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RESEARCH ARTICLE

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The size of the visual size cue used for programming manipulative forces during precision grip

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Abstract We used a perturbation technique to quantify the contribution of visual size cues to the programming of target force when lifting an object. Our results indicate that the nervous system attaches a reasonable weight to visual size cues when programming the target grip force for a novel object. In a subsequent lift of the same object, however, the confidence attached to the visual size cue fell dramatically. It is not clear whether the decrease in the use of size information was accelerated by the presence of a cue conflict or whether the fall represents the normal shift towards the use of a memory-based representation for programming grip force. In a second experiment, we used the “size-weight illusion” to explore the relationship between the verbal report of an object’s weight and the programming of the grip and load force. We found that erroneous motor programming (as indexed by a number of measures) was neither necessary nor sufficient for the size-weight illusion to occur. These findings call for a re-evaluation of a previous explanation for the size-weight illusion. We suggest that the illusion arises because the cognitive system attempts to rationalise the fact that objects of apparently equal density but different size feel as if they have the same weight.

Keywords Prehension · Precision grip · Motor programming · Visual cues · Size-weight illusion · Human

Introduction

Lifting an object requires the programming of an appropriate grip (normal) and load (tangential) force. A series of elegant experiments have indicated that these forces are programmed in advance of the actual lifting movement, are adjusted in parallel and are scaled to a “target force” (Johansson and Westling 1988). Johansson and Westling (1988) have demonstrated that the scaling of the target force is based upon a representation of the weight of the object in a previous lift. In an extension of these findings, Gordon et al. (1991a) used a “size-weight illusion” to explore the use of visual size cues in the scaling of target force. The size-weight illusion describes a phenomenon in which a larger object is described as being lighter than a smaller object (that appears to be of equal density), despite both objects having an identical weight (Charpentier 1891). The experimental design used by Gordon et al. consisted of participants lifting three boxes of identical weight and surface appearance but of different size. Gordon et al. (1991a) found that an increase in box size resulted in an increase in peak grip force, grip force rate and load force rate, despite the participants reporting that the smallest box was heavier than the largest box (as predicted by the size-weight illusion). Gordon et al. (1991a) went on to suggest that a causal relationship existed between the erroneous motor programming and the verbal report of the object’s weight.

One of the disadvantages of the technique used by Gordon et al. is that it does not allow for a quantification of the confidence attached to the visual size cues in the scaling of target force. In fact, Gordon et al. (1991a, p. 481) have reported that “the effects of vision are relatively small when they are compared with the effects of changing the weight of the object by approximately the same ratio”. Unfortunately, however, the experimental paradigm employed by Gordon et al. created a situation of cue conflict where the visual size cues were in conflict with the memory representation of the object’s weight (learned on previous lifts). The creation of such a conflict may have ameliorated the confidence attached to the visual size cue. Indeed, Gordon (1994) has suggested that the relatively small effects of vision are due to interactions between the memory of an object’s weight and visual size cues (causing an amelioration of the influence of size). Gordon et al. (1991a) have argued that vision provides a strong source of feedforward information

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when lifting a novel object. Although this seems a very reasonable suggestion, the extent to which visual size cues are used when lifting a novel object remains an empirical question. One other disadvantage of the study on the size-weight illusion by Gordon et al. is that they only asked for a single weight judgement at the end of their experiment and contrasted this judgement with the mean value of their dependent variables. In this situation it is not possible to determine the extent to which erroneous motor programming accounts for how participants judged the weight of a particular object on a particular lift.

We therefore decided to study the confidence attached to the visual size cue before and after the participants experienced cue conflict (experiment 1). The results of this experiment indicated that visual size played an important role in the programming of the target grip force for a novel object, but that its contribution was greatly decreased on a subsequent lift of the same object. In a second experiment, we explored verbal judgements as a function of peak force on a trial by trial basis in the size-weight illusion. The purpose of this experiment was to discover the extent to which erroneous motor programming could account for how participants judged the weight of a particular object on a particular lift. The results indicated that the role of visual size cues is complicated in situations of cue conflict (i.e. in situations such as the size-weight illusion). Furthermore, we established that erroneous motor programming is neither necessary nor sufficient to cause the size-weight illusion.

