**RESEARCH ARTICLE**

# Obeying the law: speed–precision tradeoffs and the adherence to Weber's law in 2D grasping

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## Abstract

Visually guided actions toward two-dimensional (2D) and three-dimensional (3D) objects show different patterns of adherence to Weber's law. In 3D grasping, Just Noticeable Differences (JNDs) do not scale with object size, violating Weber's law. Conversely, JNDs in 2D grasping increase with size, showing a pattern of scaler variability between aperture and JND, as predicted by Weber's law. In the current study, we tested whether such scaler variability in 2D grasping reflects genuine adherence to Weber's law. Alternatively, it could be potentially accounted for by a speed–precision tradeoff effect due to an increase in aperture velocity with size. In two experiments, we modified the relation between aperture velocity and size in 2D grasping and tested whether movement trajectories still adhere to Weber's law. In Experiment 1, we aimed to equate aperture velocities between different-sized objects by pre-adjusting the initial finger aperture to match the target's size. In Experiment 2, we reversed the relation between size and velocity by asking participants to hold their fingers wide open prior to grasp, resulting in faster velocities for smaller rather than for larger objects. The results of the two experiments showed that although aperture velocities did not increase with size, adherence to Weber's law was still maintained. These results indicate that the adherence to Weber's law during 2D grasping cannot be accounted for by a speed–precision tradeoff effect, but rather represents genuine reliance on relative, perceptually based computations in visuomotor interactions with 2D objects.

**Keywords** Visuomotor control · Perception and action · Weber's law · 2D grasping · Object perception

## Introduction

Weber's law documents the relative nature of human resolving power. In visual perception, along with all other modalities, the smallest detectable change along a physical dimension of a stimulus increases linearly with its intensity. Perceived Just noticeable differences (JNDs) are, therefore, expected to increase with object's size, expressing a linear decrease in perceptual resolution. Yet, while Weber's law is considered as a fundamental principle of human perception, accumulating evidence suggests that it does not always apply to visually guided actions (Ganel et al. 2008, 2017; Heath et al. 2011; Ozana and Ganel 2017). In an initial demonstration of this dissociation between action and perception, Ganel et al. (2008) used a modified version of the Method of Adjustment, in which participants were asked to either grasp or to manually estimate the sizes of different objects. JNDs in this method are derived from the within-subject standard deviation of the response, which reflects an "area of uncertainty" for size detection (Baird and Noma 1978; Evans and Howarth 1966; Whalen et al. 1999). For grasping, the response was measured at the point in which maximum grip aperture (MGA) between the fingers was achieved, which arrives at a relatively late stage of the movement (60–70%). For perceptual (manual) estimation, participants were asked to adjust the opening between their fingers to fit the size of the target object. As expected, in the manual estimations condition, JNDs increased with size in a linear fashion. Conversely, for grasping, JNDs did not increase with size, violating Weber's law (Ganel et al., 2008). These findings support the proposal that action and perception are mediated by distinct visual mechanisms (Goodale et al. 1991; Milner and Goodale 2008). Specifically, it has been suggested that unlike visual perception, which relies on relative representation of size, visuomotor control toward objects relies on an absolute size representation, more closely tuned to the physical properties of the object (Ganel 2015; Ganel and

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Goodale 2003; Ganel et al. 2008; Goodale and Ganel 2015; Manzone et al. 2017; but see, Smeets and Brenner 2008; Utz et al. 2015).

Visuomotor interactions with 2D objects on touch screens have become more frequent in recent years. Previous studies showed that unlike 3D grasping, movements trajectories in 2D grasping are not immune to Weber's law (Holmes and Heath 2013; Hosang et al. 2016; Ozana and Ganel 2017). For instance, Holmes and Heath (2013) asked participants to perform grasping movements toward 3D objects or toward a matching set of simple line drawing of 2D objects. In the 3D condition, results replicated previous findings, and JNDs (at the point in which MGAs occurred) were unaffected by object size. However, in the 2D condition, JNDs linearly increased with size along most stages of the movement prior to touch (including the point in which MGAs were achieved), indicating that actions toward 2D objects adhere to Weber's law. Taken together with other behavioral evidence (Freud and Ganel 2015; Ozana and Ganel 2018), we have recently argued that these findings suggest that visuomotor control towards virtual, 2D objects is not governed by the absolute, analytic processing style which governs normal visuomotor interactions with 3D objects, and is instead intruded by task-irrelevant perceptual information on relative size, shape, and context (Ozana and Ganel 2018).

We note, however, that larger JNDs for bigger objects do not always indicate adherence to Weber's law. In a typical grasping task, JNDs, measured by the standard deviation (SD) of the aperture, increase at early stages of the movement, regardless of the adherence to Weber's law. In particular, in typical grasping experiments, participants are asked to pinch their fingers together prior to movement initiation. Such experimental design encourages participants to open their fingers faster to larger objects, and therefore results in faster aperture velocities to bigger objects. Such faster velocities also result in greater variability (hence, poorer precision) for bigger objects, which could be accounted for by a speed–precision tradeoff effect. The monotonic increase in aperture velocity with object size is usually observed at early stages of the movement (up to 50% of the standardized movement time), prior to achieving MGA. Notably, the point in time in which MGA is achieved in 3D grasping is considered as a reliable measure for the nature of the underling visual processes (Foster and Franz 2013; Jakobson and Goodale 1991; Jeannerod 1986).

In the current study, we refer to the monotonic relation between aperture velocity and aperture variability as indication for a speed–precision tradeoff effect. We note, however, that speed–precision tradeoff effects have been applied in various domains of motor control in previous literature (e.g., Schmidt et al. 1979) and have been discussed in their relevance to the adherence of grasping movements to Weber's law (Heath et al. 2012). For example, Heath et al.

