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RESEARCH ARTICLE

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Adjusting reach to lift movements to sudden visible changes in target's weight

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Abstract People can adjust their reach-to-grasp movements online to sudden changes in the spatial properties of a target. We investigated whether they can also do this when a non-spatial property, weight, suddenly changes. Guiding your movement by using visual cues about an object's weight depends heavily on experience and is expected to be processed by the (slow) ventral stream rather than the (fast) 'online control' dorsal stream. In the first experiment, participants reached out and lifted an object with an expected or an unexpected weight. As predicted, there was an effect of expected weight on the time between the end of the reaching phase and the object's lift-off. In the second experiment, the object sometimes visibly changed weight after the participants had started their movement. The lifting time did not depend on whether the object had changed weight. Thus, participants can make online adjustments to a visually indicated change in weight. These results are interpreted as being contrary to existing theories of online control.

Keywords Visuomotor control · Online control · Prehension · Perturbation · Weight

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Introduction

In everyday life, we naturally use expectations about an object's weight to program grasping and lifting forces. When these expectations are not met, the time until lift-off and the lifting speed are affected (Gordon et al. 1991a; Johansson and Westling 1988). For instance, this occurs when lifting an empty container that one expected to be full.

In estimating an object's weight for the purposes of programming forces, visual cues in combination with memory play an important role. Visual cues for the estimation of weight include: size (Gordon et al. 1991a, b, c; Mon-Williams and Murray 2000; Westwood et al. 2000); illusory size (Brenner and Smeets 1996; Jackson and Shaw 2000); color (Cole and Rotella 2002) and object identity (Gordon et al. 1993). Here, we investigated the as yet unexplored question of whether a sudden visually perceived change in object weight can be used to adjust reach to lift movements online.

Many studies show that for goal-directed movements people are remarkably adept at making rapid online adjustments to sudden changes in the spatial properties of the target, such as its position (Brenner and Smeets 1997; Desmurget et al. 1996; Prablanc and Martin 1992), size (Castiello et al. 1993), orientation (Desmurget et al. 1996) and speed (Brenner et al. 1998). In these studies, the target property was unexpectedly changed after the hand had started to move. Typically, the hand movement can be seen to adapt to the perturbation 100–200 ms after the change.

Although adjusting to changes in a target's spatial properties seems to be unproblematic, it is questionable whether people can adjust as easily to a non-spatial change, such as a (visually indicated) change in weight. Arguably, a target's spatial properties are more likely to change in the world than non-spatial properties, and thus the ability to adjust to the former may be more important for the organism than the ability to adjust to the latter. Moreover, adjusting to a change in a non-spatial property such as a visible change in weight is complicated by the involvement of learning and memory. Specifically, one cannot rely only on low-level visual features, but rather one must relate the visual appearance of the object to a remembered, accompanying weight. Thus, the process of perceiving and responding to such changes may be too complicated and slow to make online adjustment possible.

With respect to current notions regarding the neural bases of the processing of certain objects' characteristics for the purposes of online control, several authors have suggested that quick online adjustments to sudden changes in weight are not possible (Glover 2004; Goodale 1998; Milner and Goodale 1993). These authors argue that the dorsal (occipitoparietal) stream is responsible for online adjustments and does not have access to visual cues regarding a target's weight. Milner and Goodale (1993) and Goodale (1998) propose that using visual cues to determine weight is a ventral (occipitotemporal) stream process which makes this information not readily available to the more or less independent dorsal stream subserving fast online corrections. Similarly, Glover (2004) argues that the dorsal stream uses only spatial information, with weight being classified as non-spatial because the calculation of weight depends on an identification of its material makeup and density as well as size. Regarding neural processing time, Rossetti et al. (2000) review evidence indicating that the dorsal stream processes visual information quickly whereas the ventral stream is relatively slow. Thus, visual cues for weight may not be processed fast enough in order for them to be useful in adjusting movements.

