of object size and between object type was significant [$F_{(1,15)} = 4.81$, $p < 0.05$ $\eta_p^2 = 0.23$]. Planned comparisons showed that JNDs during 2D grasping linearly increased with size [$F_{(1,15)} = 7.54$, $p < 0.05$, $\eta_p^2 = 0.31$]. JNDs during 3D grasping did not reveal an effect of size [$F_{(2,30)} = 0.22$, $p > 0.05$].

The results of Experiment 1 show that richness in pictorial detail does not account for the analytic processing style during grasping. In particular, grasping movements toward 2D objects adhered to Weber's law even when high-resolution photos of the objects were presented as targets. In sharp contrast to 2D grasping, grasping movements performed toward real objects violated Weber's law. These findings show that the relative nature of size computations when actions are directed toward simple 2D objects generalizes to situations in which the objects contain rich pictorial details as well as explicit cues about pictorial depth. Therefore, even when such visual details are provided, grasping movements toward 2D objects are intruded by irrelevant perceptual information.

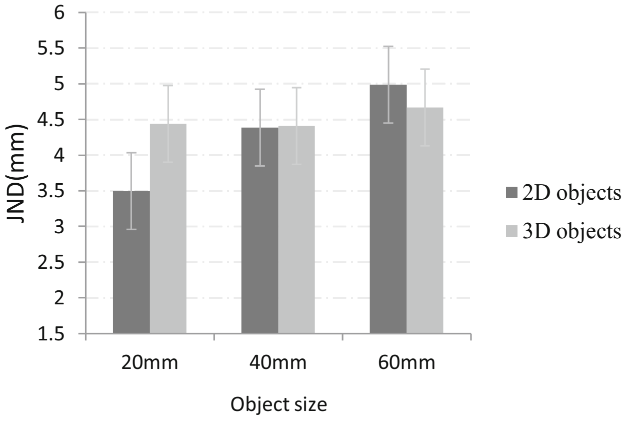

Fig. 3 JNDs during grasping movements toward 2D and 3D objects. JNDs during 2D grasping showed a linear increase with size, in adherence to Weber's law. In contrast, grasping trajectories for 3D objects did not increase with object size, in violation of Weber's law. *Error bars* represent confidence intervals in repeated measures ANOVAs (Jarmasz & Hollands, 2009)

The mechanisms underlying the different processing styles during 3D and 2D grasping are, therefore, yet to be revealed. Experiments 2 and 3 were designed to further explore this issue by disentangling the contributions of two different aspects of the task that are essentially different for 2D and for 3D grasping. First, the failure to perform the movement analytically during 2D grasping may stem from differences in the availability of tactile feedback at the end of the movement. In particular, real objects provide unique haptic feedback when the fingers contact the object's edges. Such object-specific haptic feedback is absent in 2D grasping, where participants are required to touch the flat surface of the computer screen at the end of the movement. The task of 2D grasping, therefore, provides only general, indirect haptic information at the end of the movement. We note, however, that it has been recently suggested (yet not empirically tested) that the denial of direct tactile cues from the object edges is not crucial for normal grasping selectivity and that general (indirect) haptic information at the end of the movement may suffice to enable analytic processing during grasp (Whitwell et al., 2015).

A second, and perhaps a more crucial difference between 2D and 3D grasping, is related to the visual cues provided in the two conditions. Simply, real objects are visually presented during 3D grasping. Real objects contain binocular and monocular cues which allow the visual system to compute their distances and sizes in an efficient manner. It is not surprising, therefore, that recent imaging and behavioral studies showed that the presentation of real objects may trigger a unique processing style and a distinguishable pattern of fMRI activation compared to a situation in which 2D photos are presented (Freud et al., 2017; Gerhard, Culham, Schwarzer, Horst, & Kovack-lesh, 2016; Snow et al., 2011; Snow, Strother, & Humphreys, 2014).