(2012) manipulated grasping time in 3D object grasping, and showed a similar relation between JND and size for fast and for slow grasping movements. Heath and his colleagues used these data to propose that aperture velocity does not modulate adherence to Weber's law at early stages of the movement. However, it is important to note that the general relation between size and aperture velocity was not canceled out in Heath et al.'s (2012) study and that aperture velocities within each condition still increased with the target object's size (Ganel 2015). The specific relation between size and velocity was manipulated in a more recent study (Ganel et al. 2014) by matching the initial grip aperture to the target's size, or by asking participants to hold their fingers wide open prior to movement initiation. The results of Ganel et al.'s study (2014) showed that Weber's law was violated throughout the movement in both conditions, supporting the idea that speed–precision tradeoff effects may affect grasping trajectories at early stages of the movement (Ganel 2015).

While these findings suggest that speed–precision tradeoffs due to aperture velocity do not modulate the relation between JND and size in 3D grasping, aperture velocity may still modulate this relation (and the adherence to Weber's law) in 2D grasping. Movement trajectories during 2D grasping lack several kinematic signatures that are inherent to normal grasping, which could make such movements vulnerable to unwarranted effects of speed–precision tradeoff. For example, unlike 3D grasping, in which a "safety margin" in aperture is required to firmly grasp and lift a physical object, such safety margin is not required in 2D grasping. Thus, grip apertures in 2D grasping lack a distinct point of a maximum aperture prior to contact (for discussion, see Ozana et al. 2018). Instead, in 2D grasping, the point of MGA typically occurs late during the movement, just when the fingers touch at the surface on which the virtual object is presented (Holmes and Heath 2013). Given that previous studies of 3D grasping showed that movements prior to MGA in which apertures are more likely to increase with size, could be susceptible to speed–precision tradeoff effects (Foster and Franz 2013; Ganel et al. 2014; Ganel 2015), it is possible that the adherence to Weber's law in 2D grasping is confounded by aperture velocity. In particular, in all previous studies of 2D grasping, participants were asked to start their movement with their fingers pinched together, which leads to larger aperture velocities to bigger objects. Given that larger velocities can also result in larger variability and less precise performance, and that this pattern persists throughout the entire movement in 2D grasping, it is possible that the adherence to Weber's law in 2D grasping is mediated by speed–precision tradeoff effects even at late stages of the movement and even when the fingers touch the surface on which the 2D object is presented.

The main goal of the current study was to test whether such a speed–precision tradeoff effect mediates the

adherence to Weber's law in 2D grasping. In particular, we tested whether the linear increase in JNDs (scalar variability, measured by the within-subject SD of the apertures) during 2D grasping represents genuine adherence to Weber's law, or is rather the result of an increase in the aperture's velocity with size. The possible confound of aperture velocity on the pattern of JND was tested by adjusting the distance between the fingers prior to movement initiation (Ganel et al. 2014).

In Experiment 1, the initial distance between the fingers was dynamically adjusted to be correlated with the size of the target object. In particular, the initial distance between the fingers was set to always be 10 mm smaller than the target object's size. This manipulation was effectively used in a previous study from our lab to cancel out the relation between velocity and size in 3D grasping (Ganel et al. 2014). Therefore, this manipulation allows testing adherence to Weber's law, regardless of speed–precision tradeoff effects. Based on the idea that 2D grasping movements are intruded by perceptual, relative computation of size, it is predicted that aperture trajectories would adhere to Weber's law even when the relation between aperture velocity and size would be attenuated or canceled out.

## Experiment 1

### Methods

#### Participants

Twelve healthy right-handed undergraduate students (5 males, average age = 24, SD = 1.5) participated in the experiment for the equivalent of 5$. All participants provided informed consent. The experimental procedures were approved by the ethic committee of the BGU psychology department. The results of two participants were excluded from the analysis, one due to failure to follow the experimental procedure and the other due to technical issues in the recording of the movement by the Optotrak device.

#### Apparatus and stimuli

Participants sat on a height-adjustable chair in front of a black tabletop, on which a touchscreen (Dell, 1366 × 768), and an LCD display (EIZO, 1920 × 1080) were placed horizontally. The distance between the two devices was 10 cm (top to low edges). 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). Three different-sized rectangular objects were used as targets and were displayed in the center of the LCD screen (height: 20, 40, 60 mm, width: 10 mm). Two circles (10-mm radius each) in three different distances (10, 30, 50 mm) were presented in the center of the touchscreen, and were used as starting points. The physical distance between the upper circle (displayed on the touchscreen) and the center of the target (displayed on the LCD screen) was 30 cm (Fig. 1). Viewing distance from the target was about 50 cm. Trial sequence and stimuli presentations were controlled with Kivy package (version 1.10.0) of the Python software (2.7.14).

### Procedure

Prior to each trial, participants positioned their fingers on the starting points, so that their index finger covered the upper circle and their thumb covered the lower circle. The distance between the two points was set to be correlated with the target object and was always 10 mm smaller than the virtual object. Each trial began with an auditory tone singling the participants to initiate their movement towards the target. Participants were instructed to touch the edges of the target, then to keep them still at the end location, until the goggles were set to their translucent state. Participants were further asked to return to the approximate location of the starting point. The goggles were kept open for 4.5 s, allowing full visual feedback while adjusting the fingers to the starting point, and during the execution of the trial. The auditory tone was presented 2 s after the initial opening of the goggles (see Fig. 1).

After a training period of 10 trials, each of the participants performed one block of 60 pseudo-randomized experimental trials (20 repetitions per size).