We here investigated directly whether people can adjust their movement plan to sudden changes in weight. We asked our participants to reach out, grasp and lift an object that visibly changed weight after the participants had started their movement in 20% of the trials. The grasped portion of the object always remained the same. The movements of the hand and the cylinder were recorded. Following Brenner and Smeets (1996), we took the time between the end of the reaching movement and the start of the lift as our main dependent variable ('lifting time'). This reflects the time that the grasp- and lift forces are accumulating. If one plans to lift a light object which turns out to be heavy, time is needed to increase the grasp- and lift force before the object will actually move, resulting in a longer lifting time. Conversely, if one plans to lift a heavy object that turns out to be light, the programmed force will be above that required, and the object will lift off quickly, resulting in a shorter lifting time (Johansson and Westling 1988). This rationale as used by Brenner and Smeets (1996) was verified by Jackson and Shaw (2000) who used force meters.

In the first (baseline) experiment, participants were not allowed perceptual cues as to the weight of the object. Rather they were encouraged to expect a certain weight because the object weighed the same (light or heavy) in 80% of the trials. We compared the lifting time for lifting a light object that was presented in a block of light objects (so that the forces were programmed appropriately) to the lifting time for lifting a light object that was presented in a block of heavy objects (so that the forces programmed were initially too weak). Similarly, we compared the lifting time for lifting a heavy object that was presented in a block of heavy objects to the lifting time for lifting a heavy object that was presented in a block of light objects. This baseline effect of programming the wrong forces was compared with the effect of a sudden, visually perceived change in weight in the second (perturbed weight) experiment. If people cannot adjust to a sudden perceived change in weight, we would expect a similar effect of the change on lifting time as was observed for an unexpected weight in the baseline experiment. However, if people adjust for a sudden change in weight, we would expect no difference in lifting time for objects that changed weight and objects that did not change weight. Our core results are that lifting time was affected by expected weight in the first experiment, whereas there was no effect of weight change on lifting time in the second experiment. This indicates that subjects adjusted online to a visually indicated change in weight.

Experiment 1: baseline

Materials and methods

Participants

Twelve right-handed volunteers from Royal Holloway University of London (11 females, 1 males; mean age 23 years) participated. All had normal or corrected-to-normal vision and were naïve as to the purpose of the experiment. All subjects gave informed consent to participate in the study. The experimental procedures were approved by the Institutional Review Board at Royal Holloway and were in accordance with the Declaration of Helsinki.

Apparatus

Figure 1a shows the target object. It consisted of a 15-cm-long plastic cylinder with a diameter of 2 cm, and two 5-cm-long leaden halves of a cylinder, with a diameter of 3 cm. The plastic cylinder, and each one of the halves, weighed 100 g. The cylinder stood upright on a pin on the surface to ensure that it was always in exactly the same position at the start of the trial. The two halves were placed in small mechanical carriers which could attach or detach the halves to the inner cylinder by means of pins on the halves and holes in the inner cylinder. When the halves were attached to the cylinder, the object was heavy (300 g). When they were detached, the object was light (100 g). The halves could be automatically detached or attached in between trials in order to set the object in the proper configuration for the next trial. The start button was 7.0 by 10.5 cm and its center was located 34 cm away from the target object.

For Experiment 1, a screen was placed in front of the lower part of the cylinder (see Fig. 1b). Thus, the participants could not see whether the halves were attached to the cylinder. To prevent the participants from using the noise caused by the attachment or detachment of the halves to the cylinder, they wore earphones through which was played music, covered with another set of soundproof earphones. To prevent the participants from seeing the upper part of the cylinder move when the halves were attached or detached, they wore PLATO shutter spectacles that were closed in between trials.

We marked the participant's thumb, index finger and wrist, as well as the central cylinder with reflecting tape and measured their movements with the ELITE system. We used four cameras and measured at 100 Hz. Details of this system are presented elsewhere (Castiello 1996).

Design

Every participant performed one block of 50 trials in which the target was most often light (40 light trials, 10 heavy trials) and one block in which the target was most often heavy (40 heavy trials, 10 light trials), resulting in a total of 100 trials for each participant. Within each block, the trials were presented in random order. Half of the participants performed the heavy block first, the other half performed the light block first.

