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WORST-CASE PREDICTION STRATEGY IN FORCE PROGRAMMING WHEN VISUAL INFORMATION IS OBSTRUCTED[1,2]

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Summary.—A person's strategy for applying force while lifting an object is dependent upon visual cues. This study investigated the alteration of strategy in force programming when visual information about an object's size was obstructed at the moment of lifting. Seven subjects were instructed to use a precision grip for repeated lifts of a cube-like grip apparatus attached to a box. The grip apparatus was a special device designed to measure grip and load forces. Three different-sized plastic boxes of equal weight were pseudorandomly presented by attaching them beneath the grip apparatus to the subjects in two visual conditions. In the Full-vision condition, subjects could view the box's size prior to lifting. In the Obstructed-vision condition, a screen prevented subjects from seeing the box size prior to lifting. In the Full-vision condition, the grip force and load force used by subjects on the grip apparatus increased with box size. In contrast, the subjects in the Obstructed-vision condition used forces appropriate for the largest box regardless of box size. The present results suggest that absence of size information may cause an alteration of strategy used to determine force output in that subjects may apply a maximum force adequate for the largest box, which could be called a "worst-case" prediction strategy, i.e., when there is doubt, the most secure lift may be selected for all possible cases.

Visual information plays an important role when predicting the weight of an object in relation to force programming for grasping and lifting (Johansson & Westling, 1984; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990; Gordon, Forssberg, Johansson, & Westling, 1991a, 1991b; Kawai, MacKenzie, Ivens, & Yamamoto, 2000). When people know what they are to grasp and lift prior to lifting, they select a target strategy based on anticipatory mechanisms, in which they rely largely on visual information about the object combined with memory information from previous manipulation

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(Johansson & Westling, 1984; Gordon, *et al.*, 1991a; Johansson, 1996). Therefore, the forces applied to commonly handled objects are appropriately selected and used to lift such objects before actual weight information is available (Johansson & Westling, 1988; Gordon, Westling, Cole, & Johansson, 1993). Visual information about an object's size is also used for predicting weight to produce adequate force in an anticipatory manner when lifting. That is, grip and load forces increase with object size regardless of actual weight (Gordon, *et al.*, 1991a, 1991b; Kawai, *et al.*, 2000). However, when the handled objects are very small, the contribution of size information to the scaling of fingertip forces seems to be less important. Kawai, *et al.* (2000) found that some subjects preferentially relied on the visual information about box size for lifting force programming, but others did not. Thus, the role of visual assessment may only be true for large and heavy objects.

In daily life, people cannot always obtain visual information from an object, such as in darkened conditions, when sight is obstructed, or when an object is shrouded by packaging. As a consequence, visually determined target strategies are of limited use, and people generally switch from a target strategy to a feedback strategy to judge the force needed to lift an object. Feedback strategy, also defined as a probing strategy, is based largely on the somatosensory information acquired from the initial contact with the object (Johansson & Westling, 1984, 1988; Westling & Johansson, 1984; Gordon, *et al.*, 1991a; Johansson, Riso, Hager, & Backstrom, 1992).

The use of other strategies has been reported. One could be called a midway strategy, i.e., a force midway between that needed to lift the small object and that for the large box (Gordon & Ghez, 1987; Hening, Vicario, & Ghez, 1988; Gordon, *et al.*, 1991a). Gordon, *et al.* (1991a) randomly presented two objects of different size but equal weight to blindfolded subjects and asked them to lift the objects later after they learned their size-weight relation with repeated lifts. Consequently, grip and load forces used for lifting by subjects were intermediate between the two objects. Hening, *et al.* (1988) obtained similar results from their study of trajectory control in targeted force impulses.

In a similar experiment, Cole (1991) used three objects with different surface materials but equal weight. Subjects were asked to lift the different objects while visual cues regarding surface material were blocked. Cole (1991) found that, regardless of the surface material, subjects used maximum grip and load forces adequate for the slipperiest object (Cole, 1991). Thus, another strategy might be labeled a worst-case prediction strategy.

Thus, the selection of strategies seems to depend upon how many objects are given to subjects because Gordon, *et al.* (1991a, 1991b) used two objects, and Cole (1991) used three. However, one problem in comparing their studies is that the first varied object size and the second, the object's slipperiness. Further, there is a possibility that subjects may decrease forces when size information is not available.

This study, therefore, was an attempt to refine the findings of Gordon and other studies in relation to the alteration of strategies for force programming.

