Can internal models of objects be utilized for different prehension tasks?

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Abstract
We examined if object information obtained during one prehension task is utilized to produce fingertip forces for handling the same object in a different prehension task. Our observations address the task-specificity of the internal models presumed to issue commands for grasping and transporting objects. Two groups participated in a two-day experiment in which they lifted a novel object (230 g; 1.2 g/cm³). On Day One, the High Force Group (HFG) lifted the object by applying 10 N of grip force prior to applying vertical lift force. This disrupted the usual coordination of grip and lift forces and represented a higher grip force than necessary. The Self-Selected Force Group (SSFG) lifted the object on Day One with no instructions regarding their grip or lift forces. They first generated grip forces of 5.8 N, which decreased to 2.6 N by the tenth lift. Four hours later, they lifted the same object in the manner of the HFG. On Day Two, both groups lifted the same object ‘naturally and comfortably’ with the opposite hand. The SSFG began Day Two using a grip force of 2.5 N, consistent with the acquisition of an accurate object representation during Day One. The HFG began Day Two using accurately scaled lift forces, but produced grip forces that virtually replicated those of the SSFG on Day One. We concur with recent suggestions that separate, independently adapted internal models produce grip and lift commands. The object representation that scaled lift force was not available to scale grip force. Furthermore, the concept of a general-purpose object representation that is available across prehension tasks was not supported.
Introduction

When gripping and transporting objects we generate fingertip forces predictively, according to the physical properties of the object (Gordon et al. 1993; Jenmalm et al. 2000; Jenmalm and Johansson 1997; Johansson and Westling 1988; Salimi et al. 2003; Wing and Lederman 1998; Witney et al. 2000). Current theory holds that internal models estimate the needed motor commands and produce sensory predictions that help adapt the models (Flanagan and Wing 1997; Flanagan et al. 1993; Flanagan et al. 2003; Jordan and Rumelhart 1992; Kawato et al. 1987; Wolpert and Ghahramani 2000; Wolpert et al. 1995). In the dominant interpretation of this theory, separate forward and inverse models are thought to exist. An inverse model generates arm motor commands and copies these commands to a forward model, which generates the commands for gripping. This forward model also sends the expected sensory consequences of the load at the fingertips for comparison with the actual sensory consequences, with the resulting error used to adapt the inverse model when these sources of information do not match (Kawato and Wolpert 1998). Smith and colleagues (Monzee et al. 2003) suggested that the internal models also require sensory information about grip, such as grip force or finger alignment, for efficient functioning and adaptation. However, it is unclear whether their observations of excessive grip force during digital anesthesia resulted from the lack of tactile input to internal models, or the failure to detect and correct misalignment errors at the fingers which resulted in horizontal torques.

Regardless of the mechanism, the process of learning how to handle new objects
is robust and efficient. Novel objects quickly become familiar, in a few to several trials, as reflected in our ability to accurately reproduce the fully adapted fingertip forces 24 hours later (Gordon et al. 1993). Likewise, the grip force required to offset load forces is predicted after only a single trial, but decays over several trials when object manipulation no longer produces the expected load forces (Witney et al. 2000). However, learning the internal models for stabilizing grip and controlling arm trajectory may not proceed at the same rates. Flanagan and colleagues (Tong and Flanagan 2003) reported that grip force adapted about seven times faster than arm trajectory upon novel loading of a transported object. This finding provides support to the theory of separately adapted internal models for grip and arm control, and illustrates that essential differences exist between the mechanisms that generate arm trajectory and those that stabilize grip.

These accurate predictions of fingertip forces require long-term memory resources for efficient prehension that, at some level, represent relevant physical properties of objects (Flanagan et al. 2001; Gordon et al. 1993). It is not clear if these memory resources can be shared across prehension tasks. In studies of arm movement, memory resources for visuomotor transformations appear to be task-specific (Tong and Flanagan 2003). In contrast, when executing reaching and drawing movements against a single rotary viscous force field, which requires a dynamic transformation, the internal model acquired during one type of movement is available for a different movement (Conditt et al. 1997).