Materials and methods

Twelve subjects participated in the experiment (six men and six women, age range 19–21 years). All of the participants were naive to the purpose of the experiment and none had previous experience of the equipment or the paradigm. The experimental apparatus consisted of a six-axis force transducer embedded in a block piece of perspex. The perspex block had a special groove on its bottom surface so that test objects could be slid on and off the block. The participants were asked to lift up the test objects by gripping the force transducer between the index finger and the thumb (see Fig. 1) and lifting the object vertically upwards until its base was at the same height as a wooden shelf mounted on the testing table (this involved the participants lifting the object by 36 cm). The subjects maintained the grip for 3–4 s, after which time they returned the object to the testing table and the experimenter changed the test object. The time between each lift was approximately 10 s. The participants were positioned in a slightly elevated position above and behind a table so that the lift mainly involved an elbow flexion. Prior to running the actual experiment, we conducted some pilot studies. In the course of running these studies, we found that it was important to ensure that the participants positioned their digits by the force transducer before the "Go" signal if we were to record a "pure" load force. If we did not take this precaution we found that participants would initiate grip force in conjunction with a negative load force, pressing the object against its base. Forssberg et al. (1991) have reported such negative load forces in children even when they have pre-positioned their digits. This strategy is presumed to allow the stabilisation of grasp and to provide additional information about the surface friction of the object to be lifted. We circumvented this strategy in our adult participants by ensuring that the digits were pre-positioned (but not actually touching the transducer) before the command to lift was given. Six of the experimental participants took part in experiment 1 and the other six took part in the 2nd experiment. We recorded the forces exerted during the lift and the subsequent 4 s (during which time the lift was maintained). Data were recorded at 100 Hz and stored in computer memory for subsequent analysis. Our two dependent variables were peak load force and peak grip force (although we also explored other measures in experiment 2).

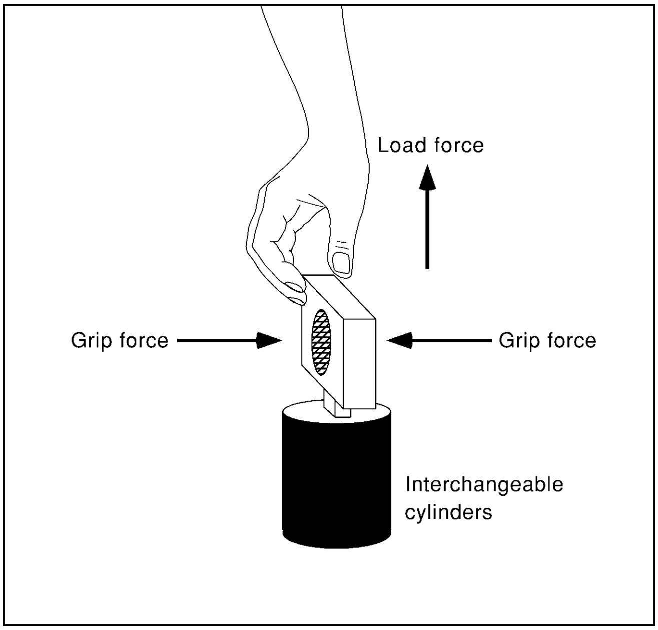

Fig. 1 Schematic of the test apparatus. A six-axis force transducer was embedded in a block piece of perspex. The Perspex block had a special groove on its bottom surface so that test objects (cylinders) could be slid on and off the block. The participants were asked to lift up the test objects by gripping the force transducer between the index finger and the thumb. The direction of the grip and load forces within the experimental procedure are indicated

Experiment 1

We used four test objects in the 1st experiment. These objects were cylinders made from opaque black plastic. The cylinders varied in diameter so that there were four different volumes equal to 107.5 cm^3, 155.8 cm^3, 213.1 cm^3 279.4 cm^3. Apart from their size, the cylinders were identical in appearance and all had a height of 5.7 cm. We will refer to these cylinders as A, B, C and D respectively. The size ratio between the cylinders was thus approximately 1:1.5:2:2.5. The weight of the cylinders was 0.25 kg (A), 0.37 kg (B), 0.25 kg (C) and 0.64 kg (D). The participants were first given practice in lifting the objects. The practice trials consisted of the participants lifting cylinder A five times, cylinder B five times and then cylinder D five times. Following the practice trials, the participants lifted the cylinders in the order A, B, D five times (i.e. a total of 15 lifts). In the next two blocks of trials, we introduced the test object C so that the participants lifted A then B then C then D (resulting in a total of 23 lifts per participant). The test object C had a white dot placed upon its surface (unlike the other test objects) to ensure that the participants realised that this was not one of the three cylinders they had previously lifted. The large number of practice trials allowed the participants to build up a good representation of the relationship between size and weight when these followed a veridical relationship for objects made from the same material. The introduction of a novel object of a different size that appeared visually to be made from the same material (but actually had a lower density than its fellow test objects) allowed us to measure the contribution of the size cue to the programming of force as outlined in the Results section.