METHOD

Subjects

Seven adults with normal vision (4 women and 3 men), aged 19 to 41 years ($M = 27.9$ yr., $SD = 8.6$), served as subjects after providing informed consent. All the subjects had participated in the previous experiment (Kawai, *et al.*, 2000) and had demonstrated that they strongly relied on visual information about the box's size in their lifting-force programming. As the same apparatus used in the previous study was also used in the present study, they were familiar with the size-weight relation of each apparatus as well as the motor task needed; they had used each apparatus at least 20 times. However, they were unaware of the hypothesis being tested in the present study and were not informed of what was measured by the grip apparatus during the experiment. The present experiment was performed two days after the previous experiment.

Apparatus

The grip apparatus (30 × 30 × 30 mm, 25 g), as shown in Fig. 1, was used to measure independently the grip forces of the thumb and index finger and load force (vertical lifting force) by force transducers (KFG-02-120-C1, Kyowa, Tokyo, Japan). The grip-force measurement of the index finger was used as grip-force data in the present study. A force platform was used to measure the reaction force to detect the time of the pick-up of the object.

In addition to force data, vertical displacement data were used, as measured by an infrared light-emitting diode (LED) placed on the top surface of the grip apparatus. A three-camera OPTOTRAK system (Northern Digital Inc., Waterloo, Canada) recorded the vertical displacement of the object. The displacement and force signals from the grip apparatus and the force platform were digitized with 12-bit resolution at a frequency of 200 Hz via OPTOTRAK data acquisition unit (ODAU).

Three different-sized plastic boxes of equal weight (30 g) were pseudorandomly attached to the center of the bottom surface of the grip apparatus. The boxes were a small 10- × 10- × 60-mm box, a medium 30- × 30- × 60-mm box, and a large 60- × 60- × 60-mm box. The volume ratio among the boxes was 1:9:36. The total mass of the grip apparatus (25 g) and a given box (30 g) was 55 g. The surface material of the grip apparatus and each box was smooth black vinyl (Tye-tac, Vancouver, Canada).

Procedure

Fig. 1 is a schematic drawing of the Obstructed-vision condition. Each subject sat in a height-adjustable chair facing the experimental table. As in the previous study (Kawai, *et al.*, 2000), subjects were requested to grasp the surfaces of the grip apparatus by the pads of the thumb and index finger of the right hand, lift it vertically with a single flowing movement to a height of 50 mm above the force platform by flexing the elbow, maintain the lift for approximately 8 sec., and then replace and release the grip apparatus. Subjects repeated the lifting task in two visual conditions, the Full-vision condition and the Obstructed-vision condition. The boxes were pseudorandomly presented to the subjects in both conditions. Each subject performed 30 trials, 10 trials for each box, in each condition.

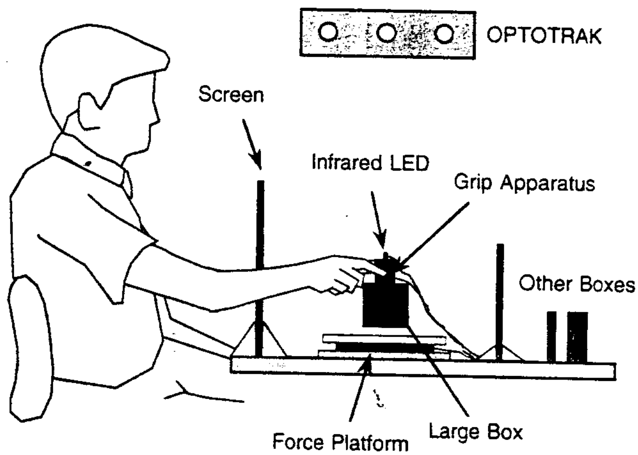

FIG. 1. Experimental arrangement. A subject is lifting a grip apparatus with a large box in the Obstructed-vision condition. The screen is removed in the Full-vision condition.

In the Obstructed-vision condition, although subjects could see the grip apparatus from over the top of screen, they could not see the box itself until the onset of lifting (see Fig. 1). The screen was adjusted for each subject to ensure that condition at the beginning. In the full-vision condition. the screen between subjects and the grip apparatus had been removed, so the subjects could clearly see the grip apparatus and box prior to lifting.