The purpose of Experiment 2 was to test whether the presentation of real objects could support analytic processing style during grasping. To this purpose, participants were presented with real objects combined with indirect haptic feedback, similar to the feedback provided during 2D grasping. This was done by placing real 3D objects beyond a surface of a clear glass. The flat surface of the glass denies contact with the object and provides general, indirect tactile feedback at the end of the grasping movement, just as in 2D grasping. Would the mere presentation of real object suffice to allow analytic processing during grasp?

Experiment 2

Participants

Sixteen participants (eight males, average age 23.6, SD 2.3) participated in the experiment and received the equivalent of $6 for their participation.

Stimuli

Target objects were the same rectangular-shaped wooden blocks used in the 3D condition in Experiment 1. The objects were placed beyond a 3 mm-thick glass surface with high clarity. The glass size was fitted to the dimensions of a 19'' monitor. Four magnets, attached to its lower corners, were used to firmly attach the glass surface to its base (Fig. 4).

Procedure and design

The procedure was similar to that used in Experiment 1 with one exception: prior to each trial, the experimenter placed a glass on the target object, denying haptic feedback from the object's edges upon contact. Participants were asked to place their fingers on the glass surface just above the edges of the object. In this respect, the experimental instructions and tactile information were similar to those presented in the 2D condition in Experiment 1. Object size (three levels) served as the within-subject independent variable. The average apertures and the JNDs served as the dependent variables.

Results and discussion

Average aperture

As in Experiment 1, average aperture trajectories throughout the movement showed sensitivity to object size (Fig. 5). A Repeated measures ANOVA with Greenhouse–Geisser correction of the aperture between the fingers at the point in which MGAs were achieved revealed a significant main effect of size [$F_{(1.2,18.5)} = 664, p < 0.05, \eta_p^2 = 0.97$]. Planned comparisons showed that apertures linearly increased with size [$F_{(1,15)} = 749$, $p < 0.05$, $\eta_p^2 = 0.97$] (38, 48, and 63 mm for the small, medium, and big objects,

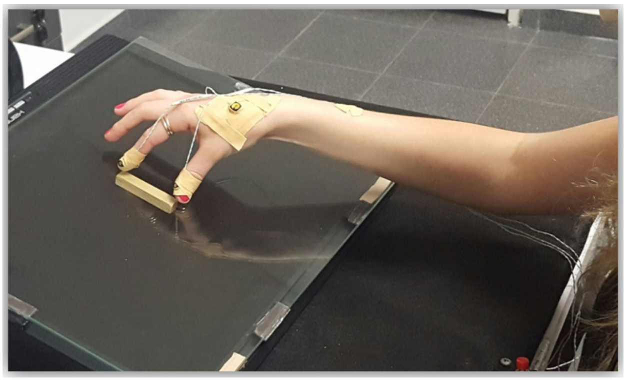

Fig. 4 Illustration of the experimental setup used in Experiment 2

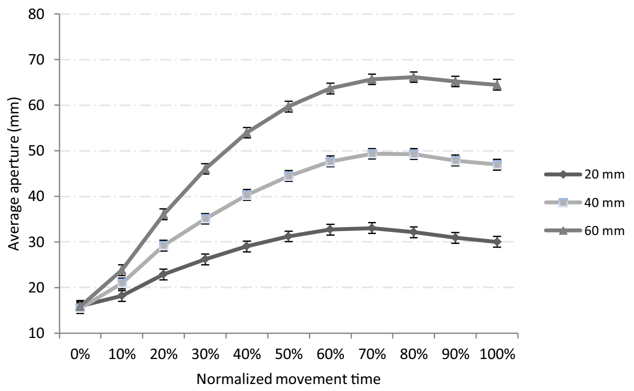

Fig. 5 Average fingers' apertures across the movement trajectory toward 3D objects placed beyond a glass in Experiment 2. Trajectories showed sensitivity to the object size. *Error bars* represent confidence intervals in repeated measures ANOVAs (Jarmasz & Hollands, 2009)

respectively). The linear slope relating MGAs to object size was 0.8.

JNDs

As can be seen in Fig. 6, JNDs did not increase with object size, in violation of Weber's law. A repeated measures ANOVA of the JND data did not show a main effect of size [$F(2,30) = 1.2$, $p > 0.05$].

