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Contextual effects on robotic experiments of sensory feedback for object manipulation

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***Abstract*—Tactile and proprioceptive feedback for prosthetic hand users is assumed to be critical, yet there is no systematic knowledge about how to provide this feedback effectively. Haptic virtual environments are ideal tools with which to manipulate properties of object interaction to build a model of such feedback. This work shows the importance of the environmental context to capture results relevant to prosthetic hand sensory feedback. While an interface utilizing manipulation of a second-order oscillatory spring-mass system at its natural frequency did not show consistent effects of haptic feedback on motor performance, an interface based on manipulation of an object with the competing goals of overcoming friction without breaking the object showed an increase in task performance with the addition of haptic feedback to visual feedback. Contextual effects such as functional relevance should be considered in robotic experiments on the role of multisensory feedback in object manipulation.**

I. INTRODUCTION

Current hand prostheses have limited ability to provide proprioceptive and/or cutaneous feedback about movement. Instead, most users must rely completely on visual feedback for prosthesis use, which requires constant cognitive attention. In fact, the third ranked design request of individuals using prosthetic hands was that they "required less visual attention to perform functions" [1].

Multi-sensory feedback (such as visual and haptic) has been shown to mediate the self-attribution of body parts [2], and to increase object manipulation performance [e.g., 3] in unimpaired individuals. Multiple channels of sensory feedback may be particularly important for learning new tasks and for online adaptation or parameter tuning [e.g., 4, 5]. Specifically, it has been shown that force feedback on fingers can allow increased task speeds and decreased error rates during object manipulation [6]. It is not then surprising that addition of sensory feedback beyond vision to hand prostheses is a top design priority of users [7, 8].

Although the technology exists to provide contact force feedback on prosthetic hands and fingers during object manipulation in real-time [e.g., 9, 10], these technologies are not typically implemented in prostheses. While cost and processing power are barriers to implementation, the biggest hurdle is in providing sensory information to users of prosthetic hands. One simple approach is to provide force feedback non-invasively to the user by an existing sensory pathway, such as skin mechanoreceptors via vibrotactile stimulation [10, 11]. The user could exploit the plasticity of the nervous system to associate the alternate sensory input location with their prosthetic hand. The non-invasive nature of this approach would allow for immediate wide-scale implementation among users of prosthetic hands.

Implementation of force feedback for users of prosthetic hands via vibrotactile stimulation has been previously investigated by Pylatiuk et al. [10], who designed a feedback system for myoelectric prosthetic hands in which contact forces felt via a piezo-resistive force sensor on the palmar tip of the prosthesis were represented to the user by vibrotactile stimulation of the prosthesis or skin of the residual limb. Their testing in 5 users of prosthetic hands found that the augmentative feedback allowed decreases in contact forces during simple object grasp. Conversely, Chatterjee et al. [11] tested 8 unimpaired individuals during use of a myoelectric prosthesis simulator to complete an interactive force-matching task using a representation of the force sensed by a strain gauge at the carpal-metacarpal thumb joint, which was presented to users via vibrotactile stimulation on the upper arm. They did not find consistent overall reduction in force-matching error through the use of the feedback.

These contradictory findings suggest a need for systematic investigation of the effect and role of force feedback on object manipulation. Haptic devices and virtual environments play critical roles in simulating experimental environments for object manipulation with the ability to add or subtract different sensory cues. This allows a comparison of augmentative methodologies for providing force feedback non-invasively using existing sensory systems.

Our ultimate goal is to characterize the role of different sensory feedback in multi-sensory fusion for prosthetic users and to discover different sensory feedback modalities for a wide range of applications. We designed a virtual environment to study object manipulation with which both visual and direct haptic (force) feedback could be

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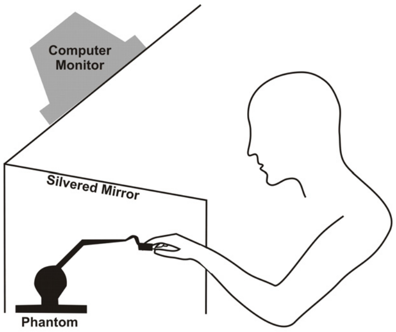

Fig. 1. Schematic of the Physical Set-up used in both Experiment 1 and 2. Participants placed their right index finger into a custom splint attached to the end effector of the Phantom.