Experiment 2

We used three test objects in the 2nd experiment and followed the basic paradigm of Gordon et al. (1991a). The objects were cylinders made from opaque black plastic. The cylinders varied in diameter so that there were three different volumes equal to 107.5 cm^3, 155.8 cm^3 and 213.1 cm^3. We will refer to these cylinders as X, Y and Z respectively. The size ratio between the cylinders was thus approximately 1:1.5:2. It should be noted that this ratio is much smaller than that used by Gordon et al. (1991a) but does reflect naturalistic differences between the size of typical hand-held objects. The weight of all three cylinders was 0.37 kg. Three participants lifted the cylinders in the order X then Y then Z for six lifts per cylinder followed by a final lift of object X (i.e. a total of 19 lifts). The order was then reversed so that the same participants lifted the cylinders in the order Z then Y then X for six lifts per cylinder followed by a final lift of object X (making a total of 38 lifts per participant). The other three participants were given the reverse order (i.e. ZYX followed by XYZ). Prior to collecting the data, the participants were given five practice lifts of the cylinder that began their trials (i.e. three participants practised on X and three practised on Z). The participants were asked to report whether the cylinder they had just lifted was heavier or lighter than the previous cylinder (i.e. a forced choice routine was used). We also asked the participants to rank the boxes in order of weight at the end of the experiment in the same manner as Gordon et al. (1991a).

Results

Experiment 1

In order to establish whether the visual size cues had an effect on the peak grip and load force, we compared the forces exerted when lifting cylinder A with those exerted when lifting cylinder C (note that both of these cylinders had the same weight but were of different size). A reliable difference was found between the grip forces (t_5=3.1, P<0.05), but no reliable differences existed between the load forces. These results indicate that the visual size cues had a reliable effect on peak grip force but not on peak load force.

We then sought to quantify the influence of the visual size cue on peak grip force. We first calculated the relationship between target volume and peak force (grip and load) by plotting the volume against the force for each participant and fitting these data using a least-squares linear regression. Figure 2 shows the mean data from across the participants. All of the participants showed a strong linear relationship between object volume and peak grip (and load) force (r^2 equal or greater than 0.97 for all participants) as previously reported (see Gordon 1994). We then quantified the contribution of size cues to force production by considering the “weight” attached to the size cue (where the weight represents the “confidence” attached by the nervous system to a particular cue). Landy et al. (1995) have developed a definition for an empirical measure of cue weight. For force production, the cue weight is the change in force expressed as a proportion of the change in that cue. The change is the difference between the force produced when lifting a target with discrepant size information and with size concordant. Thus, the ratio of difference in produced force to size discrepancy is an empirical measure of visual size weighting conforming to the definition by Landy et al. (1995). We will name this measure the “size bias ratio” (SBR). The SBR can be calculated as follows: the rela-