At the beginning of each condition, subjects repeated a few lifts of the grip apparatus for each box. The time period between trials was 5 to 10 sec. The presentation order of three boxes was determined in a pseudorandom manner for each subject before conducting each condition. The order of the conditions was counterbalanced across the subjects. Care was taken to not provide any noise between trials that could cue the subjects as to the size of the object on the next trial. Care was taken to minimize the effects of sweat on the pads of the thumb and index finger by keeping the laboratory cool (20°C) and wiping the hands with paper towels between trials.

Data Analysis

High frequency noise was removed from the sampled signals using a second order Butterworth filter with a cutoff frequency of 10 Hz. Time derivatives were calculated using a 5-point numerical rating scale for differentiation (Kawai, *et al.*, 2000). The grip force generated by the index finger (Grip Force), load force (Load Force), vertical displacement (Vertical Displacement), and their time derivatives (Grip Force Rate, Load Force Rate, and Velocity) were measured at their positive peaks as shown in Fig. 2.

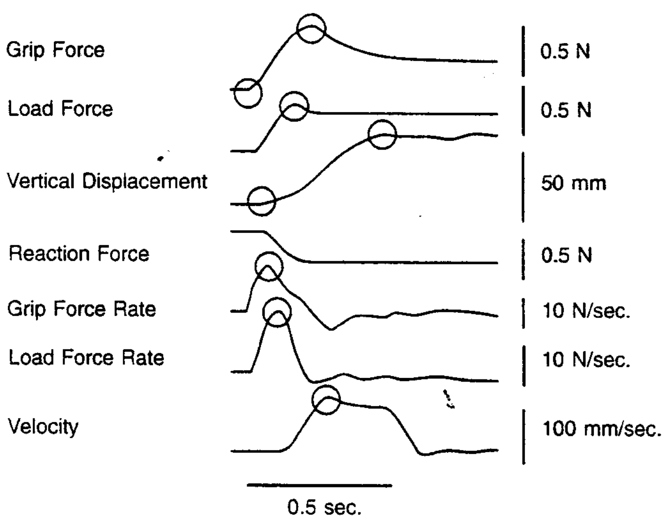

FIG. 2. Grip Force, Load Force, Vertical Displacement, Reaction Force, Grip Force Rate, Load Force Rate, and Velocity. Forces in Newtons (N).

The mean value of each parameter on the 10 trials for each box's size for each condition was computed for each subject and used to calculate the average values for all subjects. A 2 × 3 (condition × size) analysis of variance with repeated measures was performed on each dependent measure. After assessment of simple main effect, Tukey's *HSD* test (honestly significant difference test) was performed (Kiriki, 1990). Statistical significance was accepted at $p < .05$.

RESULTS

Fig. 3 illustrates the influence of size and condition on the Grip Force (upper) and Grip Force Rate (lower) during the load phase for one subject. All 10 trials for the small box (dotted line), medium box (thick line), and the large box (thin line) were synchronized at the onset of grip force and av-

