Co-Location of Force and Action Improves Identification of Force-Displacement Features

Jeremy D. Brown* University of Michigan Ann Arbor, MI USA

R. Brent Gillespie† University of Michigan Ann Arbor, MI USA

Duane Gardner‡ University of Michigan Ann Arbor, MI USA

Emmanuel A. Gansallo§ University of Michigan Ann Arbor, MI USA

Abstract

Haptic display is a promising means to deliver sensory feedback to an amputee from an upper limb prosthesis equipped with electronic sensors. Haptics, however, describes a diverse set of sensory and perceptual modalities. The question arises: which modality might best serve the purposes of the prosthesis wearer, and which body site should be used? To begin to answer these questions, we have conducted an experiment involving n=14 participants in which reaction force was displayed either to the same hand used to explore a virtual object (co-located condition), or to the opposing hand (non co-located condition). In randomly ordered trials, reaction forces were derived from the commanded motion according to one of three force-displacement relationships, describing a linear spring, a softening spring, and a stiffening spring. All springs shared a common rest length and terminal force. Results indicate a significant difference between the co-located and non co-located force display conditions in terms of identification accuracy and time length. Our findings suggest that those haptic modalities that are capable of coupling action and re-action will provide the most utility to amputees with an upper limb prosthesis.

Keywords: human-machine interface, prosthetics, sensory substitution

1 Introduction

Technological advances in electronics and mechanical hardware have opened up a tremendous opportunity to engineer new prosthetic devices that fully replicate the form and function of a lost upper limb. Advances in neural interface, including capturing user intent and relaying sensory feedback through bioelectronic transducers appear to hold significant promise as well, but these wetware technologies seem to lie a bit further out than the hardware [1, 4, 15, 20, 24]. Is there anything to be done to interface new prosthetic designs in the meantime? What can be done to discern user intent without breaking the skin, and what can be done to engage physiological receptors for sensory feedback?

To discern user intent noninvasively, a number of technologies are available and even commercialized, including electromyography (EMG) and slaving prosthetic joints to physiological joints on the body (body-powered prosthetics). To display signals acquired by electronic sensors mounted on the prosthesis, however, relatively few technologies have been developed. Direct vision is already available to the prosthesis wearer of course, but one of the features most requested by prosthesis users is the ability to perform tasks without having to visually monitor interactions between the prosthesis and task object [2].

*e-mail: jdelaine@umich.edu

†e-mail:brentg@umich.edu

‡e-mail:dgardn@umich.edu

§e-mail:emmangan@umich.edu

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It is useful to note that any attempt to relay sensory feedback from electronic transducers on a prosthesis to the body of the amputee is a challenge in sensory substitution. Generally, the sensory receptors and nerve bundles that previously served the hand are no longer available to be stimulated across the skin. What is stimulated at the display site, the residual limb or other part of the body, pertains to a distal sensing site, a site on the worn prosthesis. Thus, there is to some extent a referral or translation that must be resolved by the brain. Ideally, the prosthesis will be adopted into the body schema of the user—the prosthesis becomes a part of the body.

Waiting to be developed for application in prosthetics is quite a suite of haptic display technologies: vibrotactile [7, 9, 14, 23, 26], skin stretch [17, 28], squeeze and nudge displays [11], force feeback [21] and force feedback through exoskeletons that span joints on the residual body [12, 13], motion display [5, 18], and maybe electrocutaneous stimulation. Perhaps if we could characterize the information flow rates and the just noticeable differences for each of these display technologies, we would be in a better position to select the best technology for a given prosthesis. The displays that achieve the highest information transmission rates would certainly rise to the top. However, it might be the case that the appropriateness of a particular display technology depends on the task for which the prosthesis is employed. Indeed, we expect that the traditional psychophysical parameters, which explain the absolute and difference limens of a particular stimulus, will not provide sufficient task-specific guidelines for designing displays that incorporate that stimulus into the interface of recently developed prosthesis devices. In particular, sensorimotor processing on the part of the user must be accommodated by the interface design.