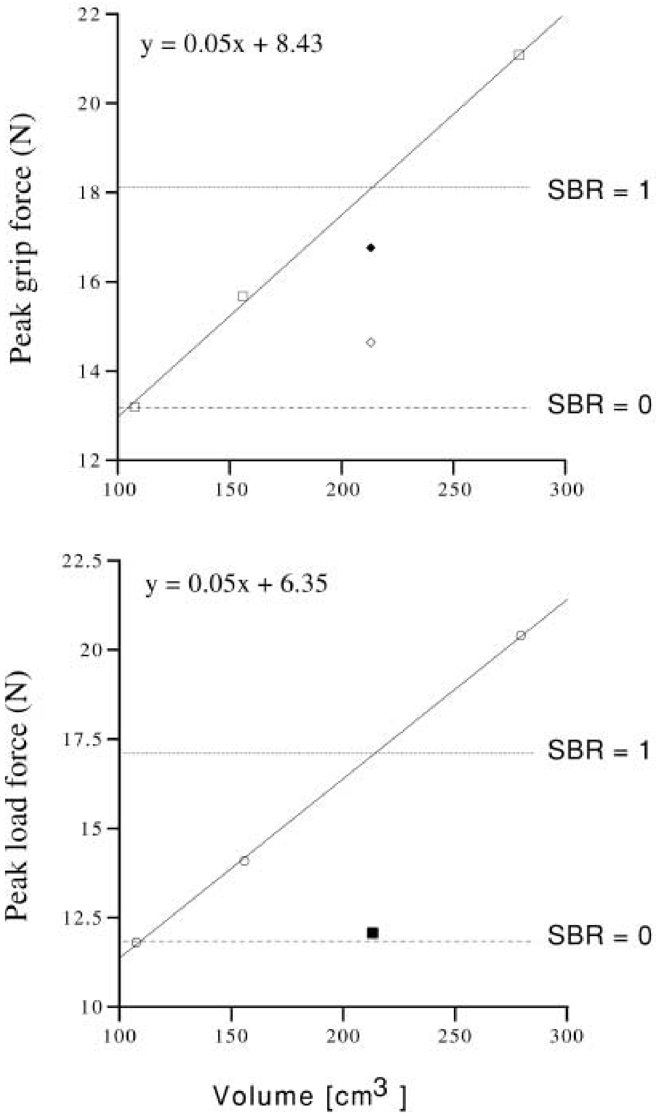

Fig. 2 The results from experiment 1. The *upper graph* shows the relationship between cylinder volume and peak grip force in newtons for the three veridical weights. The peak grip force exerted when first lifting the novel object C is shown (*filled diamond*) together with the force exerted on the second lift (*unfilled diamond*). The *lower graph* shows the relationship between cylinder volume and peak load force for the three veridical weights. The peak load force exerted when first lifting the novel object C is shown (*filled square*). In both graphs, the line through the data points shows the least-squares fit to the data (from objects A, B and D) using linear regression analysis. The equation relating peak force (y) to cylinder volume (x) determined from the linear regression analysis is provided on each graph (both r^2>0.99). The *horizontal lines* on the graph indicate the forces expected if the size bias ratios (*SBR*) were equal to 1 (*dotted line*) and zero (*dashed line*) – see text for discussion

Table 1 The mean peak grip force and peak load force in newtons together with the grip force rate and load force rate in newtons per second and the loading phase duration in ms measured for the three different box sizes (box X was the smallest and box Z was the largest). The differences across box size were not statistically reliable

	Box X		**Box Y**		**Box Z**	
	Mean	SD	Mean	SD	Mean	SD
Peak grip force (N)	10.45	5.87	11.44	6.53	11.38	6.68
Peak load force (N)	6.56	2.62	6.66	2.87	6.93	3.41
Grip force rate (N/s)	42.72	16.93	45.21	18.46	43.97	14.4
Load force rate (N/s)	33.34	11.74	39.02	17.54	35.89	14.88
Loading phase (ms)	200.00	118.99	209.17	123.46	206.67	85.94

Table 2 The data from each participant were examined by determining whether the responses on trials *k* were in the appropriate direction (assuming that visual size cues should alter the response) with respect to responses on the immediately preceding trial (*k*–1): if the object were larger on trial *k* than on *k*–1 then participants should increase the force on trial *k* relative to *k*–1 and vice versa. The table shows the percentage of verbal reports, peak grip force modulations and peak load force modulations that were in the predicted direction

Participant	Reports (% of trials)	Grip force (% of trials)	Load force (% of trials)
P 1	75	75	50
P 2	100	72	64
P 3	78	70	54
P 4	72	61	46
P 5	89	47	38
P 6	22	64	47
Group mean	72.7	65.00	49.8

tionship between size and target force is calculated from the forces produced when lifting cylinders A, B and D. The predicted force is calculated by carrying out a linear regression and using the normal relationship between size and force to calculate the force that should be produced when lifting C. The measured difference between the force exerted when lifting A and C is then calculated. This difference is divided by the difference between the force exerted when lifting A and the *predicted* force for C in order to provide the SBR.

It should be noted that the maximum weighting that can be attached to the size cue is 1 and the minimum weighting is zero. The mean (n=6) weighting attached to the size cue was found to be 0.68 (SD 0.29) for the first lift of test object C. Notably, however, the SBR fell to 0.29 (SD 0.25) the second time that object C was lifted. These results suggest that the visual size cue makes a reasonable quantitative contribution to the programming of manipulative forces when lifting a novel object. Nonetheless, the contribution of the visual size cue falls dramatically when the object is lifted for the second time. It is not clear whether the decrease in confidence attached to the visual size cue was accentuated by the presence of the cue conflict or whether the decrease represents the normal amelioration of the size contribution (with the corresponding increase in the contribution of the memory representation).