To examine if the JND pattern for real objects in Experiment 2 differs from a situation in which 2D objects are presented, a mixed ANOVA was conducted on the JNDs data in the current experiment and the JND data in the 2D condition in Experiment 1. The main effect of object size was not significant [$F_{(2,30)} = 2.6$, $p > 0.05$], as well as the main effect of experiment [$F_{(1,30)} = 0.19$, $p > 0.05$]. In addition, a significant interaction between experiment and the linear component of object size was found [$F_{(1,30)} = 8.2$, $p < 0.05$, $\eta_{\mathrm{p}}^2 = 0.21$]. The interaction indicates that unlike as in 2D grasping, for which grip apertures adhere to Weber's law, grip apertures in Experiment 2 are different and evade the influence of Weber's law. Remarkably, such analytic processing of object size was observed when indirect haptic feedback was provided at the end of the grasping movement.

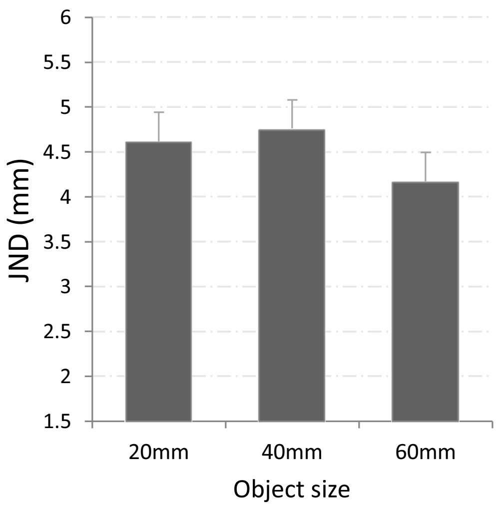

Fig. 6 JNDs for grasping movements toward 3D objects presented beyond a glass in Experiment 2. As in 3D grasping, JNDs did not increase with object size, violating Weber's law. *Error bars* represent confidence intervals in repeated measures ANOVAs (Jarmasz & Hollands, 2009)

The results of Experiment 2 show that the mere presentation of real objects can support analytic processing during grasp. When real objects were presented, aperture trajectories violated Weber's law, even when direct object-specific haptic feedback was denied. Therefore, the results of Experiment 2 show that general (indirect) tactile feedback at the end of the grasping movement may suffice to enable analytic processing during grasping, but only given that real objects are presented as targets.

We note that due to the fact that a chinrest was not used, head motion and perspective could have been used to provide efficient cues on object shape. Indeed, to account for the possibility that such motion cues mediated the violation of Weber's law in Experiment 2, we ran an independent set of control experiments with a similar design but in which a chinrest was used to restraint head movements. The results of these experiments, which for sake of brevity are not specified, replicated the findings of Experiment 2. In particular, movement trajectories violated Weber's law when grasping movements were directed toward objects placed beyond a glass surface.

Note that despite the fact that the flat surface of the glass does not provide direct haptic information from the edges of the object, it does provide some information about its size and may signal potential interaction. After all, although direct haptic feedback is not provided, the general tactile feedback received at the end of the movement reflects the actual size of the object, and entails touching a rigid surface that signals the end of the movement. Indeed, based on the performance of patient DF (Westwood et al., 2002), and on recent behavioral data (Whitwell et al., 2015), it has been suggested that such indirect tactile information may suffice to enable analytic processing during grasp.

Recent findings suggest that when haptic feedback is totally removed and grasping movements are terminated by grasping thin air, trajectories become abnormal and heavily rely on perceptual processing (Whitwell et al., 2015). This may also account for the finding that when tactile feedback is completely denied, patient DF shows no aperture calibration to object size during grasp (Goodale et al., 1994;

Schenk, 2012). The purpose of Experiment 3 was to further test the role general tactile feedback has on grasping. To this purpose, we used similar experimental conditions to those used in Experiment 2, in which real objects were presented beyond a glass. Importantly, however, no tactile feedback was provided and participants were asked to end their movement by grasping thin air just above the glass surface.