Discrimination of object stiffness is the facet of haptic exploration that we have used to begin our exploration of the relationship between display modality and task. Stiffness, or its inverse compliance, is a property of an object that may be determined through haptic exploration and often plays an important role in manipulation. Stiffness expresses the relationship between force and displacement and cannot be determined without deforming an object. Also, even though stiffness can be inferred from vision alone [10], the measurement has high variability, and depends heavily upon the ability to discriminate object deformations under common forcing conditions. Note that stiffness variations that occur during object deformation or because of nonlinear force-displacement relationships often suggest brittleness or a tendency to break. Also, except by the visual methods described above, stiffness discrimination is not possible with today's commercially available myoelectric upper limb prostheses. Yet stiffness is an important cue for identifying objects, and for assessing the composition of objects and tissues. We discriminate stiffness when we squeeze a fruit in the grocery store, shake hands, and sort objects in our pocket.

The stiffness of rigid objects and objects with surfaces that are deformable beyond the sensitivity of the cutaneous senses is encoded in a force/motion relationship [3, 25]. Therefore, when discriminating stiffness using sensory substitution, it seems that force feedback would be most appropriate. To investigate this claim, a comparison of force feedback and say, vibrotactile feedback would be one place to start. In such a case, however, it would be incumbent on the investigators to first determine the respective psychophyisical parameters of force feedback and vibrotaction at the particular display sites, so that the two modalities would operate on equal footing. In this paper, we apply that same idea to an experiment designed up front as an apples-to-apples comparison. We locate the display of force feedback on two sites of the body that are as similar to one another as possible: the two hands. One location happens to be the same as that used to generate the motion imposed on the object being explored. We call this the co-located site of display. The condition to be compared is the non co-located case, where the force feedback is delivered to the opposing hand.

In simple information processing terms, there should be no difference in the psychophysical parameters across conditions, except perhaps differences due to hand dominance. These can be accounted for by balancing the experiment design; that is, changing the site of command or action, as well as display. In sensorimotor terms, however, the two conditions could not be more different: In the non co-located condition, the force and motion cues have been dissociated from a common point of contact, or 'port'. Only in the co-located condition are the motion command and force feedback at work to couple the two systems, body and object. Only in the co-located condition is mechanical work being performed. We consider the non co-located condition to be a model for any other haptic display modality that does not play a role in coupling the dynamics of the user and remote environment.

In our previous work [6], we compared the co-located and non co-located conditions, but these locations where at the elbow and pertaining to interactions performed through a motorized gripper acting as a prosthetic hand. That is, the force feedback embodied a sensory substitution, or referral from a site more distal on the body schema. In this paper, we remove the sensory substitution and ask our participants to discriminate the stiffness of virtual objects using their hands, as when probing the objects through a stylus held in the fingers.

We also remove the terminal force cue, which has been demonstrated to be a salient cue for discrimination of the stiffness of objects [27]. We ask our participants to identify one of three objects, the first of which is described by a linear spring, the second by a softening spring, and the third by a stiffening spring. The three force/displacement relationships are designed to have the same terminal force, and our participants were asked to depress the objects to the same degree. Thus, the only cue available was the shape or force relationship across the displacement range.

1.1 Hypothesis

We expect that the brain interprets haptic information most readily when force/motion coupling exists at the contact through which the haptic information is presented. Such coupling is necessarily present in experience with the physical world. Removing this coupling requires a re-association in the brain that contradicts the expected meaning of a haptic cue based on prior experience with the physical environment. Forcing the brain to make this adjustment should have a deleterious impact on the performance of the task.

2 Methods

2.1 Experimental Setup

Our testing apparatus consisted of two linear voice-coil motors each with a 30mm throw lying parallel in the horizontal plane as shown in Figure 1. Each motor was equipped with a linear optical encoder (US Digital EM1-0-500) and driven with an H-Bridge amplifier (Advanced Motion Control 12A8). In addition, a 1kg rated beam load cell (Transducer Techniques LSP-1) was mounted to monitor force between the user and each motor carriage. A Dell Precision T1500 Desktop with a Sensoray 626 PCI data acquisition card was used for data acquisition and computer control.

A board was placed over the motors so participants could not see the carriages move. Participants interacted with the motors by placing the thumb and index finger of one or both hands on the loadcell. A hand-rest was provided to assist participants in holding the motor steady in certain conditions (Figure 1).