Experiment 2

No statistically reliable differences were found between the box sizes for peak grip force, peak load force, grip force rate, load force rate or loading phase duration in experiment 2 (Table 1 shows the mean data). This agrees with the report by Gordon et al. (1991a) of no difference in force production between their small and medium box (our experiment used a smaller ratio of size changes, 1:1.5:2, than Gordon et al., who had a ratio of 1:2:4). Nonetheless, we found that five of our six participants showed the size-weight illusion as indexed by their judgements at the end of the experiment. The other participant actually showed the inverse effect, whereby she reported that the smaller box was the lightest and the larger box the heaviest. It should be noted that all of the participants used a “target strategy” (where the grip and load force increase in parallel as one force rate pulse), with no participant showing a “probing strategy” (Gordon et al. 1991b). Examination of the verbal reports on a trial by trial basis revealed a complicated picture. This was examined by determining whether the responses on trials *k* were in the appropriate direction (as predicted by the size-weight illusion) with respect to responses on the immediately preceding trial (*k*–1): if the object were larger on trial *k* than on *k*–1 then participants should report that the object on trial *k* was lighter relative to *k*–1. The results of this analysis were conclusive: a majority of participants (n=5) gave verbal judgements in the appropriate direction on the majority of trials (Table 2). The participant who showed the inverse effect gave verbal judgements in the inappropriate direction on the majority of trials (Table 2).

We then explored whether the visual size cues influenced the forces exerted in a predictable manner on a trial by trial basis. If the size cues had the predicted effect, participants would increase or decrease the force exerted on a particular trial (trial *k*) relative to the previous trial (trial *k*–1) in a predictable manner (increase force when the object was larger and vice versa). This was examined by determining whether the responses on trials *k* were in the appropriate direction with respect to responses on the immediately preceding trial (*k*–1): if the object were larger on trial *k* than on *k*–1 then participants should increase the force on trial *k* relative to *k*–1. The results of this analysis were again conclusive: a majority of participants (n=5) modulated their grip force in the appropriate direction on the majority of trials (Table 2). A similar finding was found for grip force rate (73% of responses in the predicted direction). In contrast, the load force did not appear to modulate in the predicted direction on the basis of the size information (Table 2). A similar finding was found for load force rate (only 48% of responses in the predicted direction) and the duration of the loading phase (49% of responses in the predicted direction). Most importantly, it transpired that the verbal responses and the force production were not correlated – an increase or decrease in force production in the predicted direction was neither necessary nor sufficient to produce a verbal report consistent with the size-weight illusion. This can be seen by inspecting Table 2 : participant 6 showed the inverse of the size-weight illusion in her verbal reports and yet produced a modulation of her grip force in the appropriate direction on 64% of trials. Participant 5 showed a strong size-weight illusion in her verbal reports but only modulated her grip force in an appropriate direction on half of the trials. The same pattern of results was shown in individual trials – an appropriate verbal response was often accompanied by a modification of grip force in the inappropriate direction, and inappropriate verbal responses were often accompanied by modifications of grip force in the appropriate direction. These data strongly suggest that erroneous motor programming is neither necessary nor sufficient for a size-weight illusion.

The results of the 2nd experiment were broadly consistent with the results of the 1st experiment and the findings of Gordon et al. (1991a). Visual size cues had a predictable effect on grip force in a majority of individuals on a majority of trials in situations of cue conflict. Nonetheless, the effect was small and appeared to decrease with repeated lifts of the objects. The findings from the two experiments suggest that the influence of (erroneous) size information decreases with repeated lifts and that the (veridical) memory representation becomes increasingly important and, over time, allows the participants to tailor the target forces to the actual weight of the test objects. The general finding that visual size cues contribute to the forces programmed for lifting a novel object but that the learned representation of an object becomes increasingly influential is consistent with previous suggestions (Johansson and Westling 1988; Gordon et al. 1991a; Gordon 1994).