We investigated whether learning to handle a rigid, freely moveable object in one prehension task provides an object representation that can be used to handle the same
object efficiently in a new prehension task. We predict that the internal model for producing grip force can be utilized to scale the fingertip forces in other tasks. This is based on the assumption that grasping and lifting the same object in different ways is more akin to a dynamic transformation (Conditt et al. 1997) than to a visuomotor transformation (Tong and Flanagan 2003). Thus, we hypothesize that the internal model for producing grip commands is not task-specific, and can access memory resources about the physical properties of objects regardless of how an object was previously handled.

Materials and Methods

Subjects: Twenty healthy young adults (12 female; 8 male; 19-42 years of age) participated in this experiment. All declared themselves to be right-hand dominant and free from injury or disease of the upper limb or nervous system. Subjects were naive to the purpose of the experiment, and had not previously participated in experiments for our laboratory. The University of Iowa Human Subject Internal Review Board approved the experiment and informed consent was obtained from all subjects according to the Declaration of Helsinki.

Apparatus: Subjects used the thumb and index finger in a pinch grip to grasp and lift a novel test object (Fig.1). The gripping surfaces were two opposing vertical plates (35 X 35 mm) that were parallel to each other, with a separation of 2.2 cm between the digit contact surfaces. The plates were covered with black sandpaper (#320 aluminum oxide). Load cells measured the normal (‘grip’) force and vertical tangential (‘lift’) force separately at both grip surfaces. The linearity, repeatability and hysteresis of the force
signals were computed to be ± 0.8%, ± 1.86% and ± 1.1% full scale, respectively. An accelerometer (SenSyn SXL010G) affixed to the object measured the vertical acceleration. The total mass of the test object was 230 g, with a density of approximately 1.2 g/cm³.

During designated trials (see below), a standard oscilloscope provided visual feedback of the grip forces (but not lift forces). Subjects were instructed to target their grip forces between two horizontal cursors on the oscilloscope screen (2.85 N/division). Subjects did not have visual feedback of their lift forces at any time during the experiments.

**Procedures:** Subjects were assigned to one of the two groups, the Self-Selected Force Group (SSFG) or High Force Group (HFG), with six females and four males in each group. Other than balancing for gender, the assignments were random. All subjects participated in testing sessions that were performed over two consecutive days.

Before each testing session on both days, subjects cleaned their hands with a mixture of lemon juice and water to reduce surface contaminants and skin oils. They sat before a table upon which the novel test object rested. Subjects did not receive any information or details about the object and were not allowed to touch the object until instructed to do so. The experimenter demonstrated how the subject was to grasp and lift the object. Upon a verbal cue from the experimenter, subjects were required to reach forward toward the object with the hand in the sagittal plane using approximately 20 degrees of shoulder flexion. They gripped the object by placing their thumb and index finger at the centers of the black sandpaper grip surfaces. The object
was then lifted using primarily elbow flexion with the wrist slightly extended. Subjects lifted the novel test object vertically approximately 5-8 cm, and held it stationery for 5 seconds before returning it to the table.

On Day One, subjects in the HFG were instructed to maintain their grip force between 10 and 11.5 N (as indicated by the horizontal bars on the oscilloscope screen) until they returned the object to the table and were no longer applying a lift force to the object. When the targeted grip force was met, subjects received a verbal command to lift the object using their right (dominant) hand. This procedure required the subject to grasp and lift the object in a way that prevented them from matching their grip force to the physical properties of the object, and which disrupted the natural coordination of the grip and vertical lift forces (Fig. 2). This sequence of grip, verbal command and then lift was repeated 10 times with approximately 20-30 seconds elapsing between lifts. Occasional rests of at least 2 minutes were given between lifts to prevent muscular fatigue.