**Fig. 1** Illustration of the experimental setup in Experiment 1. Participants were asked to place their fingers on the two dots prior to initiating their movement toward the 2D object. The distance between the two dots was set to always be 10 mm smaller than the target's length

## Data analysis and design

The 3D locations of the index finger and thumb were recorded in each trial. The movement trajectories were analyzed offline using MATLAB software (Version 9.0, The Mathworks, Natick, MA). Movement onset and offset were computed based on the velocity of the index finger. Movement onset was set at the point in time when velocity exceeded 50 mm/s and offset, at the point in time in which the velocity fell below 70 mm/s, but only after 100 frames (500 ms) from movement initiation. This relatively high offset threshold was used to avoid calculating trails in which tactile feedback (from the fingers' contact with the screen) was available (Whitwell and Goodale 2013). Aperture velocity was computed by the resultant distance between the apertures in frame $i$ and $i+1$ divided by the time difference between the two frames. No filtering was applied to the data. Each movement trajectory was divided into 11 normalized time points (0–100%). The average grip apertures, aperture velocities, and within-subject standard deviations were calculated separately for each object size in each normalized time point. In addition, the within-subject standard deviations during the point in time in which maximum grip apertures (MGAs) were achieved and at the point of contact (POC) with the screen were calculated for each object. POCs were determined based on the point in time in which the index's finger velocity fell below 20 mm/s. Other kinematic aspects were also analyzed: Reaction time (RT), which represents the time to initiate the movement, time to MGA (tMGA, Experiment 1), and movement time (MT), which is the time to complete the movement. A correction for outliers was applied on each participant's aperture data. Trials for which the aperture standard deviation had a $Z$ score of above 2.5 or below $-2.5$ were excluded from further analysis. The correction resulted in the exclusion of less than 2% of the trials.

## Results

Normalized movement time (11 levels), and object size (20, 40, 60 mm) were the independent within-subject variables. Average aperture, average aperture velocity, and the aperture's standard deviation served as the main dependent variables.

## Grip apertures and response times

The apertures between the fingers along the movement trajectory are presented in Fig. 2. As can be seen in the figure, grip apertures were adjusted to the size of the target object. A repeated-measures ANOVA test with Greenhouse–Geisser correction (when required) of the grip aperture across the movement showed a significant main effect for normalized
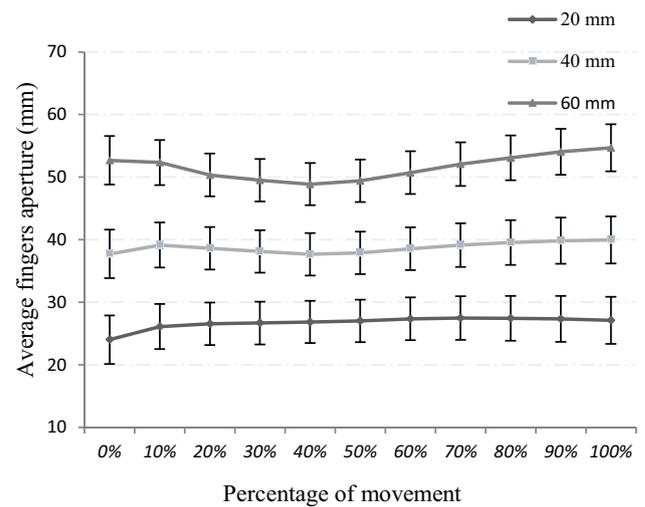


**Fig. 2** Average apertures across the movement trajectory in Experiment 1. Apertures were tuned to the size of the 2D object. Error bars represent standard errors of the mean

**Table 1** Mean RTs tMGA and MTs ($\pm 1$ standard deviation) for each object size in experiments 1–2

|  | 20 mm | 40 mm | 60 mm |
|---|---|---|---|
| Experiment 1 |  |  |  |
| RT | 472±71 | 494±75 | 481±54 |
| tMGA | 435±87 | 400±110 | 435±190 |
| MT | 702.6±76 | 707±58 | 719±79 |
| Experiment 2 |  |  |  |
| RT | 416±52 | 433±61 | 424±49 |
| MT | 846±90 | 848±89 | 873±114 |

movement time [$F_{(10,90)}=5$, $p<0.01$, $\eta_p^2=0.36$]. There was a significant main effect for size [$F_{(1.5,10.3)}=231.5$, $p<0.01$, $\eta_p^2=0.96$], which indicates that apertures were sensitive to size (26, 39, 53 mm, for the small, medium and big object, respectively). The interaction between normalized movement time and size was also significant [$F_{(20,180)}=7.5$, $p<0.01$, $\eta_p^2=0.45$]. We also note that MGAs were achieved at relatively late stages of the movement trajectory, compared with a previous study from our lab, in which we used a similar design in 3D grasping (Ganel et al. 2014). This different pattern of time-dependent aperture scaling reflects the absence of a "safety margin" when interacting with 2D targets. A similar pattern was reported in previous studies that engaged a 2D grasping task (Holmes and Heath 2013).