Discussion

The current experiment has provided empirical evidence in support of the idea that visual size cues play an important role in the initial programming of manipulative forces during precision grip. Furthermore, the experiment has shown that the weighting attached to visual size cues is decreased in subsequent lifts of the same object – although the observed decrease may have been accentuated by the presence of a cue conflict. Our findings thus confirm the suggestions made by Gordon and colleagues (Gordon et al. 1991a; Gordon 1994). The results of the second experiment using the size-weight illusion were not consistent with the proposal by Gordon et al. that the illusion is due (at least in part) to erroneous motor programming (Gordon et al. 1991a). Our results showed that erroneous motor programming is neither necessary nor sufficient to produce the illusion. We suggest that the size-weight illusion is primarily a cognitive phenomenon and arises because participants: (1) are aware that the objects are the same weight; and (2) attempt to rationalise (at a cognitive level) the discrepancy between their expectation that a larger object should feel heavier and the actual sensory feedback. The use of a forced-choice procedure made this quite apparent – when participants were asked to rank objects on a trial by trial basis they frequently complained that “they feel the same weight”. When forced to make a choice they would explicitly report that “the bigger one must be lighter if they feel the same weight”. Interestingly, the participant who showed the inverse effect also frequently reported that the objects felt the same but when forced to make a response stated that “if that one is larger then presumably it’s heavier than the smaller one”.

Gordon et al. (1991b) have also explored the size-weight illusion using two different-sized boxes under conditions where size information was specified by kinaesthesis and not by vision. In this situation they found that 5 out of 24 participants did not show the size-weight illusion and instead reported that the boxes were the same weight. Gordon et al. (1991b) highlighted the fact that all 5 (and none of the other 19) of these participants showed a probing strategy (where the grip and load forces increased discontinuously in multiple force steps) rather than a target strategy (where the grip and load force increase in parallel as one force rate pulse). Gordon et al. (1991b) suggested that this finding supports their conjecture that the size-weight illusion is caused by erroneous motor programming. The results are somewhat difficult to interpret at a psychophysical level (the choice of “no difference” is not normally available in a psychophysical experiment) but do not conflict with our explanation of the size-weight illusion. We suggest that the participants who used a probing strategy might have been unable to obtain reliable estimates of object weight. In the absence of reliable information, the cognitive system may not have experienced a conflict between expectation and outcome and therefore the participants were happy to report no difference (whereas the other participants attempted to rationalise reliable sensory information that conflicted with cognitive expectation).

The results of the present study suggest that care must be exercised when interpreting the results of experiments involving the size-weight illusion. Brenner and Smeets (1996) used an interesting version of the size-weight illusion in order to explore the effect of a visual illusion on force production and grasp aperture in prehension. They asked participants to move their hand from a starting position to grasp and lift a disk (three different-sized disks were used). In an elegant manipulation, Brenner and Smeets placed the disks on a background containing the Ponzo illusion. The background was randomly reversed so that the disk would either look relatively larger or smaller depending on the background direction. Brenner and Smeets reported that the illusion did not affect grip aperture but did influence the force used to lift the disk. Unfortunately, the force was not measured directly but, instead, the authors reported that the duration between the time the hand reached lowest velocity at the end of the transport phase and the point at which the disk began to move. Brenner and Smeets found that the duration decreased when the disk appeared relatively larger and, from this, they argued that a larger target force was programmed for this background configuration. The results of the current experiment make this interpretation seem unlikely as: (1) the ratio between the illusory disks was only about 1:1.1, and (2) each disk was lifted 160 times. These two factors would have resulted in a negligible influence of size cues on the mean force production over trials. We suggest that a more plausible explanation of the results is that the increased duration was due to a Fitt's law relationship between perceived target size and movement time. It is known that most minor on-line adjustments occur in the very low velocity portion of the movement trajectory at the end of the transport phase (Soechting 1984; Fisk and Goodale 1988). It seems reasonable to argue that the nervous system allowed more time for on-line modifications at the end of the movement when moving to the "small" target than when moving to the "larger" disk. With this assumption in place, it is clear that taking the point of lowest velocity as the criterion for the end of the movement would produce exactly the pattern of results reported by Brenner and Smeets (1996), despite the illusion having no effect on target force. In support of this general idea, van Donkelaar (1999) has shown that pointing movements are affected by size-contrast illusions in line with predictions made by Fitt's law.

In summary, our results have shown that visual size cues affect the programming of target force. The size cue makes a reasonable contribution to the programming of force when lifting a novel object but the weighting attached to the size cue decreases on subsequent lifts. In situations where participants lift objects that differ in size by a very large amount, it is possible to observe visual size cues influencing force production in a manner commensurate with the size-weight illusion (Gordon et al. 1991a). Our findings suggest, however, that the changes in force production are a co-occurring feature of the experimental paradigm but are neither necessary nor sufficient for the appearance of the size-weight illusion. These results suggest that caution is required when interpreting the results of experiments in which participants repeatedly lift objects in situations of cue conflict (i.e. in experiments that rely on the size-weight illusion).

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