Procedure

Each trial began with the shutter spectacles closed and the hand on the start button. The opening of the shutter spectacles was the signal for participants to reach out, grasp and lift the cylinder about 10 cm above its resting position using the index finger and thumb. Following each lift, the experimenter put the cylinder back in the correct position. Prior to each block, the participants were given 10 practice trials in which the same proportion of heavy and light objects were presented as in the subsequent experimental block.

Analysis

For each trial, we computed several variables (illustrated for a sample trial in Fig. 2). The reach time was the time that the subject needed to transport the hand to the object. It was defined as the time between the moment that the velocity of the wrist first exceeded 5 cm/s and the moment that the velocity of the finger dropped below a velocity threshold; the latter was computed as 5 cm/s above the finger's minimum velocity occurring after the first velocity peak was reached. The lifting time was the time between the end of the reaching movement and the moment that the object was lifted. The latter was defined by the moment that the cylinder's upward speed exceeded a threshold of 5 cm/s. Finally, we determined the maximal lifting speed, which is the maximal velocity of the cylinder in the upward direction. We expected that this variable could also show an effect of inappropriate planning, by being lower if one planned to lift a light weight that turned out to be heavy, and being higher for the reverse case (as one seems to experience in lifting a container that one expected to be full but that turned out to be empty).

We obtained a quantitative measure of the effect of programming for the wrong weight in the baseline experiment by subtracting the lifting time for lifting a light object in a heavy block (short lifting time expected) from the lifting time for lifting a light object in a light block

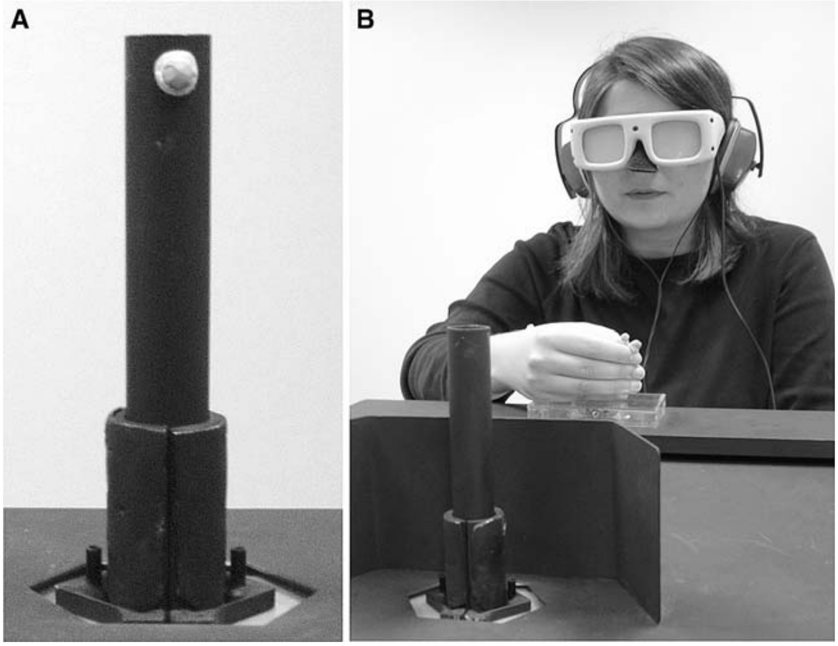

Fig. 1 Pictures of the target object (**a**) and the complete setup (**b**) as used in Experiment 1. For Experiment 2, the setup was identical except for the removal of the occluding screen, the shutter glasses and the earphones

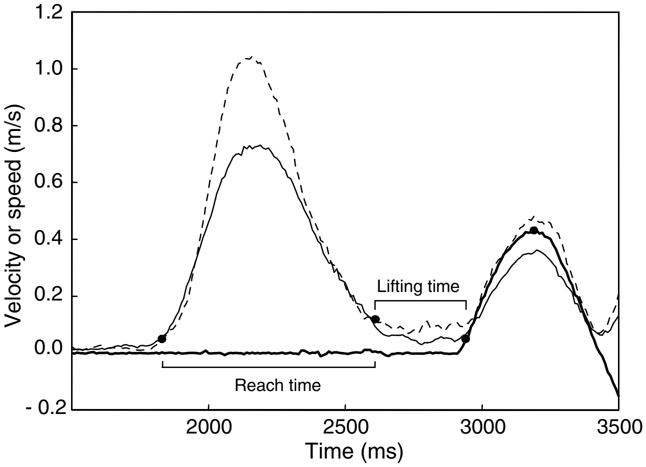

Fig. 2 Velocity of the wrist (*thin line*), velocity of the finger (*dashed line*) and upward speed of the cylinder (*bold line*) over time for one trial. The *dots* mark from *left* to *right* the start of the reaching movement, the end of the reaching movement, the start of the lift and the maximum cylinder speed