Experiment 3

Participants

Twelve participants (five males' average age 24.1, SD 1.4) participated in the experiment and received an equivalent of $6 for their participation.

Procedure and design

The procedure was similar to that used in Experiment 2, with one exception; instead of ending the movement by touching the flat surface of the glass, participants were instructed to end their movement at a distance of about 1 cm above the surface of the glass, by opening their fingers and holding them still above the objects and above the surface of the glass, without touching it. This was monitored by the experimenter online. Trials in which participants touched the surface of the glass (less than 1% of the trials) were excluded from the analysis. Hence, in Experiment 3, tactile feedback has been completely denied.

Results and discussion

Average apertures

As in the previous experiments, average aperture trajectories throughout the movement showed sensitivity to object size (Fig. 7). A repeated measures ANOVA with Greenhouse–Geisser correction of the aperture between the fingers for the MGA data revealed a main effect for object size [$F_{(1.2,18.2)} = 96$, $p < 0.05$, $\eta_p^2 = 0.98$]. Planned comparisons revealed that MGAs linearly increased with size [$F_{(1,11)} = 894$, $p < 0.05$, $\eta_p^2 = 0.98$] (34, 50, and 66 mm for the small, medium, and big objects, respectively), indicating sensitivity to object size.

An additional analysis was conducted to confirm that average MGAs were not overall larger in Experiment 3 compared to the MGAs in Experiment 2. Such a pattern of results could suggest that differences in the pattern of adherence to Weber's law along the JND data could be accounted for by the possibility that MGAs in Experiment 2 were larger and could, therefore, gave a greater potential to be limited by biomechanical constrains of the maximum grip aperture (Bruno, Uccelli, Viviani, & de'Sperati, 2016; Utz, Hesse, Aschenneller, & Schenk, 2015). To this purpose, we compared the results of Experiments 2 and 3 at the point in which MGAs were achieved. A mixed ANOVA model with experiment as a between subjects variable and object size as a within subject showed a main effects of size [$F_{(1.2,32.3)} = 1287$, $p < 0.05$, $\eta_p^2 = 0.98$]. There was no effect for experiment [$F_{(1,26)} = 0.24$, $p > 0.05$]. The interaction between experiment and object size was also not significant [$F_{(1.2,32.3)} = 0.8$, $p > 0.05$]. In addition, an independent t test did not show difference in the sizes of the linear slopes [0.80 and 0.79 in Experiments 2 and 3, respectively, $t_{(26)} = 0.3$, $p > 0.05$]. These results indicate that tactile feedback did not produce a different average aperture trajectory pattern when actions were directed at real objects beyond a glass. In addition, these analyses show that any difference along the pattern of the JND data between Experiments 3 and 2 data could not be accounted for by irrelevant aspects related to biomechanical constrains (for a similar idea, see Ganel, Namdar, & Mirsky, 2017; Heath, Manzone, Khan, & Jazi, 2017; Manzone, Jazi, Whitwell, & Heath, 2017).

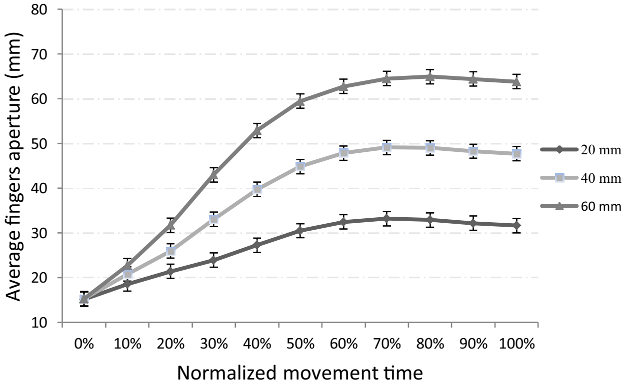

Fig. 7 Average fingers' apertures across the movement trajectory in Experiment 3. Grasping trajectories that ended on thin air showed sensitivity to object size. *Error bars* represent confidence intervals in repeated measures ANOVAs (Jarmasz & Hollands, 2009)

JNDs

As can be seen in Fig. 8, JNDs during MGAs increased with object size, in adherence to Weber's law. A repeated measures ANOVA revealed a main effect of object size [$F_{(2,22)} = 8.85$, $p < 0.05$, $\eta_p^2 = 0.42$]. Planned comparisons showed that JNDs linearly increased with size [$F_{(1,11)} = 11.3$, $p < 0.05$ $\eta_p^2 = 0.50$], indicating adherence to Weber's law.