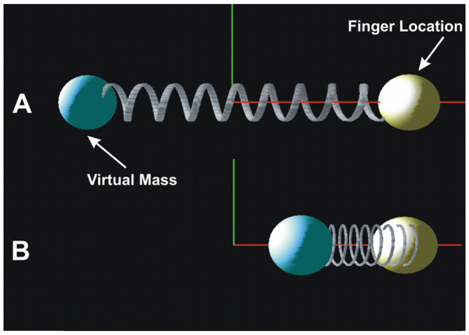

Fig. 2. Example of a screenshot of the visual feedback used in Experiment 1. Panel A shows the visual representation of the system with the spring extended, and Panel B during compression.

experimentally controlled. In setting up this environment, we have learned that "context" plays a significant role in the effect of force feedback. Specifically, the same hypothesis in a differing experimental context can result in an entirely different conclusion. In this paper we present two different experiments testing for the role of force/haptic feedback in task performances, with two contradictory results. The two experiments are described in detail below and are discussed in terms of the implications of these differences.

II. EXPERIMENT 1: A VIRTUAL SPRING-MASS-DAMPER

A. Robotic Implementation of the Virtual Environment

For this experiment, the role of force/haptic feedback was tested by asking participants to find the natural frequency of a spring-mass-damper system as quickly as possible. A Phantom Premium 1.0 robotic device (Sensable Technology) was used to monitor the three dimensional positions of the tip of the index finger, and to supply force-based haptic feedback. A projection system consisted of a frame above the Phantom, which supported an inverted video monitor, positioned at 45º toward the participant. A mirror was placed between the virtual environment and the monitor, allowing reflection of images from the monitor (see Fig. 1). The visual and haptic feedback was spatially aligned. Participants interacted with the virtual environment by placing their right index finger into a custom splint attached to the end effector of the Phantom.

The virtual environment was programmed in C++, with graphics driven by OpenGL. The virtual system consisted of a mass, connected by a spring and damper to a representation of the subject's index finger (the end effector of the Phantom), allowing the participant to indirectly drive the motion of the mass. System dynamics were simulated in real time using the Euler method to numerically integrate the equations of motion (see equations 1 and 2). Visual feedback was updated at 60 Hz, while the haptic feedback to the Phantom was updated at 1000 Hz. Dynamics of the second-order system were defined as in (1), where the natural frequency is ω_n, the damping ratio is ς, the acceleration, velocity and displacement of the virtual mass are $\ddot{x}_{vm}$, $\dot{x}_{vm}$, and x_{vm}, respectively, and velocity and displacement of the finger are $\ddot{x}_f$, $\dot{x}_f$, and x_f, respectively.

$$\ddot{x}_{vm} + 2\varsigma\omega_n\dot{x}_{vm} + \omega_n^2 x_{vm} = 2\varsigma\omega_n\dot{x}_f + \omega_n^2 x_f \tag{1}$$

During use of haptic feedback, the force applied to the finger via the Phantom was defined as in (2), where m is the mass of the virtual object, b is the damping coefficient and k is the stiffness, as defined by $\omega_n = \sqrt{k/m}$ and $\varsigma = b/(2m\omega_n)$.

$$F = b(\dot{x}_f - \dot{x}_{vm}) + k(x_f - x_{vm}) \tag{2}$$

The parameters for stiffness, k, and zeta, ς, were held constant at 292 N/m and 0.02. The appropriate mass was chosen based on the desired system natural frequency.

The visual feedback was a real time depiction of the virtual mass (shown as a sphere), a spring, and the finger position (shown as a sphere). Figure 2 shows a compilation of two screen shots of the feedback during interaction with the environment, with the spring extended and compressed.