(normal lifting time expected). Similarly, we subtracted the lifting time for lifting a heavy object in a heavy block (normal lifting time expected) from the lifting time for lifting a heavy object in a light block (long lifting time expected). These programming errors were computed for each subject separately.

We conducted repeated measures ANOVAs on reach time, lifting time and maximum lifting speed with lifted weight (100 and 300 g) and block (100 and 300 g) as within-subjects factors. We took 0.05 as our level of significance; all P values <0.10 are mentioned.

Results and discussion

We discarded 231 of the total of 1,200 trials because of technical problems. Of the 231 discarded trials, 49 were trials in which an unexpected weight was presented.

Figure 3 (left) shows the reach time, lifting time and maximum lifting speed as a function of lifted weight and block. There were no effects of the independent variables on reach time. The lifting time was affected both by lifted weight ($F_{(1,11)}=16.72$, $P<0.01$) and block ($F_{(1,11)}=7.33$, $P=0.02$). The lifting time was longer when heavy objects were lifted than light objects (mean difference of 41 ms) and it was longer in the light block compared to the heavy block (mean difference of 29 ms). This means that when the object was light, the lifting time was shorter if the object was presented in a heavy block compared to if it had been presented in a light block. When the object was heavy, the lifting time was longer if the object was presented in a light block compared to if it had been presented in a heavy block. This led to an average programming error of 28 ms. The maximum cylinder speed was only affected by lifted weight ($F_{(1,11)}=43.70$, $P<0.01$), with the speed being on average 0.60 cm/s faster if the object was light than if it was heavy.

Experiment 2: perturbed weight

Materials and methods

Participant

Twelve new right-handed volunteers from Royal Holloway University of London (9 females, 3 males; mean age 22 years) participated in Experiment 2. Two of them were authors on this paper; the others were naïve to the purpose of the experiment. All had normal or corrected-to-normal vision. All subjects gave informed consent to participate in the study. The experimental procedures were approved by the Institutional Review Board at Royal Holloway and were in accordance with the Declaration of Helsinki.

Apparatus

The same apparatus was used as in Experiment 1 except for some modifications. The screen blocking the view of the bottom portion of the target was no longer present and the earphones and shutter glasses were not worn. In this way, participants had perceptual cues available about the weight of the object. As in Experiment 1, the leaden halves could be detached or attached in between trials in order to set the object in the proper configuration for the next trial, but now the halves could also be attached or detached during a trial, after the participants had left the start button. To measure when the halves started moving, we attached a marker to the index finger of one of the authors (IG) and a marker on one of the halves. IG moved her finger as quickly as possible upwards away from the start button. This revealed that the halves started to move about 190 ms after the finger started to move. However, when IG performed a normal reach to lift movement from the start button towards the cylinder, the halves were found to move only about 470 ms after the hand had started to move (where the start of the hand's movement was defined as described in the Analysis section of this study). This is possible because parts of the hand can start to move before the start button has been released completely. Thus, the exact time that the cylinder started to change weight relative to the start of the hand's movement was variable and depended on the exact movement of the participant.

Design

In this experiment, the lifted object could be heavy or light, and its initial weight could be heavy or light. We presented 40 trials with light objects that did not change weight, 40 trials with heavy objects that did not change weight, 10 trials in which the object changed from light to heavy and 10 trials in which the object changed from heavy to light. This resulted in 100 trials for each participant, presented in random order.

Procedure

Because the earphones and shutter glasses were not worn in this experiment, a tone now served as the signal for the subject to reach out and lift the cylinder. Apart from these differences, the procedure was identical to that used in Experiment 1.