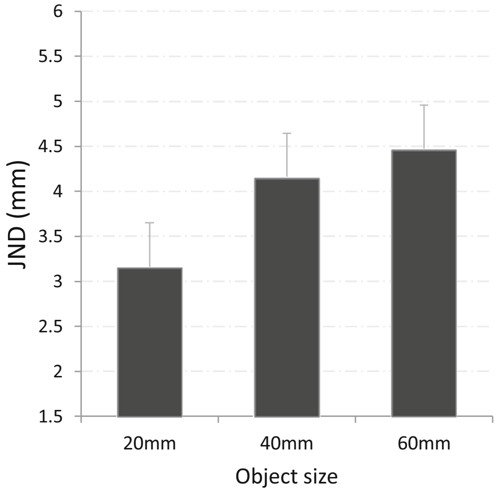

Fig. 8 JNDs in Experiment 3. When haptic feedback was not available, JNDs showed a linear increase with object size, in adherence with Weber's law. *Error bars* represent confidence intervals in repeated measures ANOVAs (Jarmasz & Hollands, 2009)

A mixed ANOVA design analysis of the JNDs data of Experiment 2 and Experiment 3 with experiment as a between subjects variable and object size as a within-subject variable was conducted. The main effects of size [$F_{(2,52)} = 2.47$, $p > 0.05$] and experiment [$F_{(1,26)} = 0.99$, $p > 0.05$] were not significant. Importantly, a significant interaction was found between experiment and the linear component of size [$F_{(1,26)} = 9.32$, $p < 0.05$, $\eta_p^2 = 0.26$], indicating that the adherence to Weber's law in Experiment 3 was significantly different than the analytic processing style obtained in Experiment 2.

The results of Experiment 3 show that the availability of at least partial tactile feedback at the end of the movement is required to support analytic processing during grasp. These findings also show that the mere presentation of real objects does not suffice to support analytic processing during grasping movements. Indeed, the presentation of real objects can support such processing only when general, indirect tactile feedback is provided at the end of the movement.

General discussion

The current study explored the mechanisms that allow analytic processing during simple-grasping movements. More specifically, we examined the contribution of visual and tactile information for such analytic processing. Our findings suggest that the presentation of real objects has a vital role in supporting analytic processing during grasping. Indeed, while actions performed toward high-resolution photos of objects adhered to Weber's law, actions toward real objects placed beyond a glass, violated this fundamental psychophysical principle. In addition, our findings suggest that the total provision of tactile information at the end of the movement disrupts analytical processing during grasp. When tactile feedback was totally denied, visually guided actions toward real object could no longer be performed in an analytic manner and adhered to Weber's law.

It has been established that unlike perceptual estimations, simple-grasping movements toward real objects do not adhere to Weber's law (Ganel et al., 2008; Ganel, Chajut, Tanzer, & Algom, 2008; Ganel, Freud, & Meiran, 2014). In an initial demonstration of this effect, Ganel and his colleagues (2008) asked participants either to grasp objects or to estimate their sizes. While adherence to Weber's law was found for perceptual estimations, JNDs during grasping were not affected by object size, reflecting the different ways that object size is computed for action and perception. The current study extends these findings, showing that actions toward real objects are not subjected to a relative processing style even when only partial tactile feedback is provided.