RTs, tMGAs, and MTs in Experiment 1 are presented in Table 1. A repeated-measures ANOVA was conducted on the different aspects of the response time data. The main effects for size were not significant for MT [$F_{(2,18)}=1.8$, $p>0.05$], tMGA [$F_{(2,18)}=0.3$, $p>0.05$], or RT [$F_{(2,18)}=1.3$,

$p > 0.05$]. We note, that the null finding with respect to MT indicates that movement time was not correlated with the size of the target. Thus, it can be reasonably assured that the comparisons of MT-normalized measures across target size are not confounded with MT (Whitwell and Goodale 2013).
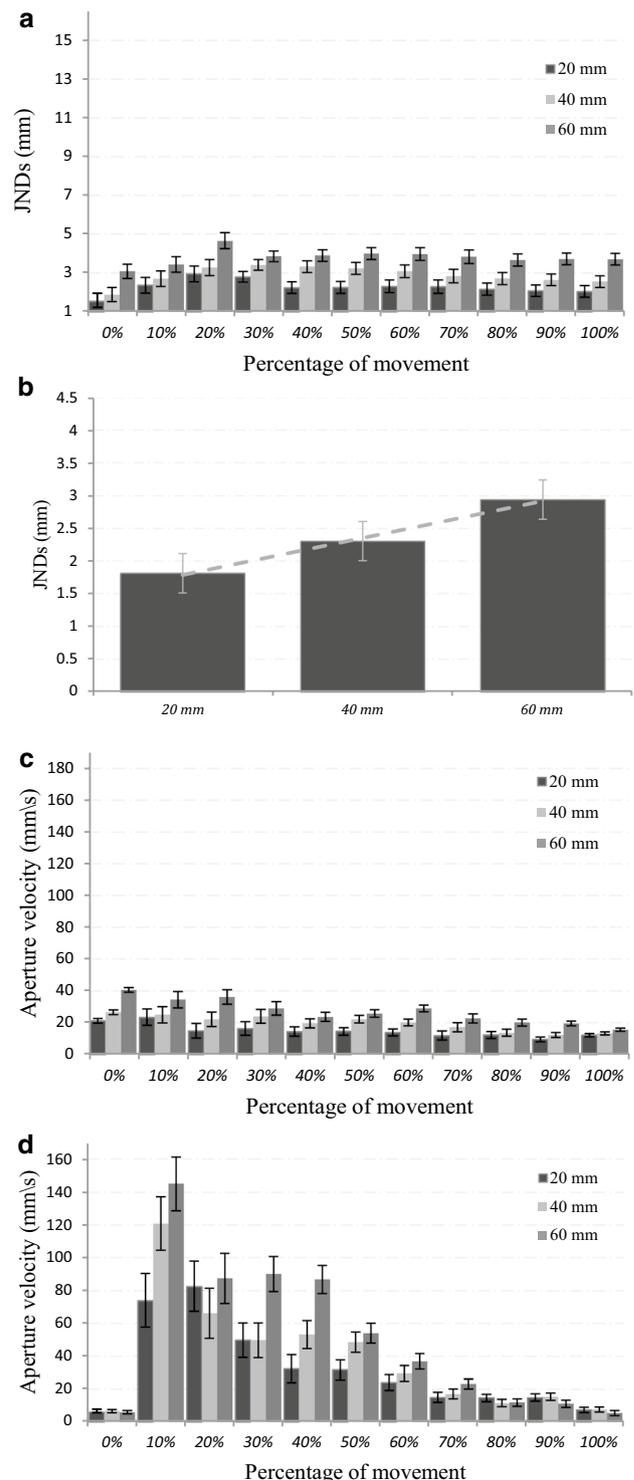
## JNDs and aperture velocities

JNDs across the normalized movement trajectory and the point of contact with the screen are presented in Fig. 3. Note that JNDs increased with object size, in line with Weber's law. A repeated-measures ANOVA of the JNDs across the movement trajectory showed significant main effects for normalized movement time [$F_{(10,90)}=3.4$, $p < 0.01$, $\eta_p^2=0.27$] and for object size [$F_{(1.2,10.8)}=21.2$, $p < 0.01$, $\eta_p^2=0.70$]. The interaction between movement and size was not significant [$F_{(20,180)}=0.6$, $p > 0.05$]. Planned comparison of the linear component of size confirmed that JNDs linearly increased with size throughout the movement [$F_{(1,9)}=33.2$, $p < 0.01$, $\eta_p^2=0.78$] (2.3, 2.9, 3.8 mm, respectively). Separate planned comparisons tests showed a significant linear pattern of JNDs in each of the normalized movement time point (see Table 2). We note that JNDs linearly increased with size even in the point of movement initiation, just when the fingers left the starting position (0%). Analysis of the MGA data did not show significant effect for size [$F_{(1,9)}=2.8$, $p > 0.05$].

An analysis conducted for the POCs data showed a similar pattern of results to the analysis of the normalized movement. There was a significant main effect for size [$F_{(2,18)}=10.7$, $p < 0.01$, $\eta_p^2=0.54$]. A planned comparison indicated that JNDs linearly increased with object size [$F_{(1,9)}=16.3$, $p < 0.01$, $\eta_p^2=0.64$], in adherence with Weber's law (Fig. 3b).

To test for possible size-related effects on velocity, we analyzed the absolute aperture velocity data in Experiment 1 (Fig. 3c), and compared it with the data obtained in a different, recent study from our lab in which we asked participants to hold their fingers pinched together prior to grasping initiations (directed to 2D objects of similar sizes, Ozana & Ganel, 2017) (Fig. 3d). As can be seen in Fig. 3, aperture velocities were considerably smaller in Experiment 1 compared to those obtained in Ozana and Ganel's (2017) study (20, 45 mm\s, respectively). Yet, in both cases, velocities increased with object size at most stages of the normalized movement.

A repeated-measures ANOVA was conducted for the aperture velocity data along the movement trajectory of Experiment 1. Significant main effects were found for normalized movement time [$F_{(10,90)}=7.5$, $p < 0.01$, $\eta_p^2=0.46$] and for object size [$F_{(1.1,10)}=12.5$, $p < 0.01$, $\eta_p^2=0.58$]. A significant interaction between normalized movement time and size [$F_{(20,180)}=1.8$, $p < 0.05$, $\eta_p^2=0.16$] was also found.