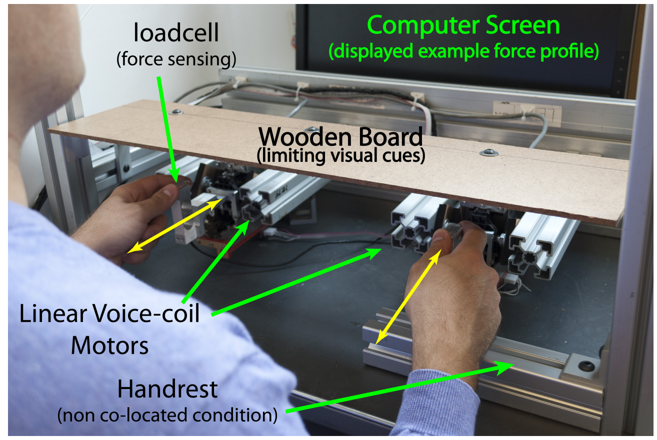


Figure 1: Testing Setup showing two linear voice-coil motors with loadcells attached. Yellow arrows indicate direction of motion.

The motors were operated in an open-loop position-force control architecture to render three virtual springs with the following linear and non-linear constitutive laws:

$$F_1 = K_1 x$$
$$F_2 = K_2 \sqrt{x}$$
$$F_3 = K_3 x^2$$

where ($K_1 = 0.6075\,\mathrm{N/mm}, K_2 = 3.0979\,\mathrm{N}/\sqrt{\mathrm{mm}}$, $K_3 = 0.0234\,\mathrm{N/mm^2}$) respectively. Each spring had a resting length of 26mm. All three springs produced 0N of force at the resting length and 15.8N when compresed 26mm as shown in Figure 2.

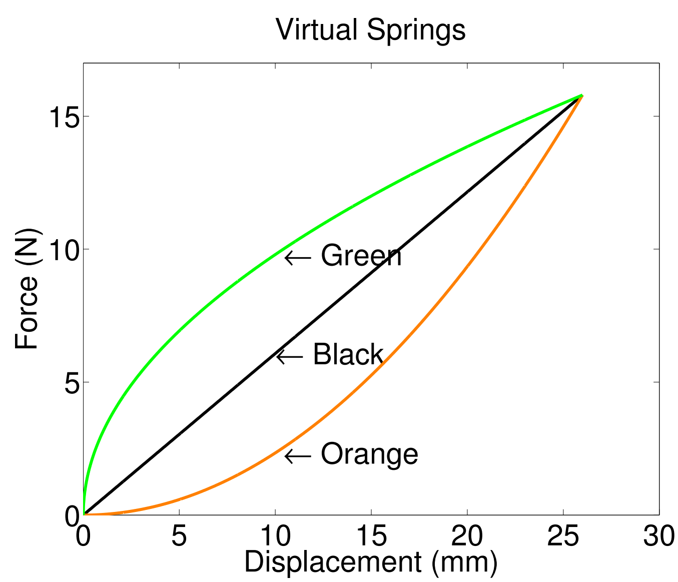


Figure 2: Virtual Springs (Black, Orange, Green)

There were two conditions tested. In the first (co-located) condition, the displacement(x) and resultant force ($F_{i,\ i=1,2,\text{ or }3}$) output of only the right motor was used to display the virtual springs. In the second (non co-located) condition, both motors were used to display the virtual springs as the motor on the left measured displacement (x) and the motor on the right was commanded with the resultant force ($F_{i,\ i=1,2,\text{ or }3}$).

2.2 Experimental Protocol

In the present study, n=14 able-bodied participants were tested. All participants signed an informed consent document approved by the University of Michigan's Institutional Review Board. Of the 14 participants, 13 reported their dominant hand being their right and 1 reported their dominant hand as their left. In the co-located condition, participants explored the virtual springs with the right motor only. In the non co-located condition, participants explored the virtual springs using the left motor to control the displacement and the right motor to sense force. In order to best percieve the force in the non co-located condition, participants were instructed to hold the motor carriage in the middle of its throw range and use the handrest to ground their hand and hold it steady.

Prior to testing, participants were given a training session to become familiar with the operation of the device. In this session, a sample virtual object (Figure 3) was displayed on the computer screen, and participants were given an opportunity to explore it in both the co-located and non co-located conditions. The force-displacement graph, as well as its relationship to the displacements and forces produced by the motors, was explained to the participants. The sample object was only used to familiarize participants with the operation of the motors and was not used in the actual test. The three virtual springs used in testing were given a non-descriptive identifier ('black,' 'orange,' and 'green'). Participants were asked to use these names, and were told that the objects might consist of linear and non-linear components. They were not given an opportunity to explore any of the three test springs in either condition, nor were they given any clues as to the association between the three springs and their names prior to beginning the test. They were also not shown any graphs of the springs used in testing. Participants were told that the goal of the experiment was to accurately identify the objects in the shortest time possible in both conditions.