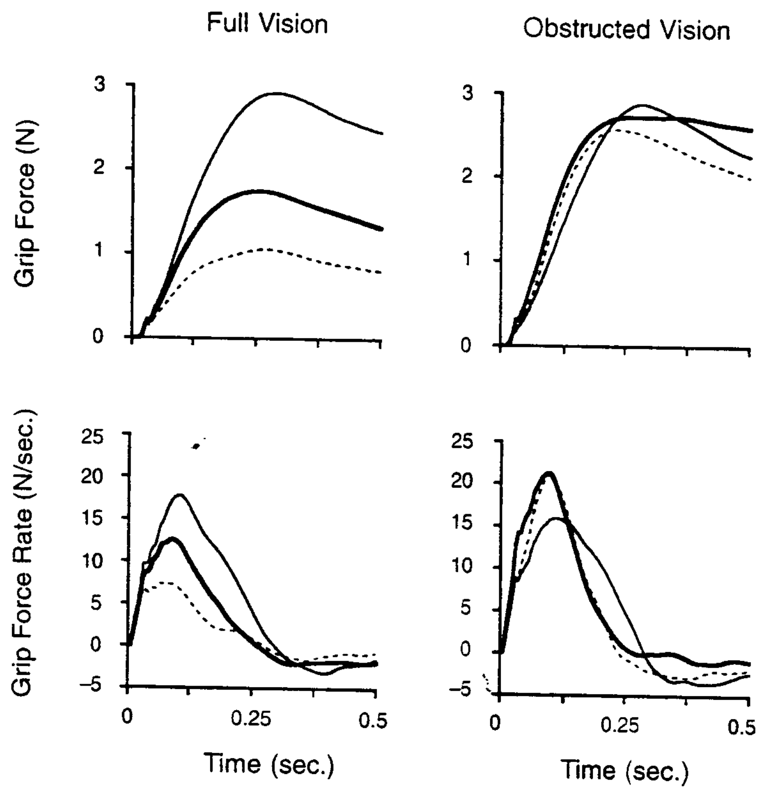

FIG. 3. Influence of box's size (Small - - - - - , Medium ——, Large ——) and visual condition on Average Grip Force (upper) and Average Grip Force Rate (lower) as a function of time for one typical subject

eraged as a function of time. As an illustration, the subject in Fig. 3 was clearly affected by size in the Full-vision condition (left column) as reported in the previous study (Kawai, *et al.*, 2000). That is, the Grip Force and Grip Force Rate increased with the box's size. The other parameters were also characterized by an increase with the box's size. On the other hand, in the Obstructed-vision condition (right column), these force profiles were almost constant regardless of the box's size. The magnitudes of these means were very similar to those exerted for the large box in the Full-vision condition.

Fig. 4 presents means and standard deviations of Peak Grip Force Rate (left) and Peak Load Force Rate (right) for all subjects as a function of box size and visual condition. The peak values increased as the box's size increased in the Full-vision condition, although these values were almost constant among the three box sizes in the Obstructed-vision condition. The other dependent measures indicated a similar tendency (see Table 1).

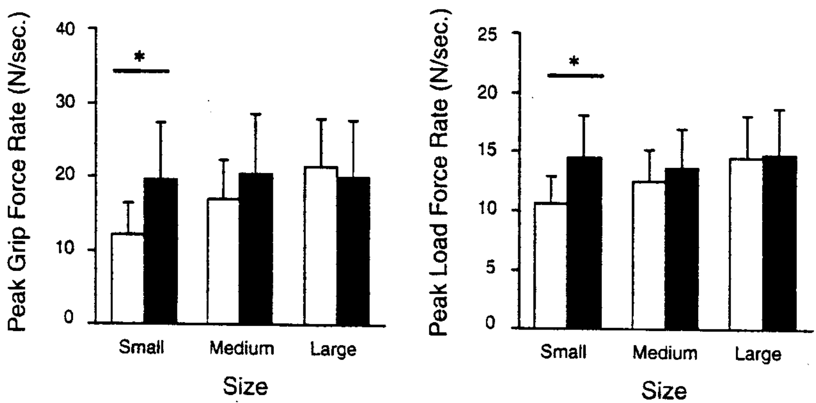

FIG. 4. Means and standard deviations of Peak Grip Force Rate (left) and Peak Load Force Rate (right) as a function of size of box and condition, (□) Full Vision; (■) Obstructed Vision. $^*p<.05$.

Table 1 presents group means and standard deviations for dependent measures as a function of size and condition. A 2 × 3 (condition × size) analysis of variance with repeated measures indicated that main effects for condition were significant on Peak Grip Force ($F_{1,6}=8.86$, $p<.05$) and Peak Load Force ($F_{1,6}=10.81$, $p<.05$), Peak Velocity ($F_{1,6}=12.65$, $p<.05$). Main effects for size were significant on Peak Grip Force ($F_{2,12}=11.30$, $p<.01$), Peak Load Force ($F_{2,12}=14.70$, $p<.001$), Peak Grip Force Rate ($F_{2,12}=25.49$, $p<.001$), Peak Load Force Rate ($F_{2,12}=24.71$, $p<.001$), and Peak Velocity ($F_{2,12}=18.76$, $p<.001$). There were significant interactions between condition and size with regard to effects on Peak Grip Force ($F_{2,12}=10.50$, $p<.01$), Peak Load Force ($F_{2,12}=21.67$, $p<.001$), Peak Grip Force Rate ($F_{2,12}=16.11$, $p<.001$), Peak Load Force Rate ($F_{2,12}=7.20$, $p<.01$), and Peak Velocity ($F_{2,12}=16.29$, $p<.001$). The significant interactions indicate that the effects of perceived size on the grip and load forces were different between the two conditions.