In addition, and in line with recent work (Freud & Ganel, 2015; Holmes & Heath, 2013; Hosang et al., 2015), we also found that unlike in the case of 3D grasping, grasping movements performed toward 2D objects adhered to Weber's law. The 2D objects that were used in the current study were high-resolution photos of the 3D objects that were presented for grasping. Such photos contain information on texture and pictorial depth. Therefore, the photos could have potentially served as excellent proxies for real objects. Nevertheless, the findings show that even when such high-resolution photos were presented for view, grasping trajectories were not performed in an analytic manner that characterizes simple-grasping movements toward 3D objects but instead, adhered to Weber's law (Experiment 1). This may imply that richness in pictorial detail does not account for the different processing styles during 2D and 3D grasping reported in the previous studies (Freud & Ganel, 2015; Holmes & Heath, 2013; Hosang et al., 2015). Furthermore, the findings provide converging evidence for the idea that actions performed toward virtual objects are intruded by perceptual information, and are, therefore, essentially different compared to actions performed toward real objects. This notion is also consistent with recent imaging studies that indicate that the visual processing of 2D and 3D objects is supported by dissociable neural mechanisms (Freud et al., 2017; Snow et al., 2011, 2014).

The findings of the current study may also be accounted for by object affordance (Gibson, 1979). More particularly, the potential result in respect to the interaction with object could have influenced the processing style supporting visuomotor control. While actions toward 2D photos and actions toward 3D objects that end on thin air (Experiments 1 and 3, respectively) share visual similarities, it can be argued that both types of actions do not lead to a potential interaction with the object. The results of the current study could, therefore, be accounted for by the potential outcome of the visuomotor task (for a similar idea, see Freud et al., 2017). In other words, it can be argued that when actions do not evoke such potential interaction, those actions are more likely to be affected by irrelevant perceptual information. In such cases, analytic processing is disrupted. The interaction with an object placed beyond a glass, on the other hand, may appear more reliable in the sense that actions toward real objects that end with tactile feedback could signal potential interaction. This interpretation of the results is also consistent with the previous reports that suggested that object affordance has a significant effect on motor control (Pavese, Buxbaum, & Laurel, 2002; Tucker & Ellis, 1998, 2004).

Weber's law is considered as a hallmark of relative processing in the perceptual domain. It is, therefore, reasonable to assume that adherence to Weber's law during a motor task provides indication that the task in hand interacts with perceptual processing. Moreover, we argue that the fact that adherence to Weber's law during grasping is consistently found in specific experimental conditions but not in other, tightly controlled experimental conditions, suggests that the presence/absence of Weber's law during movement trajectories can serve as an indication for the nature of the underling process. In other words, adherence to Weber's law during grasping provides indication for possible interactions between visuomotor control and perceptual processing of relative size. This idea has been proposed in several previous studies that compared 2D and 3D grasping. For example, Holmes and Heath (2013) proposed that the adherence to Weber's law during 2D grasping can be accounted for by the idea that perceptual processing intrudes into unskilled grasping movement directed to 2D objects. A similar idea was conveyed in a more recent paper from our lab (Freud & Ganel, 2015), in which we showed that 2D, but not 3D grasping, is performed in an holistic rather than in an analytic manner, for which one dimension of an object cannot be processed independently of other dimensions belonging to the same object. Finally, a different line of support for the idea of intrusion has been put forward by Gonzalez and her colleagues (Gonzalez et al., 2008) who showed that awkward, unskilled grasping movements are more likely to be affected by visual illusions and that this effect diminishes with extensive practice (but see Eloka, Feuerhake, Janczyk, & Franz, 2015; Janczyk, Franz, & Kunde, 2010, for a different pattern of results).