Subjects in the Self-Selected Force Group (SSFG) also lifted the novel object 10 times with their right hand. However, they did not receive verbal instructions other than to lift the object to a height of 5-8 cm “naturally and comfortably”. The SSFG returned four hours later with instructions to lift the same object in the manner as described for the HFG. Although the SSFG experienced twice as many lifting trials on the first day (20 lifts versus 10 lifts for the HFG), ten lifts is more than sufficient to learn the fingertips forces needed to efficiently handle novel objects (Flanagan and Beltzner 2000; Gordon et al. 1993; Johansson and Westling 1988; Witney et al. 2000); also see Results).
On Day Two, subjects returned for additional testing. We asked them to disregard the instructions and events from the previous day, and lift the object in a natural and comfortable manner to a height of 5-8 cm, beginning with their left (non-dominant) hand. The oscilloscope was removed from view. All subjects performed 10 such lifts before switching to their right hand for ten more lifts. Then subjects performed two trials each with their right and left hands in which they were instructed to slowly decrease the grip force on the lifted object until it slipped from grasp. After these ‘slip’ trials, subjects then performed ten additional ‘natural and comfortable’ lifts of the test object with both their right and left hands.

Data Analysis: Force and accelerometer signals were sampled at 400 samples/second with 16-bit resolution. Grip force was calculated from the normal force measured at the index finger and thumb \( \left( \frac{\text{normal}_{\text{finger}} + \text{normal}_{\text{thumb}}}{2} \right) \). The lift force was calculated from the vertical tangential force at both digits \( \left( \frac{\text{tangential}_{\text{finger}} + \text{tangential}_{\text{thumb}}}{2} \right) \). On Day Two, slips of the test object were measured during the phase of the lift when subjects steadily held the object 5-8 cm above the table. The slip trials were marked by the onset of vertical acceleration along with a sharp decrease in lift force at one digit and a simultaneous increase in lift force at the other digit. The slip force was taken as the normal force at the onset of acceleration for the digit with the decreased lift force. The slip forces were measured separately at each digit across both hands for all subjects.

For each trial we determined the grip and lift forces at lift-off of the object from the table, the peak grip and lift forces, and the grip force once the object stopped moving in the vertical direction. Analysis of Variance (ANOVA) was used to assess the effects of
group on these dependent variables. Statistical comparisons between the first and last lifts in a series were made using Matched-Pair t-tests. Data in the text and figures refer to group means and standard error.

**Results**

We hypothesized that the internal model that generates grip force commands for one prehension task can be exploited for other prehension tasks with the same object. If true, then the HFG should show grip forces at the start of Day Two scaled for the object mass. Accordingly, the HFG grip forces on Day Two would be similar in magnitude to those used by the SSFG at end of the first session on Day One.

*Grip Force and Memory*

*Day One.* Subjects who used self-selected forces (SSFG) to lift the test object on Day One used grip forces at the time the object lifted-off from the table (‘lift-off”) that averaged 5.8 N ± 0.46 N on the first lift (Figs. 2B, 4). They rapidly decreased their grip forces across the next four lifts and then more slowly across the last five lifts. By the tenth lift of this session, the grip force at lift-off averaged 2.6 N ± 0.21 N, which is consistent with previous studies of healthy young adults when lifting this same object (Cole and Rotella 2002).

The *peak lift force* was similar between groups on Day One across all testing sessions ($t_{1,18} = 1.32; p= 0.28$). For the HFG, the peak lift force on Day One averaged 3.1 N ± 0.18 N. The average peak lift force for the SSFG on Day One was 2.9 N ± 0.10 N when lifting the object with self-selected grip forces and 3.0 N ± 0.14 N for the lifts using 10 N grip force.
Day Two. During this session, both groups lifted the object ‘naturally and comfortably’ with the opposite hand (left hand) from the previous day. Subjects in both groups used low peak lift forces that remained stable across all lifts of the object (3.2 N versus 2.8 N for HFG and SSFG, respectively; \( t_{1,18} = 4.33; p = 0.07 \)), and were no different than the peak lift forces of Day One. The mean peak acceleration of the object was also equivalent between the HFG and SSFG across lifts (0.75 m/s\(^2\) and 0.91 m/s\(^2\), respectively; \( t_{1,18} = 1.04; p = 0.31 \)). These observations suggest that a long-term memory of the load was consolidated and that an internal model of the arm and object was accurately adapted for controlling lift force.