Fig. 3 JNDs across the normalized movement (a) and at the point of contact with the screen (b). Aperture velocities (c) in Experiment 1 and aperture velocities obtained in Ozana and Ganel's study (2017) (d). Aperture velocities and JNDs increased with object size, along the normalized movement trajectory. JNDs also increased with size at the point of contact with the screen. Error bars represent standard error of the mean

**Table 2** Planned comparison tests of the effects of the linear component of size on JNDs and aperture velocities for at each normalized movement time point (prior to touch)

| | Experiment 1 | | | | Experiment 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | JNDs | | Aperture velocity | | JNDs | | Aperture velocity | |
| | $F$ | $\eta_p^2$ | $F$ | $\eta_p^2$ | $F$ | $\eta_p^2$ | $F$ | $\eta_p^2$ |
| 0% | 7.2* | 0.44 | 11.1** | 0.55 | 0.5 | 0.05 | 3.7 | 0.25 |
| 10% | 14.8** | 0.62 | 2 | 0.18 | 2.3 | 0.17 | 25** | 0.69 |
| 20% | 8.1* | 0.47 | 7.7* | 0.46 | 1.6 | 0.13 | 1.4 | 0.11 |
| 30% | 13.6** | 0.6 | 7.1* | 0.44 | 0.03 | 0.003 | 27.5** | 0.71 |
| 40% | 38.6** | 0.81 | 16.5** | 0.64 | 0.1 | 0.01 | 5.4* | 0.33 |
| 50% | 47.9** | 0.84 | 8* | 0.47 | 0.03 | 0.003 | 3.3 | 0.23 |
| 60% | 46.5** | 0.83 | 11.9** | 0.57 | 0.5 | 0.04 | 1.6 | 0.12 |
| 70% | 18.2** | 0.66 | 23.1** | 0.72 | 4.6 | 0.16 | 0.05 | 0.05 |
| 80% | 11.2** | 0.55 | 9* | 0.5 | 29** | 0.72 | 0.3 | 0.02 |
| 90% | 17** | 0.65 | 11.2** | 0.55 | 16.2** | 0.59 | 0.6 | 0.05 |
| 100% | 10.4* | 0.53 | 2 | 0.18 | 15.2** | 0.58 | 0.02 | 0.002 |

*$P < 0.05$, **$P < 0.01$

Planned comparison [$F_{(1,9)}=13.8$, $p < 0.01$, $\eta_p^2 = 0.60$] of the linear component size across the movement confirmed that aperture velocities increased with size. As for the JND data, separate planned comparison tests showed a significant linear pattern along most sages of the movement (see Table 2). As expected, aperture velocities did not increase with size during POC [$F_{(1,9)}=1.1$, $p > 0.05$]. These results suggest that aperture velocity could have accounted for the pattern of scalar variability along several stages of the movement, but not during the final stage of the movement, when the fingers approached and touched the 2D object.

The results of Experiment 1 show that actions toward 2D objects adhere to Weber's law, even when the initial distance between the fingers was adjusted to correspond to the target's size. In line with the results of previous studies, in which participants were asked to hold their fingers pinched together prior to grasp (Holmes and Heath 2013; Hosang et al. 2016; Ozana and Ganel 2017, 2018), JNDs measured along different stages of the trajectory still increased with object size, obeying to Weber's law.

Yet, it is still unclear whether or not the finding of an increase in JNDs with size represents genuine adherence to Weber's law throughout the entire movement trajectory. First, although aperture velocities were significantly smaller than those obtained in typical 2D grasping tasks (see Fig. 3c, d), the manipulation we used did not completely cancel out the relation between aperture and size, and participants still opened their fingers faster to bigger targets, at most stages of the movement. As we suggested in the introduction, this increase in aperture velocity with size could lead to a decrease in precision, and therefore could potentially account for the adherence to Weber's law along different points of the normalized movement time.

In addition, the results show that JNDs increased with size even at movement onset (0%). This result may suggest that actions toward 2D objects are subjected to Weber's law throughout the entire movement. Yet, another possibility is that the design we used might be influenced by early adherence to Weber's law when participants manually adjusted the positions of their fingers to the different-sized starting points (the two dots that were presented at different distances). Notably, the findings of Experiment 1 also show that JNDs increased with size during final stages of the movement's trajectory, in which velocities did not increase with size. Although it is tempting to consider that this pattern represents genuine perceptually driven effect in 2D grasping, the entire pattern of results of the current study limits our ability to draw a conclusive inference. After all, despite the fact that aperture velocities in Experiment 1 were relatively small compared to previous studies, it could still be argued that JNDs at different stage in the movement were affected by the association between velocity and size.

In Experiment 2, we address this issue by completely reversing the relation between aperture velocity and size (Ganel et al. 2014, Experiment 1). To this end, participants were asked to keep their fingers wide open prior to initiating each grasping movement, encouraging them to close their fingers faster to smaller objects rather than to larger objects. We reasoned that if velocity mediates the pattern of scalar variability during 2D grasping, JNDs should decrease with size along the movement, and should not adhere to Weber's law even at late stages of the movement. However, if perceptual processing intrudes to 2D grasping, an increase in JNDs with size is predicted to emerge along the movement.

# Experiment 2

## Methods

### Participants

Twelve undergraduate students (3 males, average age = 23, SD = 1.1) participated in the experiment for the equivalent of 5$.

