An asymmetry in force perception contingent on motion reversal

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ABSTRACT

We investigated the perception of differences between direction-dependent, movement-opposing forces. The magnitude of these forces changed in whenever the direction of motion reversed. They were felt by participants during an experiment that required them to scan a virtual surface, represented by a planar haptic interface, via left-right motions of the index finger. We found that individuals are surprisingly insensitive to changes in opposing force magnitude that are contingent on reversals in direction of motion, despite large contrasts in force magnitude. Forces of 1 N failed consistently to be discriminated from forces of 0 N during sequential presentation at the highest speeds. As the mean scanning speed of the digit was reduced, the effect progressively vanished. The effect we observed is simple and robust enough to be demonstrated on virtually any haptic force-feedback interface. We suggest possible interpretations based on temporal information processing in the nervous system, on physiology and biomechanics, and through inferences that the nervous system may rely on to relate motor commands to sensory input during dynamic haptic interaction. The results obtained raise fundamental questions about the perceptual interpretation of kinesthetic stimuli involving rapid movement, and may also suggest a reconsideration of requirements for haptic interfaces.

Index Terms: H.1.2 [User/Machine Systems]: Human Factors—Human information processing; H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

Forces and displacements vary in complex, time-dependent ways during normal haptic exploration of objects and surfaces with the hand or a tool. They can arise due to spatial variations in object properties, object geometry, tool geometry and dynamics, exploratory movements, or other factors. A major task for the nervous system is to analyze the resultant time-varying sensory-motor signals in order to extract stable percepts corresponding to invariant features of the world. However, when individuals are asked to attend to and report on the sensory signals themselves, rather than to the environmental interactions that they reflect (e.g., forces felt during exploration of a surface instead of physical surface properties), perceptual results can conflict with the impression of stability that is formed via the senses. In this contribution, we report on one situation of this kind, involving basic asymmetries in individuals' abilities to detect changes in the magnitude of movement-opposing forces felt during the scanning of a surface with a finger.

Some unusual haptic effects have been identified that depend on directional asymmetries in force perception, including the "Lead-me" effect of Amemiya et al. [1], which uses asymmetrically oscillating ungrounded forces to give the impression that its user is being tugged in a particular direction. However, a general explanation for how such asymmetries may arise is lacking.

1.1 Perception of unexpected force changes

Prior assumptions about the physical origin of forces and displacements that are felt during haptic interaction are arguably required for haptic sensory signals to be interpreted in ways that are consistent with the physical interactions through which they originate. In the simplest cases, assumptions such as continuity or object constancy are involved. When they are violated, sensory stimuli can meet with unexpected interpretations. The ways in which component signals of haptic experiences may be perceived likely depend on factors like the instantaneous state of the limb (e.g., arm stiffness), the perceptual or motor task being executed at the time of stimulation, and prior expectations or models for the dynamics of the interaction involved. Consider the following simple, yet illustrative, scenarios:

- A constant force field unexpectedly changes in magnitude. Such a force can be regarded as a basic disturbance applied to the (nonlinear) haptic perceptual-motor system. The "unexpected" nature of the stimulus may lead to important inferences (e.g., contact with a previously undetected object).
- A change in force magnitude when the speed of the finger or tool is constant but the direction of motion is changed. This could be the case when the friction coefficient of a scanned surface depends on the direction of exploration – perhaps due to asymmetric microstructure (e.g., fine hairs or asperities aligned along one direction).

Occurrences like these can be thought of as "disturbing" in a few different ways. For example, they may violate basic presumptions such as temporal or spatial continuity. Alternately, they may conflict prior expectations for the relation between motor actions and sensory input during physical interaction – i.e., an "internal model" of the interaction scenario (Sec. 1.2). Either result may lead to a reinterpretation of the felt forces involved. The latter could be perceived as unchanged, or might be felt more prominently if the impression they give conflicts with prior expectations (e.g., the expectation that the same surface scanned identically in two directions should feel the same).

1.2 Force adaptation: movement and perception

While perceptual adaptation to unexpected force changes has received some attention in the haptics literature, the adaptation of movement strategies to modified sensory input has been a topic of extensive investigation in motor control. Numerous studies suggest that individuals compensate for forces that arise during interaction with the environment by forming an internal model of the dynamics of interaction, relating motor commands to sensory input [9, 7, 6, 5, 12]. If the sensory input that is felt during interaction conflicts with what is expected, online error correction and model adaptation may ensue. Such an internal model is instrumental to controlling the musculature so as to reproduce a desired kinematic trajectory (i.e., that of the hand or tool). Studies have also suggested that internal dynamical models play a role in adapting limb impedance to best suit the dynamics of the environment and task – in particular, in compensating for external disturbances during movement [2]. The resulting changes changes in limb impedance

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or forces could also be expected to have important effects on how haptic stimuli are perceived during interaction; For example, the perception of an unexpected force change might be masked by its own tendency to modulate arm impedance. Although there seems to have been limited prior research on this topic, a study of Watson et al. demonstrated that if the limb is required to compensate for an externally-imposed force field during a position-matching task involving pointing with the forearm, both the force exerted by the limb and the position influenced perceived direction, as reflected in the pointing arm [10].