The test consisted of 60 trials with a short break after the first 30 trials were completed. Each trial alternated between the co-located and non co-located conditions. During each trial, one virtual spring was presented at random, and the participant was asked to complete a three alternative forced choice identification of the virtual spring presented. Each trial started when the tester verbally announced "begin," and ended when the participant verbalized their object choice. Correct answer feedback was provided at the end of each trial by the tester verbally providing the correct name ('black,' 'orange,' 'green') of the object just presented. In both conditions, the participant was instructed to explore and probe the object as many times as needed using the entire displacement range. Dwelling or wiggling in any particular region was discouraged to ensure that participants used the entire work profile to identify the spring instead of the force in a single small region. Participants were instructed to refrain from looking at their hands or the motors to minimize visual cues. There were no unique identifying auditory cues to minimize, so the use of noise-canceling headphones was unnecessary. The tester registered the answer on an answer sheet, and time was recorded by the computer.

Following the test, subjects were given a post-test questionnaire which asked them to describe the differences, if any, that they noticed between the three springs and between the two conditions. Participants were also asked if they preferred one condition over the other.

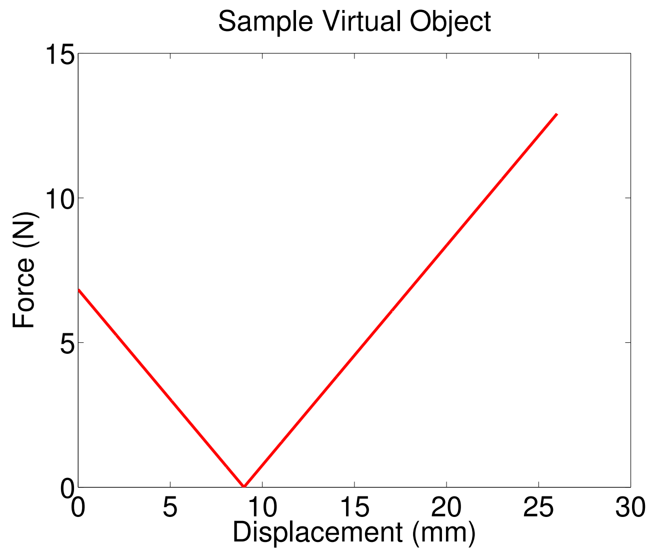


Figure 3: Sample object displayed to participants prior to testing. Used to familiarize participants with the motor operation.

2.3 Performance Metrics

We measured the kinematics and kinetics of both motors. In addition, we recorded the spring presentation and participant choice in the object identification task. In order to test our hypothesis, we set as performance metrics the object identification accuracy (%), trial duration (s), number-of-probes, and probe rate Trial duration was measured as the time in milliseconds from the time the tester announced begin to the time the participant verbalized their object choice. To measure the number-of-probes, two threshold values were set at 5mm and 26mm. Passing both thresholds in one direction as the spring was compressed accumulated a 0.5 (half) probe. Subsequently passing both thresholds in the opposite direction as the spring was released accumulated another 0.5 probe. Passing only one threshold in either direction accumulated 0.25 probe.

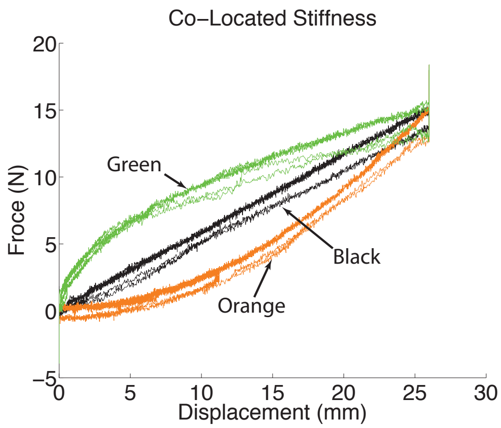
2.4 Assessments and data analysis

Our statistical analysis corresponded to a pairwise t-test of each outcome measure in both conditions. For each test, the outcome measure was averaged over multiple trials for each subject. A p-value of .05 was used as the threshold to determine statistical significant.