### Design and procedure

The procedure was similar to the one used in Experiment 1, but now participants were instructed to extend their fingers wide open prior to movement initiation, creating an "L" shape between their finger and thumb (Fig. 4). As in Experiment 1, less than 2% of the trials were defined as outliers (based on the same criterion) and were excluded from further analysis.

## Results

### Grip apertures and response times

The apertures between the fingers along the movement trajectory are presented in Fig. 5. Grip apertures were adjusted to the target's size. A repeated-measures ANOVA showed a significant main effect for normalized movement time [$F_{(1.6, 17.7)}$=109.9, $p$ <0.01, $\eta_p^2$=0.90]. A significant main effect for size [$F_{(2,22)}$=143.4, $p$ <0.01, $\eta_p^2$=0.92] indicated that grip apertures were adjusted to the size of the target object. Finally, a significant interaction between normalized movement time and size [$F_{(20,220)}$=26.2, $p$ <0.01, $\eta_p^2$=0.72] showed that grip apertures were scaled differently to size at
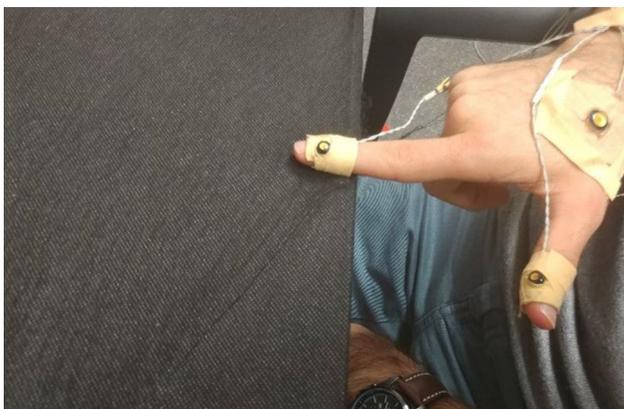


**Fig. 4** Illustration of the experimental setup used in Experiment 2. Participants were asked to extend their fingers wide open prior to initiating their movements toward the 2D target
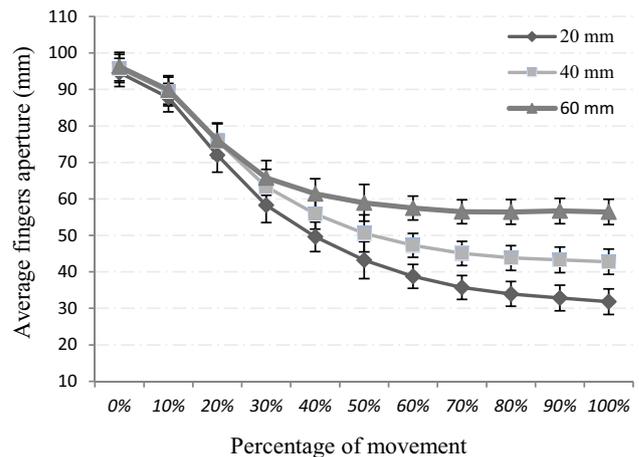


**Fig. 5** Average fingers apertures across the movement trajectory. Grip apertures were adjusted to the target's size. Error bars represent standard error of the mean

different parts of the movement. We note, that as in Experiment 1, grasping trajectories in the current experiment were different than those obtained in a corresponding 3D condition (Ganel et al., 2014, Experiment 1). Specifically, the participants in the current experiment did not reopen their fingers after reaching a minimum aperture, but rather maintained a general decrease in aperture throughout the movement. Once again, this result demonstrates the movement control of 2D objects is different than that directed to real 3D objects.

Response times for Experiment 2 are presented in Table 1. A repeated-measures ANOVA of the MT data revealed a significant main effect for size [$F_{(1.2, 13.8)}$=4.7, $p$ < 0.05, $\eta_p^2$ = 0.30]. Follow-up specific comparisons showed that while MTs were larger for the big object compared to the small and medium objects [$F_{(1,11)}$=5.4, $p$ <0.05, $\eta_p^2$=0.33], MTs did not differ between the small and the medium object [$F_{(1,11)}$=0.1, $p$ >0.05]. Unlike for MTs, analysis of the RT data did not show a significant main effect for size [$F_{(1.2, 14.2)}$=1, $p$ >0.05].