Simple main effects of condition for Peak Grip Force were significant both for the small box ($F_{1,18}=22.68$, $p<.01$) and for the medium box ($F_{1,18}=5.82$, $p<.05$) and only for the small box for Peak Load Force ($F_{1,18}=38.54$, $p<.01$), Peak Grip Force Rate ($F_{1,18}=14.44$, $p<.01$), Peak Load Force Rate

TABLE 1

Means and Standard Deviations of Dependent Measures as a Function of Size of Box For Full-vision and Obstructed-vision Conditions

Condition		Measure				
		Peak Grip Force, N	Peak Load Force, N	Peak Grip Force Rate, N/sec.	Peak Load Force Rate, N/sec.	Peak Velocity, mm/sec.
Full-vision						
Small	*M*	1.17[a,b]	0.67[a,b]	12.23[a,b]	10.45[a,b]	85.30[a,b]
	SD	0.32	0.05	4.71	2.62	26.81
Medium	*M*	1.64[b]	0.72	17.03[b]	12.32[b]	99.84[b]
	SD	0.58	0.04	5.92	3.09	28.75
Large	*M*	2.17	0.74	21.37	14.35	106.03
	SD	0.94	0.02	7.27	3.91	28.77
Obstructed-vision						
Small	*M*	2.07[c]	0.74[c]	19.64[c]	14.33[c]	105.35[c]
	SD	0.88	0.02	8.29	3.92	28.66
Medium	*M*	2.09[c]	0.74	20.37	13.54	104.26
	SD	0.92	0.02	8.78	3.58	27.85
Large	*M*	2.11	0.74	20.02	14.68	105.01
	SD	0.90	0.01	8.22	4.16	28.37

[a]Significantly different from a medium box in Full-vision condition ($p<.05$). [b]Significantly different from a large box in Full-vision condition ($p<.05$). [c]Significantly different from the same-sized box in Full-vision condition ($p<.05$).

($F_{1,18}=9.35$, $p<.01$), and Peak Velocity ($F_{1,18}=41.45$, $p<.01$). There was also a significant simple main effect of size in the Full-vision condition for Peak Grip Force ($F_{2,24}=21.79$, $p<.01$), Peak Load Force ($F_{2,24}=35.50$, $p<.01$), Peak Grip Force Rate ($F_{2,24}=40.01$, $p<.01$), Peak Load Force Rate ($F_{2,24}=22.66$, $p<.01$), and Peak Velocity ($F_{2,24}=34.67$, $p<.01$), but no significant difference in the Obstructed-vision condition. The results of Tukey's honestly significant difference test are shown in Table 1 ($p<.05$).

Discussion

The present results in the Obstructed-vision condition support a worst-case prediction strategy as observed in the experiment by Cole (1991) rather than a default or midway prediction strategy. That is, the forces applied to three boxes were scaled to the largest box when size information was not available. This suggests that the subjects had programmed a force adequate to lift the largest box regardless of box's size.

Johansson and Westling (1984) found that, when manipulating an object, a person adds a slightly increased but not extreme force to the minimal grip force necessary for holding it. This extra force was defined as a safety margin and was thought to have an important function in lifting and holding tasks. That is, the safety margin is needed not only to prevent accidental slipping but also to avoid muscle fatigue or destruction of an object by excessive grip force (Johansson, 1996).

The safety margin increases with increasing possibility of slipping, as objects become slippery due to sweating on the pads of the fingers (Johansson & Westling, 1988). After subjects encountered unexpectedly heavier or more slippery objects, the safety margin was also set at higher levels during the following few trials than for the normal conditions wherein the same objects are repeatedly given to the subjects (Kawai, Kinoshita, & Ikuta, 1994; Kawai, Kinoshita, Ikuta, & Yamamoto, 1995). The safety margin tends to increase during periods of general activity such as rubbing of the skin on the face with the free hand due to localized itching (Westling & Johansson, 1984). The present results suggest that subjects may provide the same safety margin for the small and medium boxes as for the large box just in case of encountering the large box.

The worst-case prediction strategy seems more effective and practical in force programming because the subject can surely lift any of the possible objects with only one attempt. However, using a midway prediction strategy, subjects may not lift the heavier or more slippery object because their grip and load forces were insufficient. The worst-case prediction strategy would become useful in cases where there are more than three objects, so the person would be certain in lifting the object, i.e., prepared for the largest, most slippery, or heaviest object. On the other hand such a strategy may include some risks in conditions where the object may break, fluid may be spilled, or injuries may occur by using the extra forces.

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