3 Results

In analyzing the results, we found a bimodal distribution, representing two distinct groups of participants. 11 of the 14 participants followed very similar and consistent trends with an overall trial duration average of 8.6 $\pm$1.8 seconds and an overall average number of probes of 2.6$\pm$0.4. The other three participants followed a completely different and more volatile trend with an overall trial duration average of 24.2$\pm$10.5 seconds and an overall average number of probes of 5.6$\pm$2.2. In addition, the outlier group differed from the normal group in that there were no clear learning effects on identification performance. Despite these differences, however, overall object identification performance was almost identical to that of the normal group: 53$\pm$30% and 53$\pm$15% respectively. Since there were no significant differences between the two conditions for the outlier group, we will continue our analysis including only the normal group.

The kinematic data (from the encoders on both motors) contains information regarding what the participants experienced when each object was probed. The force/displacement traces recorded from the motors and loadcells for three seperate co-located (Figure 4a) and non co-located (Figure 4b) trials for participant 7 are shown. These traces have been colored (in post-processing) by object and demonstrate that the virtual objects displayed to the participants do fall into three distinct groupings based on their characteristic shape. These relationships hold for every participant, regardless of their respective rate of interaction.



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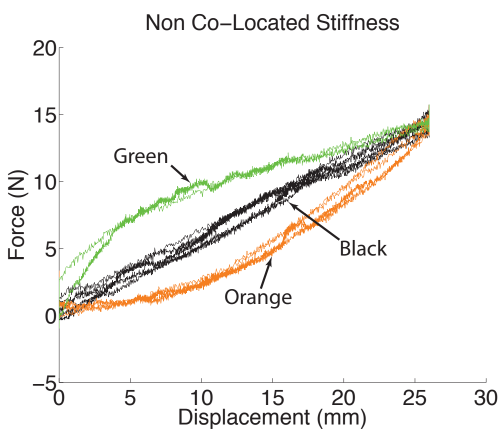


(b)

Figure 4: Force/displacement traces for the virtual objects displayed to participant 7 in three co-located and three non co-located trials

Object identification accuracy increases during the first seven trials of the co-located condition, suggesting that learning is taking place. For the non co-located condition, there is not an observable increase to suggest learning. By the second set of 30 trials, object identification accuracy is mostly stable in both conditions (Figure 6a). On average, for the last 30 trials, participants were more accurate in the co-located condition (M=63.64%, SE=7.8%) than in the non co-located condition (M=52.12%, SE=7.93%), $t(10) = 4.03$, $p < .01$ (Figure 5a). It is worth noting that for the last two trials in the non co-located condition the average percent correct increased from 54.55% to 72.73%. Whether this is the beginning of a sustained increase can not be answered with results from the current experiment.

Trial duration decreased in the first set of 30 trials for both conditions. The decrease in the co-located condition lasts for all 15 trials in that condition and that for the non co-located condition lasts for about nine trials. By the second set of 30 trials, trial duration levels off for both conditions and remains stable throughout the remainder of the test (Figure 6b). The levels at which they level off, though, differ by condition. On average, for the last 30 trials, trial duration was significantly lower in the co-located condition (M=6.85s, SE=0.63s) than in the non co-located condition (M=8.48s, SE=0.77s), $t(10) = -3.82$, $p < 0.01$ (Figure 5b).

The average number of probes remained stable in both conditions for the first set of 30 trials (Figure 6c). For the second set of 30 trials, there was a steady increase in the number of probes in the co-located condition from 1.89 probes to 2.68 probes. The average number of probes for the co-located condition in the second set of 30 trials was 2.24±0.79. For the non co-located condition, the number of probes remained stable with an average of 2.72±1.57 probes. The difference between the two is not significant.

The probe rate for the first set of 30 trials in the co-located condition increases from 0.11 probe/sec in trial 1 to 0.31 probe/sec in trial 12. In the non co-located condition there was a slight increase over the 15 trials from 0.21 probes/sec to 0.28 probes/sec. In the second set of 30 trials, the probe rate was stable with an average of 0.29±0.02 probe/sec in the co-located condition and 026.±0.03 probe/sec in the non co-located condition.