### JNDs and aperture velocities

JNDs across the movements are presented in Fig. 6. As can be seen in the figure, JNDs increased with size during the final stages of the normalized movement, and at the point of contact with the screen. A repeated-measures ANOVA of the JND data across the movement showed a significant main effect for normalized movement time [$F_{(21,23.5)}$=17.4, $p$ <0.01, $\eta_p^2$=0.61]. The effect of object size [$F_{(2,22)}$=0.1, $p$ >0.05] was not significant. However, a significant interaction between movement and the linear component of size [$F_{(1,11)}$=5, $p$ <0.05, $\eta_p^2$=0.31], indicated that the relation between JNDs and size was different at different stages of
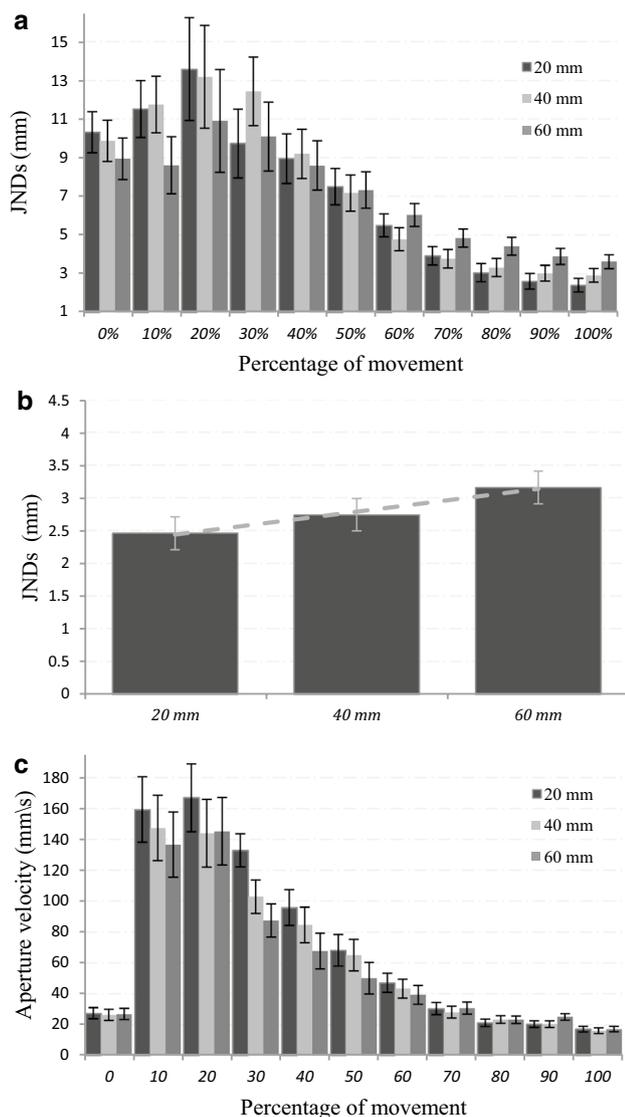
**Fig. 6** Experiment 2: JNDs across the normalized movement (**a**) and at the point of contact with the screen (**b**). **c** Aperture velocities throughout the movement prior to touch. Aperture velocities decreased with object size. More importantly, JNDs increased with size during the final stages of the movement, in adherence to Weber's law. Error bars represent standard error of the mean

the movement. The linear component of size in each normalized movement stage is described in Table 2. As can be seen in the table, JNDs increased with size during the final stages of the movement prior to touch, at 80%, 90% and 100% of the normalized movement time.

An analysis of the JNDs data during POC showed a significant main effect for size [$F_{(2,22)}$=10.7, $p$ <0.01, $\eta_p^2$=0.49]. A planned comparison showed a significant linear trend of JNDs with size [$F_{(1,11)}$=13.7, $p$ <0.01, $\eta_p^2$=0.55 (Fig. 6b). These results show that trajectories during the late

and critical stages of the movement in which the fingers approach and touch the target object adhere to Weber's law.

Absolute aperture velocities along the trajectory are presented in Fig. 5c. As expected, aperture velocities did not increase, but rather decreased with object size. A repeated-measures ANOVA test of the velocity data revealed significant main effects of normalized movement time [$F_{(1.5,17.4)}$=28.6, $p$ <0.01, $\eta_p^2$=0.72] of object size [$F_{(1.1,13.1)}$=11.4, $p$ <0.01, $\eta_p^2$=0.50] and of the interaction between movement and size [$F_{(20,220)}$=3.3,, $p$ <0.01, $\eta_p^2$=0.23]. Finally, a planned comparison of the linear component of size showed that velocities *decreased* with size at initial parts of the movement (Table 2). Such decrease in size is expected due to the experimental design of Experiment 2, in which movements were initiated when the fingers are wide open. This design encourages participants to close their fingers faster for smaller rather than for larger objects (also see Ganel et al. 2014, Experiment 1). This opposite relation between velocity and size at initial stages of the movement probably obscured possible effects of increase in JNDs with size at initial stages of the movement. Importantly however, in stages of the movement in which the pattern of opposite relation between velocities and size was not found, the results show an increase in JNDs with size, indicating adherence to Weber's law. Such adherence to Weber's law was found at the final stages of the movement in which the fingers approach to touch the 2D object and at movement completion.

The results of Experiment 2 strongly suggest that the adherence of 2D grasping to Weber's law is mediated by genuine, relatively based processing of size. While overall aperture velocities decreased with the size at earlier parts of the movement, and were unrelated to size later along the movement, JNDs increased with size during the critical stages of the movement, when the fingers are well adjusted to the perceived size of the object.

# General discussion

The current study aimed to explore whether JNDs during 2D grasping adhere to Weber's law, or alternatively, increase with size due to speed–precision tradeoff effects. The findings show that when the relation between speed and size in controlled for, movement trajectories still adhere to Weber's law. The findings also show that aperture velocity could affect the JND pattern to a limited degree, especially at initial stages of the movement. Yet this effect disappears at the final stages of the movement, when the fingers approach to touch the 2D object. We argue that this task-independent pattern of scalar variability reflects genuine adherence to Weber's law.

The results of the current study are in line with previous work, which demonstrated that the relation between aperture velocity and size does not modulate adherence to Weber's law during 3D grasping (Ganel et al. 2014). In a typical 3D grasping task, participants are asked to pinch their fingers together prior to the initiation of the grasp, which leads to an increase in aperture velocity (and JNDs) with size at early stages of the movement. Based on this pattern, it has been suggested that visually guided actions toward 3D objects adhere to Weber's law at initial parts of the movement (Heath et al. 2011, 2012). Yet, using a design similar to the one used in the current study, Ganel et al. (2014) argued against this idea and showed that even when aperture velocities were controlled for, Weber's law was still violated throughout the movement's trajectory (but see Heath and Jazi 2015). In a similar manner, the current results show that although the velocity pattern can affect JNDs at early stages of the movement, JNDs still adhered to Weber's law independently of the relation between velocity and size. Taken together, the findings suggest that the different pattern of adherence to Weber's law in 2D and 3D grasping reflects genuine modification in the way object size is computed for these tasks.