Analysis

As in Experiment 1, we determined the reach time, the lifting time and the maximal lifting speed for each trial. Analogous to the programming errors as computed in Experiment 1, we computed 'adjustment errors' for each subject in Experiment 2. This was done by subtracting the lifting time for lifting a light object that had been initially heavy (a short lifting time is expected if participants do not adjust for the change) from the lifting time for lifting a light object that was also light before (normal lifting time expected), and by subtracting the lifting time for lifting a heavy object that was also heavy before (normal lifting time expected) from the lifting time for lifting a heavy object that had been initially light (a long lifting time is expected if participants do not adjust for the change). We conducted repeated measures ANOVAs on reach time, lifting time and maximum lifting speed with lifted weight (100 and 300 g) and initial weight (100 and 300 g) as factors.

If subjects in Experiment 2 could adjust their motor plan to the change in weight, the programming error observed in Experiment 1 should be higher than the adjustment error in Experiment 2. We tested this hypothesis using an independent samples *t* test.

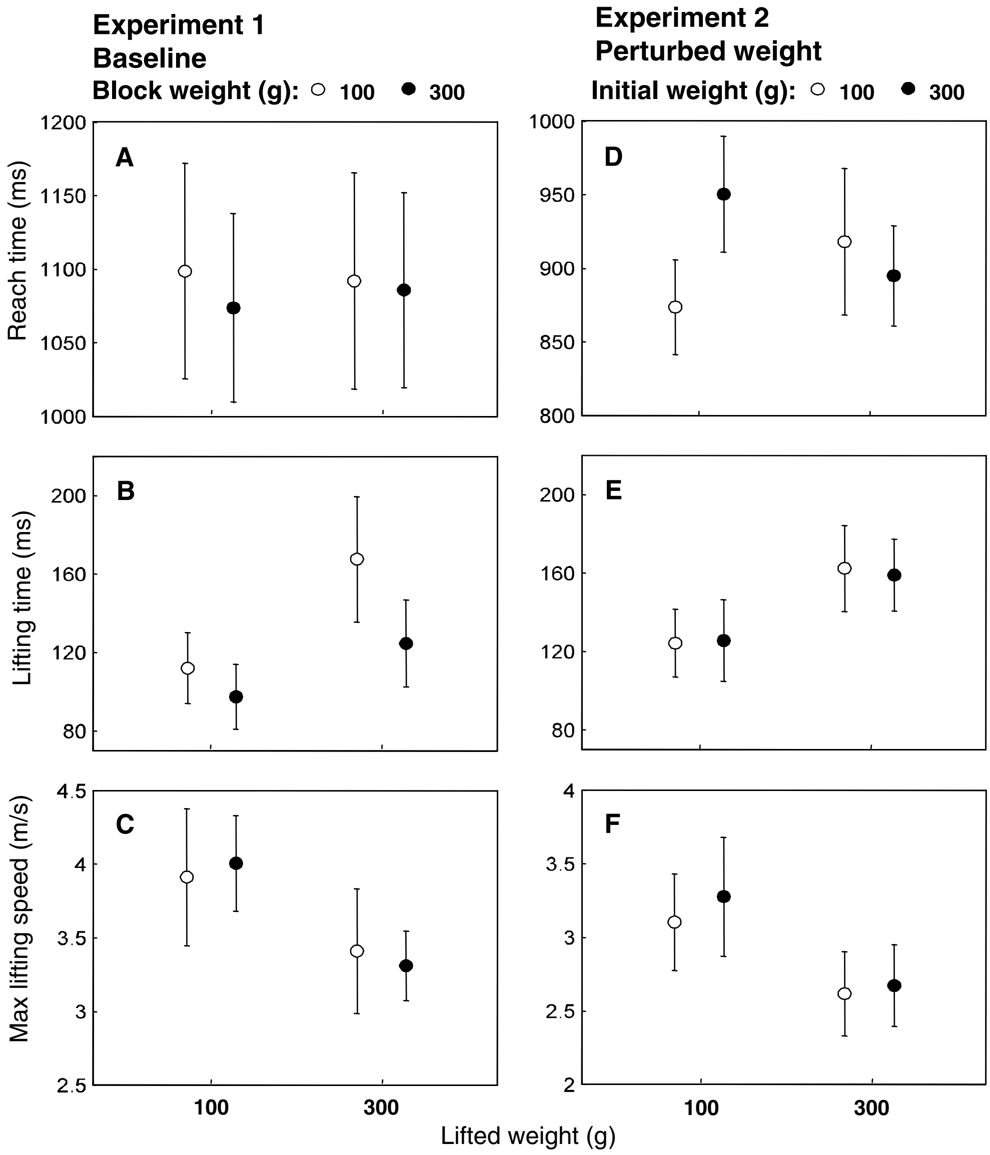

Fig. 3 Reach time (**a**, **d**), lifting time (**b**, **e**) and maximum lifting speed (**c**, **f**) plotted as a function of lifted weight and block (Experiment 1, *graphs* on the *left*) or initial weight (Experiment 2, *graphs* on the *right*). The *error bars* represent standard errors between subjects

Results and discussion

We discarded 96 of 1,200 trials due to technical problems. Of the 96 discarded trials, 18 were trials in which the weight had changed.

Figure 3 (right) shows the reach time, lifting time and maximum lifting speed as a function of lifted weight and initial weight. The effect of initial weight on reach time almost reached significance ($F_{(1,11)}=4.77$, $P=0.051$), but more importantly, there was an interaction between lifted weight and initial weight ($F_{(1,11)}=11.27$, $P<0.01$). This interaction indicated that reach time was longer for trials in which the object changed weight compared to trials in which it had not changed weight (mean difference of 50 ms). As in Experiment 1, lifting time was longer for the heavy weight compared to the light weight (mean