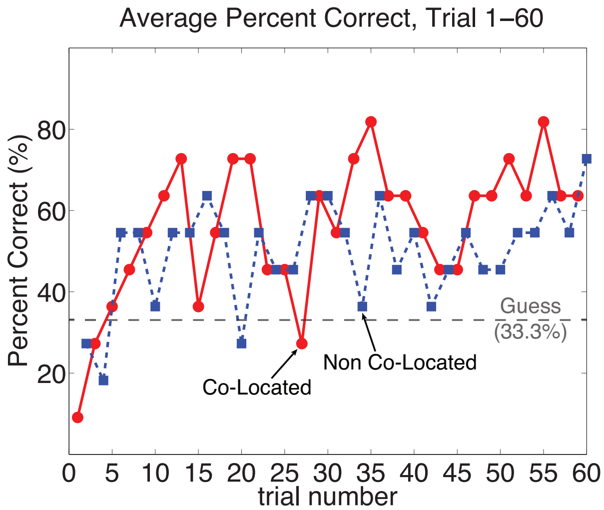
There was a significant relationship between the probe rate and the object identification accuracy in the co-located condition in the first set of 30 trials, $r = .60$, $p < .05$.

4 Discussion

In this current study, we have reduced our original comparison of haptic modalities down to a fundamental comparison of how these modalities couple the user and the environment. Although a traditional psychophysical study would provide more insight in terms of the scalability of the display in each condition, it would not provide the task-specific knowledge, such as learning affects, gained from the current study. Having knowledge of the absolute and difference thresholds of a display is only half the battle. The other half involves interfacing that display to the user in a context that supports easy adaptation. We are no longer only in search of an ideal display, rather we are also concerned with the ideal interface.

In both conditions, the same information is available to the user (Figure 4), and in both conditions the user explored the objects using the principles of active touch [19]. In the co-located condition, this information comes in a format consistent with the user's prior experience in the physical world: force and motion are coupled and exchanged across the same hand or joint. In the non co-located condition, the motion form the left hand has to be synthesized with the force sensed in the right hand. This synthesis appears to affect the participants' ability to perform the task as well as they did in the co-located condition. Although all the outcome measures were not statistically significant across conditions, the two most important, identification accuracy and trial duration, were.

The first set of 30 trials differs from the second set in that learning is taking place in the first set. As a result, participants take more time, use more probes, and subsequently utilize a smaller probe rate to explore the unique features of each spring. As the test proceeds, these measures all plateau out to more stable variations. The learning that occurs is more identifiable in the co-located condition but can be seen in the non co-located condition in trial duration, number-of-probes, and probe rate. In terms of object identification accuracy, it seems as though the objects are learned in the co-located condition and that knowledge is used to make educated guesses in the non co-located condition. For example, in the co-located condition, the percent correct starts below guessing and continues to rise with every successive attempt before eventually plateauing. For the non co-located condition, the accuracy starts around guessing, then gets worse before getting better. If participants are relying upon knowledge from the co-located condition to assist with the non co-located condition, they are trusting knowl-



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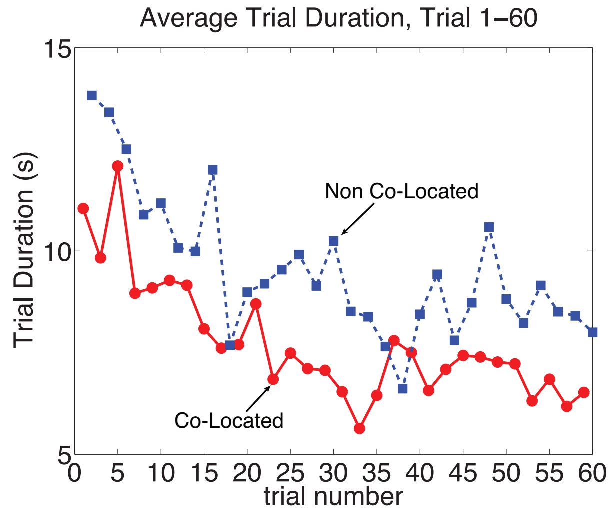