The results also show that 2D grasping movements can be subjected to unwarranted effects of speed–precision tradeoffs. In particular, actions such as 2D grasping, that do not involve grasping a 3D object, typically do not entail a "safety margin" that is usually required to firmly grasp a physical object. Therefore, the grasping profile of such movements is essentially different than the profile of movements directed to 3D, real objects. The former is characterized by an overall monotonic increase in grip aperture throughout the movement, with a relatively late point in time in which MGAs are achieved (Fukui and Inui 2013; Goodale et al. 1994; Whitwell et al. 2015). In addition, the results of Experiment 1, as well as our analysis of the 2D grasping condition in Ozana and Ganel's study (2017, Experiment 2) show that during 2D grasping, aperture velocities increase with size up until late stages of the movement, which makes the task vulnerable to unwarranted effects of velocity. These findings suggest that in atypical grasping tasks, such as in 2D and in virtual grasping, one should be cautious about making inferences from early stages of the movement trajectory as to the nature of the underling visual process (Afgin et al. 2017). In particular, kinematic characteristics of the movement such as the aperture's velocity and the point in which MGA occurs should be taken into account (Ozana et al. 2018). In the current study, the final part of the movement's trajectory effectively provided a reliable measurement for performance. At this movement stage, JNDs increased with size, in adherence to Weber's law and irrespectively of the specific experimental settings. Such adherence to Weber's law probably reflects perceptual processing that intrudes into action during 2D grasping control (Ozana and Ganel 2017).

The results of the current study should be also discussed with relevance to Smeets and Brenner's double pointing model (Smeets and Brenner 1999). According to this model, grasping an object is achieved by independent directing of the fingers (the index and thumb) to two different locations. Such a strategy does not necessarily require computing the size of the target object. This model can account for the wide range of behavioral findings that show that actions toward real objects are resistant to irrelevant perceptual information about target size and context (Smeets and Brenner 2008). However, the model cannot easily account for the dissociation between 2D and 3D grasping. Evidently, as in 3D grasping, 2D grasping entails placing the fingers at two different locations. Yet, the trajectories are effectively subjected to information about the distance between the fingers and are therefore not immune to effects of relative size and context (Freud and Ganel 2015; Holmes and Heath 2013; Hosang et al. 2016; Ozana and Ganel 2017, 2018). The results of the current study further converge with the idea that visually guided actions toward 2D (and perhaps toward 3D objects) are based on the representation of size, not only of position. Controlling for possible effects of aperture velocity, the current results provide additional evidence for perceptually driven, relative processing of size during 2D visuomotor control.

We note that the dissociation between 2D and 3D grasping extends beyond Weber's law. Recent studies showed that unlike movements directed to 3D objects, which are typically immune to task-irrelevant information (Aglioti et al. 1995; Ganel et al. 2008; Ganel and Goodale 2003), actions directed to 2D targets are affected by irrelevant information about the shape of the target object (Freud and Ganel 2015), or the context in which it is embedded (Ozana and Ganel 2018). For instance, we recently showed that unlike 3D grasping, the visual resolution during 2D grasping is affected by the magnitude of other, irrelevant stimuli presented within the same session. JNDs for a standard stimulus were, therefore, smaller within a context of narrow range size, compared to a context of wide range size (Ozana and Ganel 2018). This Range of Standards effect has been shown to modulate visual perception of size but had no effect on the kinematics of 3D grasping (Namdar et al. 2018). Taken together with the results of recent imaging studies (Freud et al. 2018; Snow et al. 2011), the accumulating evidence suggests that actions toward 2D objects and 3D objects are mediated by different representation of size, both at the functional level and at the neuroanatomical level.

The exact nature of the mechanisms that govern the dissociation between visuomotor interactions with 2D and 3D grasping still needs to be detailed. Clearly, there are

substantial differences in the visual and tactile information available in 2D and 3D grasping. Previous studies conducted in our lab suggest that providing additional visual and tactile cues to 2D objects does not necessarily lead to typical, analytical action control (Ozana et al. 2018; Ozana and Ganel 2017). For example, in a recent study, we examined grasping movements within a computerized telerobotic system that provided object-specific haptic information by inducing force to the operator's fingers upon contact with virtual objects. The results showed that grasping movements within this environment adhered to Weber's law, which suggests that tactile feedback upon contact with the target object cannot solely account for the observed dissociation between 2D and 3D grasping (Ozana et al. 2018); but see, Hosang et al. 2016). The distinction between 2D and 3D grasping could be attributed to task differences which cannot be easily controlled for, even within state-of-the-art virtual environments. It is possible, for example, that the perceived outcome of grasping a real, physical object evokes dedicated processing style, associated with elevated precision. Indeed, the complex and accurate computations of size and location which are inherent in 3D grasping are not necessarily required to efficiently interact with 2D objects. The possible role of task demands in visuomotor interactions with 2D objects should be examined in future studies.

## Conclusion

Typical grasping tasks, in which participants are asked to pinch their fingers together prior to grasp, lead to a potential confound of aperture velocity on JNDs, and are, therefore, prone to speed–precision tradeoffs effects. This confound could be critical when making inferences as to the adherence of the grasping trajectories to Weber's law. Here, we showed that the scaler variability in 2D grasping is a genuine phenomenon that reflects adherence to Weber's law rather than specific task demands. The findings suggest that visuomotor interactions with 2D objects are prone to task-irrelevant perceptual information on relative size. Taken together with the results of previous studies, our findings imply that 2D and 3D grasping rely on qualitatively different types of visual processing.

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