difference of 36 ms, $F_{(1,11)}=24.92$, $P<0.01$). However, there was no effect of initial weight ($F_{(1,11)}=0.08$, $P=0.79$). This was reflected by the low average adjustment error of 1 ms. As in Experiment 1, the maximum cylinder speed was only affected by lifted weight ($F_{(1,11)}=18.26$, $P<0.01$), with the speed being on average 0.55 cm/s faster if the object was light than if it was heavy.

A one sample *t* test indicated that the adjustment error was not significantly different from 0 ($t_{23}=0.18$, $P=0.86$); that is, participants seemed to have adjusted their motor plan precisely to the change in weight. As described above, the reach time was longer for trials in which the weight changed compared to the ones in which weight remained constant. If the increase in reach time was used for adjusting the movement, we would expect a greater adjustment if the increase in reach time for changed objects was large compared to when it was small, for individual subjects. To investigate this, we performed a regression analysis on the adjustment error on the one hand and the increase in reach time for the changed object relative to the unchanged object on the other hand for each participant and each final weight. Figure 4a shows that there was no negative correlation: participants who took more time to reach for the changed object compared to the unchanged object did not adjust their motor plan more precisely ($r^2=0.16$, $F_{(1,22)}=0.36$, $P=0.55$). Figure 4b shows that the overall reach time did not correlate negatively with adjustment error either: slower participants did not adjust their motor plan more precisely than fast participants ($r^2=0.18$, $F_{(1,22)}=0.39$, $P=0.54$).

The longer reach time for trials in which the weight changed was the result of a longer deceleration phase as indicated by additional repeated measures ANOVAs. The acceleration phase of the movement (times to peak velocity) was not affected by initial weight and final weight, but for the deceleration phase (times between peak velocity and the end of the reaching movement) there was the expected interaction between initial weight and final weight ($F_{(1,11)}=5.82$, $P=0.03$). However, the lack of effect of change on the acceleration phase is not surprising considering that the object changed around 470 ms after the participant started to move and the average time of peak velocity was 404 ms.