In contrast, the two groups used substantially different grip force for the first lift of the object on Day Two, even though both groups ended Day One handling the object by applying a 10 N grip force prior to applying the lift force (Figs. 3-4). Only the HFG on Day Two appeared to be affected by the ‘high grip force’ task from the previous day. On the first lift of Day Two, the grip force at lift-off was 6.9 N ± 0.72 N for the HFG versus 2.5 N ± 0.13 N for the SSFG (\( t_{1,18} = 20.46, p<0.0002 \)). No subject in the SSFG began Day Two using a grip force greater than 2.9 N, whereas no subject in the HFG began Day Two with a force less than 4.8 N. Grip force for the SSFG on the first lift of Day Two did not differ from the grip force used on their last lift of the self-selected grip force session on Day One (2.5 N ± 0.13 N vs. 2.6 N ± 0.21 N; \( t_{1,9} = .35; p = 0.73 \)). Moreover, the SSFG subjects did not decrease their grip force across the remaining nine lifts on Day Two (\( t_{1,9} = 0.43; p = 0.67 \)).

Subjects in the HFG rapidly adapted their grip forces on Day Two. After their
first lift, subjects in the HFG substantially decreased their grip force across the remaining nine lifts (Fig. 4). The grip force at lift-off for first lift on Day Two (6.9 N ± 0.72 N) significantly differed from the average of lifts nine and ten (2.8 N ± 0.21 N) of this day ($t_{1,9} = 6.16; p< 0.0002$). Their grip force levels on lifts nine and ten were comparable to those of the SSFG’s lifts on Day Two ($F_{1,18} = 0.38; p= 0.55$).

Differences in grip force between groups on Day Two cannot be attributed to differences in hand slipperiness. The grip force at which the object would slip from subject’s grasp (‘slip force’) in each group was similar (High Force group = 1.1 N ± 0.07 N; SSFG = 1.1 N ± 0.08 N). Likewise, differences between days cannot be attributed to differences in slipperiness between the right hand (Day One) and the left hand (Day Two). The difference in slip force between hands never exceeded 0.2 N.

Upon considering reasons for the large unexpected differences in grip force between the two groups on the second day of testing, we became concerned that at the start of Day Two subjects in the HFG merely persisted with the instructions of the previous day. We compared the grip force across trials when each group was first asked to lift the test object ‘naturally and comfortably’ (Day One for the SSFG; Day Two for the HFG). Both the SSFG and HFG applied about 6-7 N of grip force for the first lift and rapidly decreased the applied grip force across subsequent lifts (Fig. 4). The Group x Trial interaction was not significant ($F_{9,180} = 0.42; p= 0.93$), indicating both groups used a similar pattern of grip force across the ten lifts in this comparison. The 3-4 N decrease in grip force between the end of Day One and the start of Day Two indicates that most subjects in the HFG were not merely beginning Day Two by performing the task learned on Day One. Taken at face value, the HFG appeared to start Day Two by treating the
object as the SSFG had at the start of Day One, when the object was unfamiliar or novel.

Inspection of the data from individual subjects further reveals that the ability of the HFG to adapt their grip force on Day Two was not compromised by the instructions they received on Day One, with the possible exception of two subjects. All but two subjects in the SSFG used a grip force of 6-8 N for the first lift and then steadily decreased the grip force across the remaining trials (Fig. 5). One subject in the HFG (Fig. 5, ‘S1’ in inset) used nearly twice the force of all other HFG subjects during the first few lifts. The other subject, (Fig. 5, ‘S2’ in inset) used unusually high grip force over trials five through seven. The behavior of only these two subjects is consistent with the interpretation that subjects in the HFG began Day Two by repeating the task they learned on Day One, at least with regard to grip force level. The remaining subjects used forces across the first ten lifts that were remarkably similar to the SSFG on Day One (compare open triangles and filled squares in Fig. 5; $F_{1,180} = 0.94; p= 0.34$). It also appears unlikely from these data that the SSFG’s performance on Day Two reflected the opportunity to lift the object twenty times on Day One (10 lifts under each condition) as compared to 10 lifts (‘high force’ condition) for the HFG. That is, the HFG began the process of rapidly adapting their grip force on the first lift of Day Two (lift eleven overall), which matched the behavior of the SSFG on their first lift overall.