B. Experimental Protocol

Over 1.5 hours, N=6 unimpaired, right-handed individuals, aged 19 - 24 (MEAN 21.5, STD 2.1; 2 male, 4 female) completed 96 16-s trials. Participants were asked to find the natural frequency of the system as quickly as possible, and to excite the system at that frequency throughout the trial. Participants were briefed beforehand on the nature of resonance, and were exposed to a physical mass-spring. They were not given specific instructions for exciting the virtual system, but were told that at resonance, finger displacements would result in larger displacements

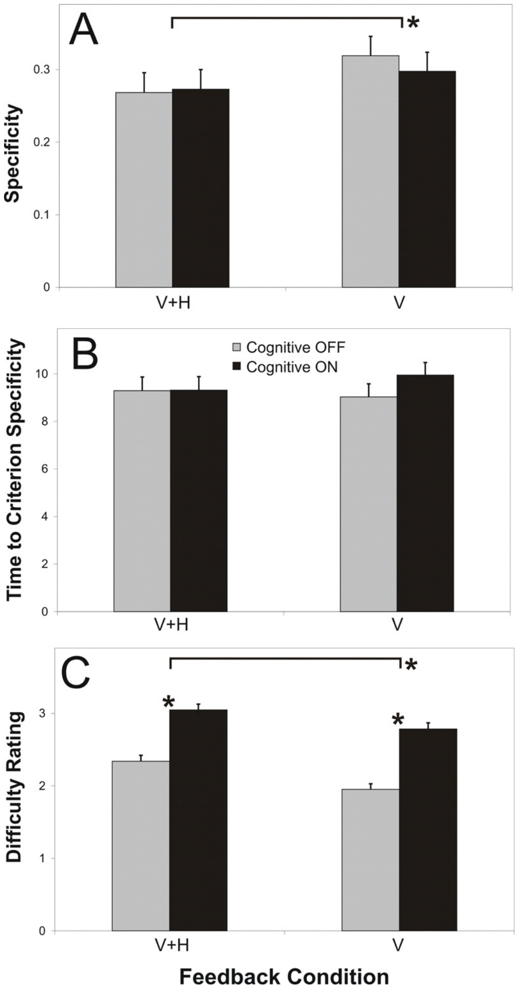

Fig. 3. Summary of results of Experiment 1. Bracketed asterisks show significant ($p < 0.05$) effects of feedback condition on performance outcomes, whereas asterisks shown immediately above data bars show significant effects of the cognitive task.

of the virtual mass. During interaction, participants sat with their forearm extended, and their hand grasped around a fixed handlebar, and excited the system through flexion/extension of the index finger.

Trials were presented in a series of 4 blocks, each block consisting of conditions randomized by ω_n (0.75, 1, 1.25, 1.5, 1.75, 2 Hz), feedback (V=visual or V+H = visual + haptic), and cognitive load (ON, OFF). During the V and V+H conditions, the Phantom robotic device was used to monitor the position of the index finger, and was also used to supply force-based haptic feedback during the V+H condition. The cognitive load consisted of an auditory n-back test, in which participants listened to random digit strings during experimentation and were asked to respond verbally. In order to reduce the effect of auditory cues available from the hardware, numbers were presented with simultaneous masking noise during trials in which the cognitive load was ON, and masking noise alone during trials in which the cognitive load was OFF. At the end of each trial, the participant was asked to report the difficulty of completing the motor task on an ordinal scale 1 – 5, in which 1 was very easy and 5 was very difficult.

Performance variables were specificity, time to criterion specificity, and difficulty ratings. Specificity was defined based on [3], in which the power spectral density of x_f within a band centered on ω_n (here bandwidth = 0.2 Hz) is normalized by total spectral energy. The final 12 s of each 16 s trial was used to calculate specificity. Specificity was also calculated for each trial as a function of time. Using 1-s windows with 75% overlap, the time at which specificity reached and maintained 0.16 or higher was termed the "time to criterion specificity." Data analysis was performed in MATLAB (Mathworks, Natick MA). General linear models in Minitab Statistical Software (Minitab Inc., State College, PA) were used to assess the effects ($p \leq 0.05$) of feedback, cognitive load, ω_n, participant, and block on outcomes, with *post hoc* two-sided Tukey's Simultaneous tests.

C. *Results*

A summary of the relevant results from Experiment 1 is shown in Figure 3. A five factor ANOVA showed statistically significant effects of feedback condition ω_n, block, and participant on specificity, but no effect of the cognitive task. *Post hoc* testing showed that participants had significantly higher specificity during V than V+H.

A five factor ANOVA showed statistically significant effects of ω_n, block, and participant on the time to criterion specificity, but no effect of feedback type or cognitive task.

Finally, a five factor ANOVA showed statistically significant effects of feedback condition, cognitive task, block, and participant on difficulty ratings, but no effect of ω_n. P*ost hoc* tests showed significantly lower difficulty ratings during V than V+H, and that participants rated trials with a simultaneous cognitive task as significantly more difficult than those without.