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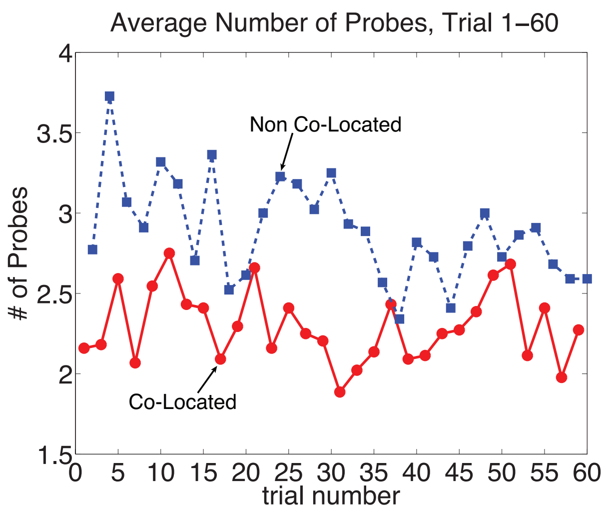

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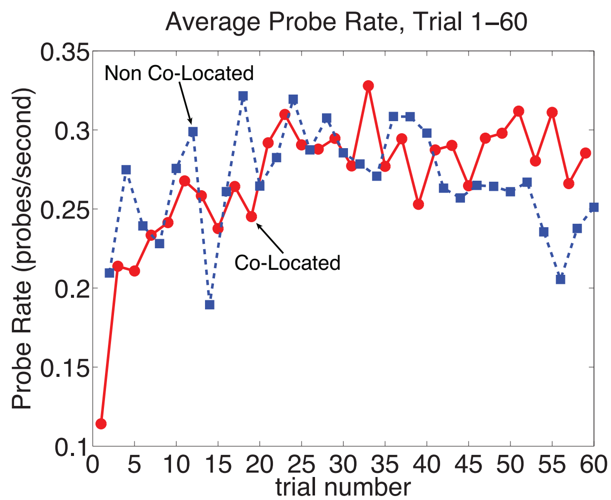


(d)

Figure 6: Average Outcome metrics for all normal subjects trial 1-60. Object identification accuracy (a) trial duration (b) number-of-probes (c), and probe rate (d).

edge that itself is not substantially different than guessing. As a result, performance declines.

Also, the fact that the correlation between probe rate and object identification accuracy was significant in the co-located condition strengthens the argument that participants were definitely learning in that condition.

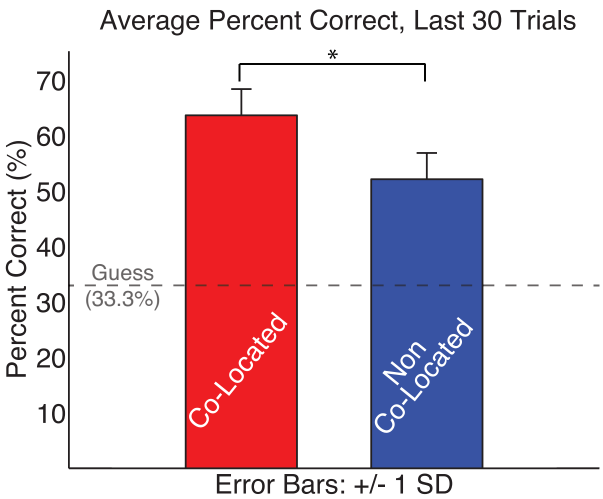
In the second set of 30 trials, the outcome measures have plateaued out and are mostly stable. Although participants do have to do some re-familiarization after the break between sets of trials, the true learning process has ended. For these last 30 trials, the results tell a very clear picture.

In terms of object identification accuracy, the fact that accuracy in the non co-located condition stays close to 50% could be attributed to the fact that knowledge of the springs is better understood in the co-located condition, and this knowledge is then used to help rule out one of the three choices. Participants could very well still be guessing in the co-located condition, with the exception that they only have two choices to choose between. In contrast, the accuracy in the co-located condition is approaching 66%, suggesting that most subjects have a handle on at least two springs.

In terms of trial duration, participants are on average 1.63 ± 1.41 seconds faster in the co-located condition. This suggests that the synthesis of decoupled information requires more time than the information that is presented in a coupled manner.

The number-of-probes and the probe rate were not significantly different between conditions. This supports the interpretation that participants sought some consistency between conditions. It also suggest that participants had some ideal concerning the number-of-probes and probe rate that ensured the best accuracy.