Both groups applied low grip forces during Day Two upon resuming lifting with their right hand (3.3 N ± 1.43 N and 3.1 N ± 0.72 N for the HFG and SSFG, respectively; $F_{1,18} = 0.06; p= 0.81$). This indicates that the adaptation in grip force exhibited by the HFG over the previous ten trials with the left hand also was expressed in the grip force at the right hand. Nor did subjects alter their grip forces based on the ‘slip’ trials, when the
minimum grip force needed to maintain a stable grip was experienced. On Day Two, the grip force applied by each hand before and after the slip trials did not change ($F_{1,18} = 2.81; p=0.60$). Thus, when first lifting the object without artificially imposed grip forces, the HFG used a similar efficient process as the SSFG to quickly reach their ‘preferred’ minimum grip force.

The Availability of Sensory Signals While Gripping at 10 N

We were also concerned that the 10 N grip force may have impaired the ability to encode, detect, or respond to cutaneous information about the physical properties of the object. Although this seems unlikely (see Discussion), we examined this issue in a single subject (42 y/o female; right hand dominant) who did not participate in the main experiment. The subject held a test object using 10 N of grip force while the experimenter randomly pulled vertically on a cord suspended from the object. The cord and experimenter were shrouded from the subject’s view. The pulls on the object produced slow load perturbations at a peak rate = 25.80 N/s ± 5.93 N/s, similar to the object lifts (Fig. 6). Grip force increased reliably upon each pull at a latency of ~100 ms, consistent with previous studies when random load perturbations were applied to grasped objects (Cole and Abbs 1988; Cole and Johansson 1993; Johansson et al. 1992a; Johansson et al. 1992b; Macefield and Johansson 1996).

Discussion

Our observations challenge the concept of a general-purpose object representation for prehension, or the robustness of such a resource. Both groups obtained an accurate
object representation during Day One, because peak lift forces at the start of Day Two were scaled to object weight. Contrary to our predictions, subjects who only handled the novel object using a moderately high grip force failed to apply grip force efficiently the next day when these restrictions were removed. Conversely, no subject who handled the object in a natural manner on Day One used high grip forces the next day, despite ending Day One with instructions to handle the object with a high grip force. Taken together, these observations support a theory of separate, independently adapted internal models for producing grip and lift commands (Flanagan et al. 1996; Salimi et al. 2003; Salimi et al. 2000; Tong and Flanagan 2003). Furthermore, our results are consistent with Tong and Flanagan’s (Tong and Flanagan 2003) conclusion that memory resources are task-specific, in contrast to Conditt and colleagues’ (Conditt et al. 1997) report that different arm movement tasks performed under a single, novel force field shared the same internal model.

High Force Task versus Natural Grasping

High Force Task on Day One was unusual in its combination of a moderately high grip force and a strictly enforced sequential application of grip and lift force (Johansson and Westling 1984; Westling and Johansson 1984). These complex grasping and lifting requirements that were enforced for the High Force Task on Day One may have interfered in various ways with the ability of a grip controller to access putative general memory resources about the object on Day Two. This interpretation would not support our conclusion that internal models are task-specific. We entertain such speculation, but in doing so note that one conclusion remains secure; the object was
represented in the nervous system by Day Two, and this resource was not used to scale
grip force.