III. EXPERIMENT 2: VIRTUAL CYLINDER TO TARGET

A. *Robotic Implementation of the Virtual Environment*

Experiment 2 investigated the role of force/haptic feedback for dragging a breakable object on a frictional surface to a target as quickly as possible. The virtual environment was implemented as in Experiment 1, utilizing congruent haptic and visual feedback as implemented using the Phantom in conjunction with a projection system (see Fig. 1). As previously, participants interacted with the virtual environment by placing their right index finger into a custom splint attached to the end effector of the Phantom.

The virtual system consisted of one of three possible virtual objects (all cylinders oriented with the flat surface parallel to the ground plane) at the left end of the

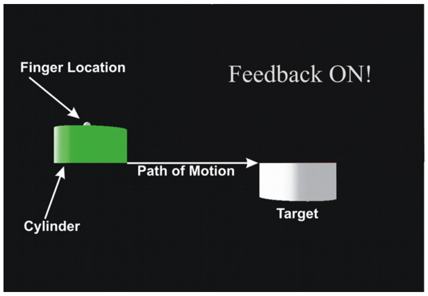

Fig. 4. Example screenshot of the visual feedback used in Experiment 2.

workspace. Three cylinders with distinct stiffness characteristics modeled after the force-displacement relationship of a disposable plastic cup were used. The stiffness characteristics of each box were defined as two continuous piecewise functions of vertical displacement. For displacements less than 1.7 cm, a linear stiffness (e.g., $F = kx$) was defined; for displacements greater than 1.7 cm, the force-displacement was defined by a quadratic polynomial (e.g., $F = k_1x^2 + k_2x + k_3$). Stiffness coefficients employed are shown in Table 1. Force required to overcome the friction to translate the cylinder was defined as 1.2 times the force at displacements of 1.7cm. After a sufficient normal force was applied to the cylinder, the participant was able slide the object to a target located 12.1 cm to the right. The force threshold to "break" each cylinder was defined as 0.75N greater than the normal force required for movement. Three boxes of varying levels of stiffness were used, with cylinder 1 at the lowest stiffness and cylinder 3 at the greatest.

The visual feedback was a real time depiction of the location of the finger in the virtual environment (shown as a sphere), and the position of the object. No deformations of the object were shown, and visual feedback of finger location was occluded during penetration. Figure 4 shows a screen shot of the feedback during interaction with the environment.

TABLE I

STIFFNESS COEFFICIENTS OF VIRTUAL CYLINDERS

coefficients	Cylinder 1	Cylinder 2	Cylinder 3
k (N/cm)	0.34	0.68	1.02
k_1 (N/cm^2)	4.65	9.59	18.55
k_2 (N/cm)	-14.33	-30.67	-56.17
k_3 (N)	11.55	25.56	43.86

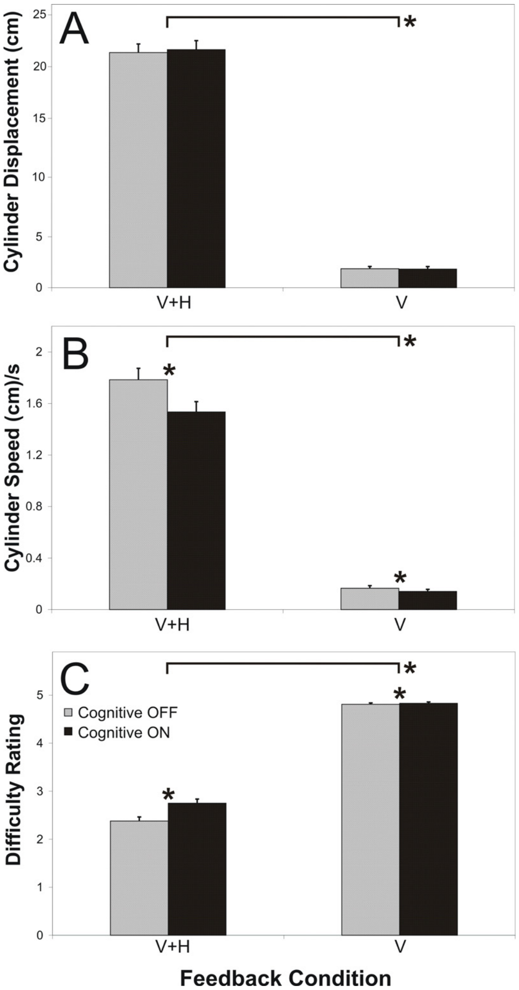

Fig. 5. Summary of results of Experiment 2. Bracketed asterisks show significant ($p < 0.05$) effects of feedback condition on performance outcomes, whereas asterisks shown immediately above data bars show significant effects of the cognitive task.