Therefore, it could be assumed that unlike in the case of 2D grasping, simple, skilled grasping tasks in which 3D objects are presented in view can be considered as non-perceptual in that they are immune to the relative influence of Weber's law. However, the question of when a grasping task can be considered to be performed in a skilled and automated manner and under which conditions the adherence to Weber's law indicates a perceptual processing style still needs to be resolved. For example, a recent study that focused on 3D grasping did not find adherence to Weber's law during grasping even in a condition in which no vision was allowed and grasping was performed based on symbolic rather than on visual information (Löwenkamp et al., 2015). Clearly, such a condition does not represent a skilled grasping task, which leaves the question open of how it could have evaded the influence of Weber's law. Löwenkamp et al. (2015) suggested that this may have been due to various noise sources inherent to grasping or can be attributed to ceiling effects due to biomechanical constrains (Utz et al., 2015). These results highlight the fact that researches need to be careful when designing their grasping tasks and the appropriate experimental control tasks to avoid possible pitfalls and confounds and to consider the possibility of task-specific noise sources. A useful way to avoid such pitfalls is to show, within the same experimental design, that the adherence of motor trajectories to Weber's law can be manipulated between tightly controlled experimental conditions. Here, we managed to do so by showing that grasping trajectories are immune to Weber's law only when real objects are presented in view and given that at least partial tactile feedback is provided. Yet, we note that although we believe that the present results provide a promising step in determining which grasping tasks could be considered as skilled and automated tasks, as indicated by their analytic processing style, clearly, more research is needed to establish the relationship between the different properties of the visuomotor task and the effects of relative processing inherent to Weber's law.

It is relevant to note that the present results are also not in line with the general conclusion made by Löwenkamp et al. (2015), according to which adherence to Weber's law cannot be found during grasping due to various sources of inherent noise. Clearly, the present results converge with the previous literature on 2D grasping to suggest that such a general conclusion may be inappropriate. Indeed, Weber's law was consistently found during 2D grasping movements under controlled experimental conditions in which the possibility of potential noise sources such as biomechanical constraints was accounted for. The present findings are also not in line with a proposal by Smeets and Brenner (2008) according to which grasping movements are programmed solely based on the independent end locations of the fingers, rather than on object size. According to this view, Weber's law, which is based on magnitude, cannot apply to discrete aspects such as location and should, therefore, never be observed during grasping or pointing tasks. The findings that 2D grasping adheres to Weber's law across different experimental conditions are, therefore, not in line with this general proposal. Instead, it seems that a more balanced and elaborated view, which takes into account possible interactions between motor control and perceptual processing, needs to be considered.

The findings of Experiment 2 are consistent with a recent suggestion, according to which the performance of patient DF during 2D grasping relies on her ability to obtain general tactile feedback from contacting the flat surface of the tabletop at the end of the movement (Whitwell et al., 2015). When DF was asked to grasp or to manually estimate the sizes of 2D rectangular objects, she showed no sensitivity to object size in perceptual estimations, yet she was able to scale her fingers to the size of 2D objects during grasping (Westwood et al., 2002). It has been argued that the tactile contact with the uninformative flat surface could have mediated DF's sensitivity to object size (Whitwell et al., 2015). The findings of Experiments 2 and 3 are consistent with this interpretation of the results. Indeed, the participants showed analytic processing style when they were provided with indirect tactile feedback from the surface of the glass, without even touching the objects. However, when no tactile feedback was provided, movement trajectories adhered to Weber's law, indicating that such movements are intruded by perceptual processing. Note, however, that visual processing in patient DF may be essentially different than of neurologically intact individuals. The current findings show that participants were intruded by perceptual processing during 2D grasping. Given that such perceptual processing is impaired for DF (De-Wit, Kubilius, de Beeck, & Wagemans, 2013), it may not interfere with her visuomotor abilities as in the case of healthy subjects.

Conclusions

Visually guided actions toward real objects are based on informative visual and haptic cues that support analytic processing style during simple-grasping tasks. The current results show that such analytic processing can occur without direct contact with the target object, provided that real objects are presented for view. The findings suggest that such analytic visuomotor control is contingent upon the possibility of a potential interaction with the target object. Such potential interactions with real objects can in turn be used to support analytic processing during grasp, regardless to whether or not direct haptic feedback is provided at the end of the movement.

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Compliance with ethical standards

Conflict of interest Tzvi Ganel declares that he has no conflict of interest. Aviad Ozana declares that he has no conflict of interest.

Ethical approval All procedures performed in this study were in accordance with the ethical standards of the Psychology department research committee in BGU and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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