Cognitive strategies can intrude in otherwise automatic motor tasks, as was
demonstrated when comparing perceptually intrusive limb loads versus less-intrusive
loads (Malfait and Ostry, 2004). The High Force Task most likely demanded
considerable attention by the High Force Group, raising the possibility that their behavior
was dominated by unusual cognitive strategies on Day Two. First, we dismiss the
possibility that subjects in the High Force Group used the memory of a faulty weight
perception on Day Two. Grasping an object with a high grip force causes us to perceive
the object as ‘lighter’ than when grasped with a lower grip force (McCloskey et al. 1974).
Therefore, if subjects in the High Force Group had used a cognitively-driven strategy
guided by perceptually established memories of object weight, then we would expect
smaller grip forces on the second day compared to the control group. Similarly, it is
implausible that all subjects in the HFG failed to understand the implied instruction to lift
the object using a lower grip force on Day Two, while no one in the SSFG persevered
with the final instructions of the previous day. Thus, merely instructing subjects to lift
with a high grip force does not induce a similar behavior the following day.

Along similar lines, the added attentional demands of the conditioning task may
have produced the equivalent of a ‘noisy’ learning environment, impairing the acquisition
of an object representation or adaptation of an internal model. If so, one should observe
better performance on Day Two if the High Force Group is allowed to lift the object
more often during the conditioning task on Day One. Conversely, the control group
should perform worse, thus generating higher grip forces on Day Two, if required to lift
the object many times using a high grip force on Day One. This interpretation remains a possibility.

The High Force task also was unusual because a grip force target was externally set. With the predetermined 10 N grip force and visual guidance, there was no need for a forward model of arm and object to set grip force, or to scale the grip force according to inertial loads predicted from efference copy of arm commands. This possibility must be allowed, but it remains consistent with the interpretation that separate models exist for scaling grip and lift forces. That is, some memory of the object was accessed to provide for accurately scaled lift forces on Day Two, and this memory apparently was not sufficient to stimulate a process for scaling grip force.

Availability of Load Information

The strength of our conclusions relies on the availability and fidelity of sensory information about object properties in the face of a moderately high grip force (10 N). There are several logical and empirical reasons to believe that accurate information about load forces was available, apart from the evidence that lift forces were well-scaled on Day Two. Sensory information about load appears to be encoded in central commands used as ‘efference copy’ (McCloskey 1981) and in muscle receptors (McCloskey et al. 1974). Muscles generating torque at the elbow, which are minimally affected by grip force may provide an important source of load information in the present task. Cutaneous information about lateral forces at the grasping digits also remains available, via slowly adapting (SA I) mechanoreceptive afferents located in the skin adjacent to the contact patch, and in the sides and ends of the finger (Bisley et al. 2000).
Likewise, the large receptive fields and sensitivity to lateral strain allow SA II afferents to encode vertical load despite high compressive forces in the skin patch directly at grip contact (Johansson and Vallbo 1983; Macefield et al. 1996). As the skin stiffens under compressive load, we presume that lateral strain is realized at skin regions more distant from the grip contact patch. Finally, there is direct evidence that grip forces remain sensitively graded to small changes in load even when grip force is 10 N or greater (Cole and Johansson 1993). Cole and Johansson (Cole and Johansson 1993) demonstrated graded responses of grip force when a ramp load applied to an object slowed to a constant load, even though the grip force was more than 10 N. Similarly, Johansson and colleagues (Johansson et al. 1992b) demonstrated that the grip force rate fell shortly after the onset of a ramp decrease in load when grip force was ca. 10 N. This latter finding is consistent with a threshold value of 0.21 N change in load and a minimum response latency of 150 ms (Johansson et al. 1992a). Finally, Johansson and Westling (Johansson and Westling 1984) demonstrated that grip force smoothly scales with load force even with an initial grip force of 10 N when subjects pulled on an object tethered by a spring.

Sensory Information For Fingertip Forces

It is possible that memory resources were shared across prehension tasks, but the forward model for grip control was not adapted/updated in the face of the high grip force. When handling objects under tactile anesthesia, coordination is retained between the grip and load forces, but high grip forces are observed despite prior knowledge about object properties (Johansson and Westling 1984; Monzee et al. 2003; Nowak and Hermsdorfer 2003; Nowak et al. 2003). One interpretation is that the internal model for grip commands requires either continuous or intermittent cutaneous sensory information about...
grip (Monzee et al. 2003; Nowak and Hermsdorfer 2003) and this sensory information must match the model prediction (Blakemore et al., 1998).