B. Experimental Protocol

Participants were N=8 unimpaired, right-handed males, ages 19 – 28 (MEAN 22.8, STD 3.3). Over 1 hour, participants completed 120 trials of interaction with the virtual system. Participants were asked to slide a virtual cylinder across the workspace to reach a target area as quickly as possible without breaking the cylinder.

During interaction, participants sat with their forearm resting on the front of the workspace, with their hand free to move about the 3D workspace. Trials were presented in 10 blocks, randomized within block by cylinder (1, 2, 3), feedback (V, V+H), and cognitive load (ON, OFF). Trials ended when the cylinder reached the target or was broken.

The cognitive load consisted of an auditory n-back test, as described in Experiment 1. Due to the change in the motor task, no masking noise was used. At the end of each trial, the participant was asked to report the difficulty of completing the motor task on an ordinal scale 1 – 5, in which 1 was very easy and 5 was very difficult.

Performance variables were cylinder displacement, average cylinder speed (cylinder displacement normalized by trial length), and difficulty ratings. Data analysis was performed using MATLAB (Mathworks, Natick MA). General linear models in Minitab Statistical Software (Minitab Inc., State College, PA) were used to assess the effects ($p \leq 0.05$) of feedback, cognitive load, ω_n, subject, and block on each outcome, with *post hoc* two-sided Tukey's Simultaneous tests.

C. *Results*

A summary of the relevant results from Experiment 2 is shown graphically in Figure 5. A five factor ANOVA showed statistically significant effects of feedback condition, cylinder, block, and participant on cylinder displacement, but no effect of the cognitive task. *Post hoc* testing showed that participants were able to move the cylinder further during the V+H than V condition.

A five factor ANOVA showed statistically significant effects of feedback condition, cognitive task, cylinder, block, and participant on the average cylinder speed. P*ost hoc* tests showed that participants were able to move the cylinder with significantly greater average speed during V+H than V alone.

A five factor ANOVA showed statistically significant effects of feedback condition, cognitive task, cylinder, block, and participant on the difficulty ratings. P*ost hoc* tests showed that participants gave significantly higher difficulty ratings during V than V+H condition, and that participants rated trials with a simultaneous cognitive task as more difficult than those without.

IV. DISCUSSION

A. *Influence of context on the effects of haptic feedback on object manipulation*

The aim of the current work was to understand the role of force/haptic feedback using a robotic interface in unimpaired participants in order to assess possible approaches for providing sensory feedback for control of prosthetic hands. The expected outcome was that unimpaired participants would show increased motor performance with the addition of haptic feedback. Contrary to expectations, Experiment 1 showed that participants had increased task performance *without* haptic feedback.

Detrimental effects with the addition of congruent haptic feedback is at odds with [3], in which participants were able to excite a virtual rotational inertia through a spring at the system's natural frequency more successfully with combined visual and haptic feedback than with visual feedback alone. In that experiment, participants grasped a handle, performing rotation of the handle through pronation-supination of the arm. Spring stiffness was kept constant throughout trials, with the moment of inertia determined by the desired natural frequency.

Conversely, Israr et al. [12] also asked participants to excite a linear virtual two mass system connected by a spring and damper at its natural frequency by manipulating a joy stick which was directly coupled with the motion of one of the virtual masses of the system. System parameters were changed during adaptation catch trials, and three pairs of target systems were tested. In each system the stiffness, mass, or both were changed to achieve the desired natural frequency. They did not find a significant effect of adding haptic feedback to visual feedback, except in the case in which the stiffness was modified to determine the natural frequency: when higher natural frequencies were set by modifying the spring stiffness, adding haptic feedback to visual actually *increased* the error in system excitation.