These findings suggest the objects are more difficult to discern in the non co-located condition. It could be that the non co-located condition forces the brain to restructure its internal mapping, whereas the co-located condition is consistent with the mapping created from prior experience. Or it could be that synthesizing the information from two hands necessitates the use of higher level processing than does the co-located condition. Whatever the case,



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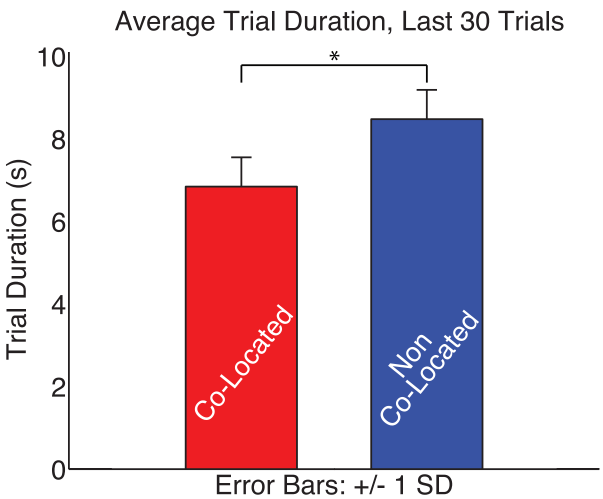

(b)

Figure 5: Performance metric averages across all normal subjects all conditions in the last 30 trials. Error bars represent the true error adjusted to reflect a repeated measure design. (a) Object identification percentage. (b) Trial duration in seconds.

it is evident that the non co-located condition is more taxing - requiring more time and a loss in accuracy. The co-located condition on the other hand we believe relies more on lower level processes and is more intuitive to the participant.

In our previous study [6] we found there to be no difference between the co-located and non co-located conditions. This finding was consistent with results [8, 27], which state that the terminal force can be used to determine the compliance of an object in the absence of work cues. The terminal force cues were available to distinguish objects in our previous study. Since our objects in that study were linear leaf springs, participants could ignore the work cues altogether and utilize only the terminal force cues. In our current experiment, we eliminated the terminal force cues by creating virtual springs with the same terminal force. What we did change however was the force-displacement profile of each object. Creating three distinct objects with different force-displacement curves and the same initial and terminal force required subjects to utilize the work cues in the co-located condition and the force-profile in the non co-located condition when exploring the objects.

Performing the non co-located condition accurately required holding the right hand as still as possible to only sense the force induced by the motion in the left hand. A few participants mentioned having difficulty sensing force in the right hand because of the motion induced by the force. Still, over half of our participants reported that the co-located condition was easier overall than the non co-located. Note that the range of forces in both conditions was not within the Just Noticeable Difference (7%) reported [16, 22] for force sensing.

Although most participants reported their right hand as their dominant hand, the current protocol does not take into account handedness. To balance the protocol, participants should be tested with the motors switched in the two conditions; left motor only for the co-located condition and both motors for the non co-located condition, with the right motor controlling displacement and the left motor displaying force.

Demonstrating that there is a significant difference in the manner in which an object is explored should have an impact on the design of haptic interfaces. Those interfaces that provide force/motion coupling (co-located action and display) will provide the user greatest utility without additional learning and cognitive processing. Perhaps the best evidence of this can be seen in the utilization of haptic feedback in upper-limb prosthetic devices. Those haptic feedback modalities that provide force/motion coupling, such as force feedback, will feel more intuitive. They will more closely align with the amputee's prior experience than do modalities such as vibrotactile feedback. For an amputee, that means giving them the ability to perform tasks often taken for granted, such as knowing how hard to squeeze a child's hand while crossing a busy intersection.

We have chosen the non co-located condition as an experimental control that allows us to isolate the contribution of force/motion coupling to the performance of a sensorimotor task. The non co-located condition serves as a model for any other haptic display modality that does not serve to couple action and re-action. One important such modality, often used for haptic display and promoted for use in delivering sensory feedback from prosthetic devices, is vibrotactile display. While vibrotaction may be robust and acute, possibly supporting high information transmission rates, and while vibrotactile displays may be a particularly wearable and economical technology, vibrotaction does not generally play a role in dynamically coupling the user to a virtual or remote physical environment. We have shown that, even when information transmission rates are held constant across conditions, coupling of force and motion across a single mechanical contact plays a significant role in the processing of information in sensorimotor loops.

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