A separate issue of sensory information transfer arises from the fact that the lifting task on the second day began with the left (non-dominant) hand. Handling a novel object with the right hand imparts accurate scaling for load on a following lift with the left hand (see Results; also (Gordon et al. 1994; Johansson and Westling 1984). However, it is not known if load information obtained during the high-force task similarly transfers. This question is relevant because some force fields or visuomotor adaptations fail to transfer across limbs (Shadmehr and Mussa-Ivaldi 1994). Thus, it remains possible that transfer might have occurred from the conditioning task to the ‘normal’ task if the same limb had been used between days.

Conclusions

The stark differences in performance between the two groups in their grip forces, along with similar lift forces, provides evidence that the internal models for grip and lift forces can be independently adapted. The inability of one group to scale grip force appropriately on the second day, despite evidence that an accurate representation of object weight was acquired, is consistent with a task-specific internal model for grip force commands. The data are inconsistent with interpretations based on faulty perceptions of object load, or cognitive strategies driven by the unusual conditioning task. Future studies that address motor learning when handling objects are warranted. For example, requiring multiple groups of subjects to repeatedly lift a novel object at different magnitudes of grip force could resolve several issues. If the specific grip force
levels used by each group transfers to object lifts on a following day, then subjects learned the forces required for the task rather than the object properties. And, as previously suggested, requiring additional lifting trials could control for potential effects of the ‘noisy’ environment produced by the incompatibility of the somatosensory and visual systems to produce force.
Figure Captions

Figure 1. Test object. Subjects grasped the object at the black, sandpaper-covered vertical surfaces with a pinch grip of the thumb and index finger. Force transducers embedded in the object measured the horizontal grip force (GF) and the vertical lift force (LF) at each surface. Total mass of the test object was 230 g. An accelerometer attached to the object measured vertical acceleration and lift-off from the support surface.

Figure 2. Fingertip force records of a single lift on Day One in which the same subject (SSFG) lifted the object with the right hand using an intentionally high grip force (A), and when instructed to lift the object “naturally and comfortably” (B). (A) The subject exerted the high grip force before lifting the object and did not decrease the grip force until the object was returned to the table. Vertical lines indicate when the object lifted from the table (‘Lift-off’), and when it was again returned to the table (‘Setdown’).

Figure 3. Force signals from typical trials on Day Two when lifting the object with the left hand. Grip and lift forces from the first lift (black) and the tenth lift (gray) are shown for subjects in the High Force Group and Self-Selected Force Group.

Figure 4. Lifts of the object for the High Force Group (HFG, open triangle, left-handed lifts) on Day Two and Self-Selected Force Group (SSFG) (Day One, solid square, right-handed lifts; Day Two, open circle, left-handed lifts) during their sessions using self-selected grip force. Both groups began by initially lifting the object with greater grip force than needed. With each subsequent lift they decreased their grip forces until reaching a stable level across trials 9-10. On Day Two, the
SSFG (open circle) used grip forces similar to those they used during the last lifts (trials 8-10) on Day One (solid square).

Figure 5. Average grip force used by the HFG on Day Two (open triangle) after removing two subjects (S1, S2) who may have persevered with the instructions from the previous day to use a high grip force (see inset). The remaining eight subjects in the HFG developed their grip forces across the ten trials in a similar manner to subjects in the SSFG.

Figure 6. Availability of sensory signals while gripping at 10 N. Ensemble average (bold) of the seven trials from single subject during load force perturbations while holding the test object with 10 N of grip force. Reactive grip force increases are observed approximately 100 ms following the increase in load force.
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Figure 1
Self-Selected Force Lift

Grip Force (N) | Lift Force (N)
---|---
 lifted | 10N

Lift-off | Set-down

A: High Force Lift

B: Self-Selected Force Lift

Time (s)

Figure 2
Figure 3

A  High Force Group

B  Self-Selected Force Group
Mean Grip Force (N) at Lift-off of the test object

Figure 4
Figure 5

Mean Grip Force (N) at Lift-off of the test object
Figure 6