Israr et al. [12] hypothesized that the differences between their results and [3] were due to differences the training. In [3], natural frequencies were changed in every trial, whereas [12] over-trained participants in the dynamics of each system. However, the results shown here in Experiment 1 replicate those found in [12], even though the participants were subjected to different natural frequencies in every trial.

There are other differences between the motor task used in Experiment 1 and previous studies [3, 12]. Both [3] and [12] asked participants to use their entire hand to manipulate an oscillatory virtual system, although in [3] the system was rotational, and in [12] linear. In Experiment 1, participants interacted with a linear oscillatory system with a single finger. It is possible that the effects of differences in training for a whole hand motor task are not consistent with a task performed with a single finger. Another explanation is that the addition of haptic feedback increases task performance of exciting rotational but not linear oscillatory virtual systems. Regardless of the reason, the robotic interface designed in Experiment 1 did not produce the hypothesized results.

Alternatively, in Experiment 2, haptic feedback was crucial to task performance. We postulate that the difference in the results stems from the fact that the motor task in Experiment 2 was more functionally relevant to participants than the task from Experiment 1. Although interacting with a spring-mass system such as that utilized in Experiment 1 is not a completely new experience for most individuals, it required more explanation of what a natural frequency was to the participants prior to the experiment since a "finding a natural frequency" task is not performed often in daily life. Conversely, applying appropriate normal force to an object to allow for translation without breakage is a typical task used in daily life. While we do not know whether prosthetic hand users have difficulties matching natural frequencies of systems, we do know that they have difficulties with appropriately applying normal force to delicate objects (e.g., picking up and manipulating a disposable plastic cup).

Another possible factor is the variability in feedback modality. It has been shown that the relative importance of visual and haptic feedback is based on the variability in each modality [4]. The visual feedback available in the robotic interfaces used here used visual feedback of similar quality, but the frequency content of the visual feedback could have played a role. The higher frequency oscillatory behavior in Experiment 1 may have been outside the typical range of haptic feedback, whereas Experiment 2 involved comparatively low frequency movements.

Finally, it is also possible that the benefit of haptic feedback is more pronounced for more difficult tasks, as has been previously shown for object manipulation [13]. As shown in Figures 3 and 5, the difficulty ratings were somewhat higher for Experiment 2 than Experiment 1. However, difficulty ratings were not perfectly correlated with objective measures of task performance, with Experiment 1 in particular showing substantial decoupling. For instance, in Experiment 2 difficulty correlated with cylinder speed with R = -0.744, whereas difficulty was correlated with specificity with only R = -0.205 in Experiment 1. Our future work will investigate this further by making Experiment 2 easier to conduct through changing the friction and thresholds for object breakage. Ultimately, differences in the conclusions between the two experiments were most likely due to contextual differences as a result of the functional relevance of the motor tasks.

B. Effects of cognitive load on object manipulation

The addition of a cognitive load caused variable changes based on experiment. In Experiment 1, only difficulty ratings were increased by the addition of the cognitive task. Although individuals were informed prior to testing that difficulty ratings should be in response to the difficulty of the motor task, some subjects may have incorporated the difficulty of the cognitive task in their response because they perceived the haptic task as relatively easy compared to the cognitive task.

On the other hand, in Experiment 2, not only were difficulty ratings significantly increased during the cognitive task, but the cylinder speed was significantly reduced. This is in contrast to the cylinder displacement, which did not show an effect of the cognitive task. Essentially, the presence of a cognitive task did not have an effect on the ability of participants to effectively translate the box toward the target, but caused them to do so at a significantly slower average speed. These effects further recommend the robotic interface used in Experiment 2 for future studies investigating the use of augmentative feedback for control of a prosthetic hand. In these future studies, differential effects of cognitive load will be used to further discriminate between control schemes to discover the optimal mode of supplying force-based feedback to facilitate quick and easy adoption by the user.

V. CONCLUSIONS

This work compared the results of testing for the role of force/haptic feedback in task performance using two robotic interfaces. The interface employed in Experiment 1 was based on a previously used set-up in the current literature. The interface used in Experiment 2 was a novel protocol based on the functional task of manipulating an object with the competing goals of overcoming friction without breaking the object. Despite their similarities, the differing experimental contexts of the two robotic interfaces resulted in divergent results. Thus, contextual effects such as functional relevance should be considered in robotic experiments to characterize the role of multisensory feedback in object manipulation.

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