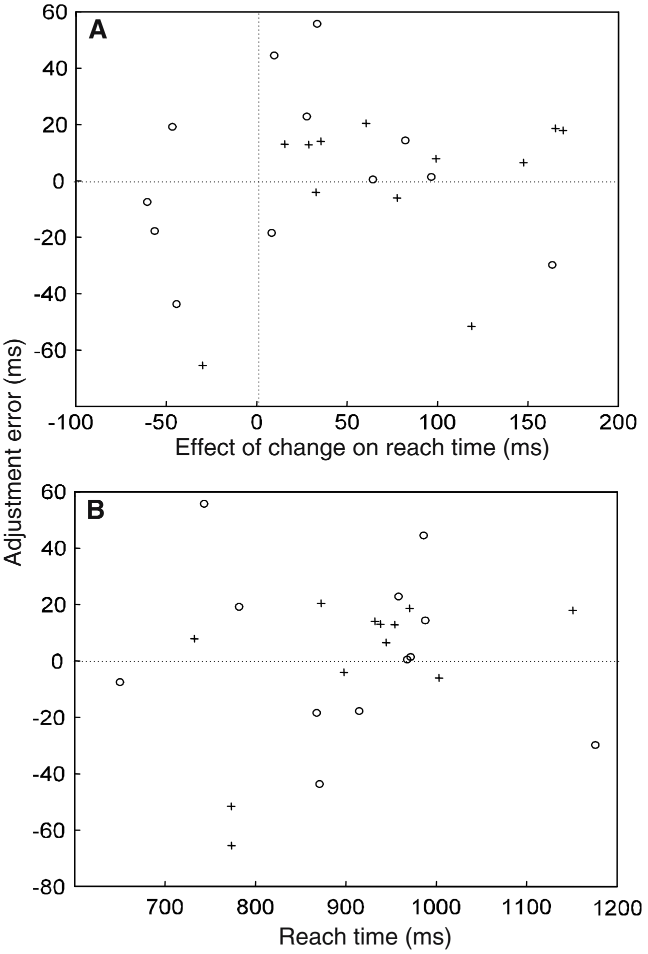

Fig. 4 Experiment 2: adjustment error as a function of the effect of weight change on reach time (**a**) and as a function of reach time (**b**). (A positive value indicating a longer reach time for changed than unchanged objects). Each *cross* represents one subject in the light lifted weight conditions, each *dot* represents one subject in the heavy lifted weight conditions

Comparing the programming error to the adjustment error

An independent sample *t* test indicated that the adjustment error as found in Experiment 2 was significantly lower than the programming error as measured in the Experiment 1 ($t_{46}=-2.18$, $P=0.03$).

General discussion

In the present study, we investigated whether people can adjust their movement online to a sudden visible change in weight. We demonstrated an effect of programming grip and lift forces for an inappropriate weight on the time between the end of the reaching phase and the time to lift-off. Such an effect was absent when the object had suddenly and visibly changed weight. This suggests that an online adjustment to a change in weight occurred.

In Experiment 1, participants were encouraged to expect a certain weight by presenting it in 80% of the trials. A relatively short lifting time for objects that were unexpectedly light and a relatively long lifting time for objects that were unexpectedly heavy demonstrated that subjects indeed programmed their grasp and lift forces for the weight that was presented more often. We did not observe a high maximum lifting speed if objects were unexpectedly light and a low maximum lifting speed if objects were unexpectedly heavy. Rather, it appeared that by the time the object was lifted, the lifting force was adjusted appropriately to the actual weight.

Both lifting time and maximum lifting speed in Experiment 1 were affected by the actual lifted weight, with the lifting time being longer and the maximum lifting speed slower for the heavy object than for the light object. This was replicated in Experiment 2. It has previously been demonstrated that lifting time increases with increasing weight, even in conditions in which the weight of the object was always as expected (Johansson and Westling 1988; Weir et al. 1991). Lifting a heavier object requires the application of larger forces (Johansson and Westling 1984, 1988; Westling and Johansson 1984). Even though these forces increase at a faster rate for objects with an (expected) heavy weight, this adaptation is not strong enough to make the lifting time equal for all weights (Johansson and Westling 1988). Apparently, people do not necessarily attempt to lift objects with different weights in the same way.

In Experiment 2, objects changed weight in only 20% of the trials. Thus, we assume that participants expected the weight to be the one they initially observed (to approximately the same extent as participants expected the weight they usually experienced in Experiment 1) and programmed their grasp and lifting forces accordingly. However, the lifting times were not affected by whether the object suddenly changed into a weight that the participant had not planned for. This contrasts with the effect of unexpected weight on lifting time in Experiment 1, and indicates that participants were able to adjust their motor plan online to visible changes in weight. A limitation of the study is that we cannot be completely sure that participants' strategies did not differ in important ways between the experiments. That remains to be investigated.

The longer reach time for trials in which the object changed than for trials with constant objects did not seem to be used for adjusting the movement, as suggested by the lack of correlation between the effect of change on reach time and the adjustment error. It could be a non-functional, involuntarily reaction to the change. A similar finding is described by Aivar et al. (2005). In their study, goal-directed pointing movements took longer when the size of a target suddenly changed compared to when it did not change, regardless of whether the size increased or decreased and without affecting the pointing precision.

The present study does not reveal how much time is required to adjust the motor program. In contrast to classic perturbation experiments in which the effect of the change can be examined directly in the trajectory of the hand, we can only start to observe adjustment responses to the change after the target has been reached. We know that the time between the object's change (which was around 470 ms for several movements performed by IG) and arrival at the target (which varied roughly between 600 and 1,200 ms, see Fig. 4b) was enough to adjust the motor program.

With only two possible weights, we may not have tested the visuo-motor system at its limits. Still, we have shown that it is possible to adjust a reach-to-lift movement to a perceived change in an object's weight, a property that is non-spatial and heavily based on experience. A similar result was found by Brenner and Smeets (2004) who showed fast online adjustments of goal-directed movements to a change in color, another non-spatial property, which in their experiment identified a target. These findings are in contrast to views of the nature of visual online control as being solely specialized for making adjustments to low-level geometrical features such as size and position (Glover 2004; Goodale 1998; Milner and Goodale 1993). Milner and Goodale (1993) proposed that determining an object's weight by using visual cues takes place in the ventral stream whereas online control of movement happens in the relatively independent dorsal stream. This view is difficult to reconcile with our findings that people can adjust their lifting movement online to a sudden visible change in weight. One possibility is that the dorsal stream does process visual cues for weight. Chouinard et al. (2005) showed that applying TMS to the dorsal premotor cortex disturbed the ability of participants to use a color cue for weight in programming the appropriate lifting forces. As the authors indicate, it remains to be seen whether the results of using an arbitrary color cue for weight can be generalized to using more pragmatic visual cues about weight such as the object's size (or, in our case, the visual appearance of an object with or without weights attached). Another possibility is that the ventral stream can be used for online correction. The ventral stream is connected to the motor areas of the brain (Lee and van Donkelaar 2002; Rossetti et al. 2000, 2003). This explains that patients with a damaged dorsal stream but a spared ventral stream can still make goal-directed movements (Himmelbach and Karnath 2005; Revol et al. 2003; Rossetti et al. 2005). This seems especially to be the case when familiar objects are grasped (Jeannerod et al. 1994). Also, interactions between the ventral and dorsal stream have been shown to exist (Rossetti et al. 2003; for monkeys: Merigan and Maunsell 1993). This is also acknowledged by proponents of the separate visual streams hypothesis (Goodale and Westwood 2004). These interactions may have allowed information about an object's weight, processed in the ventral stream, to be delivered to the dorsal stream and thus available for online control. However, as mentioned in the Introduction, the ventral stream processes information relatively slowly. The ventral stream only appears to affect movements after time intervals in the order of seconds, as shown by the finding that tapping movements by the above-mentioned patients improve only after a relatively long time has elapsed since the presentation of the target. Rossetti et al. (2003) have suggested that whereas the dorsal stream is involved in fast and unconscious online adjustments, the ventral stream may be involved in slower adjustments. For our experiment, we do not have a precise estimate of how long it took our subjects to adjust, but the time between the change of the object's weight and reaching the object seems quite short for the ventral stream to be used in online control (especially for the fastest subjects). More work is needed as to fully understand the neurological processes underlying the reported effects and the contribution of other brain areas (e.g., the inferior parietal lobe) implicated in the perception and action cycle (Rumiati et al. 2001, 2004; for review see Glover 2004).

To conclude, in contrast to what is suggested by current views of online control, our study showed that people are able to adjust their programmed lifting forces online to a visually indicated change in weight.

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