1.3 Perceived changes in movement-opposing forces accompanying motion reversal

In the experiment described below, we explored one situation of this type, using novel stimuli that consist of movement-opposing forces, similar to Coulomb-friction, whose magnitude changes upon each reversal of the direction of motion. We designed the force stimuli such that, over the course of several motion reversals, the force magnitude changes grew from zero to a maximum of 100% of the initial force value. We independently manipulated the speed of exploration. Based on our informal testing, and some of the reasoning outlined above, we expected the perception of these forces to resemble that shown in Fig. 1. We assessed individuals' abilities to perceive the reversal coincident magnitude changes and to determine what effect, if any, the temporal scale, or speed, may have had.

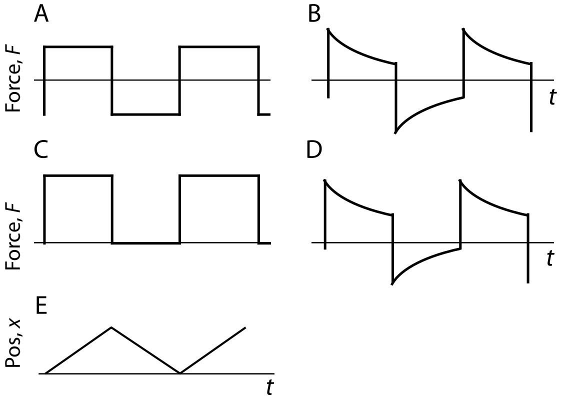

Figure 1: Force trajectories (A-D) corresponding to a position trajectory (E). For a simplified resistive force like the Coulomb friction shown (A), temporal or spatial adaptation may lead to a percept like that shown in B, which resembles a high-pass filtering effect. In such a case, a constant offset in the reference force (C) might have little effect on the perceived force profile (D). Sensory processing of this type emphasizes transient aspects of signals, which could be advantageous for change detection.

2 EXPERIMENT

We conducted an experiment to assess the perception of changes in movement-opposing force magnitude coincident with changes in the direction of exploration during a simple bilateral (left-right) exploratory task with the finger, and the dependence of individuals' abilities to detect such force changes upon the speed of exploration. We hypothesized that the force magnitude changes would be most easily detected at very low exploration speeds, since that regime most resembles one of static force perception. Thus, by varying exploration speed, we aimed to manipulate participants' sensitivity to motion-reversal coincident force magnitude changes.

2.1 Method

Because of the evanescent nature of the effect, the experiment was based on a variation of the psychophysical method of limits. Participants were presented with one-dimensional (left-right) force fields that changed in magnitude when the direction of movement reversed. The forces were explored based on a repeating left-right motion of the finger on the manipulandum. The forces during leftward and rightward motion were initially equal in magnitude, and the difference between them grew on successive reversals. In our procedure, both force values were simultaneously incremented with the difference between values held constant (see "Stimuli"). Participants judged when the magnitudes differed. We selected the psychophysical method of limits for this experiment due to its efficiency, suitability for the exploration mode and stimuli used, and because we expected it to require less cognitive effort on the part of users, who were already taxed with performing simultaneous velocity matching and force comparison tasks, than would be needed with other methods.

2.2 Participants

Seven participants (6 of them male), ranging in age between 20 and 30, volunteered for this study. All of them were research staff at the authors' institution and reported normal touch sensation. All participants were naive with respect to the purpose of the experiment.

2.3 Apparatus

The apparatus consisted of a planar haptic force-feedback device, the Pantograph mkII, that has been extensively characterized in a prior paper [3]. The maximum force the device can exert is approximately 2 N, and the sampling frequency of the computer-in-the-loop control system was 5 kHz. The device has a wide usable frequency bandwidth, from 0 to 400 Hz.

During each trial, participants explored a one-dimensional (left-right) force by using the index finger of their dominant hand to operate the manipulandum of this device; see Fig. 2. They were seated at a desk in a quiet environment with their arm at a comfortable angle. They received instructions and entered responses via the video screen and keyboard of a personal computer (operated using their opposite hand). Participants wore noise-isolating headphones during the experiment in order to aid their concentration. A computer graphic provided a real-time indication of the speed and phase of the exploratory movement for each trial, and an audio metronome also provided a synchronous, auditory indication of the required movement speed (see "Stimuli").

2.4 Stimuli

The stimuli consisted of one-dimensional (left-right) force fields presented via the Pantograph device. The force stimuli were piecewise-constant in each direction, were opposite to the velocity of movement, and could also change magnitude when the direction of motion was reversed, as the manipulandum reached the far edge of the workspace (i.e., after the rightward traversal). A stimulus trial consisted of a sequence of repeated left-right explorations of the workspace. For each stimulus trial, participants began at the left side of the workspace and made a rightward-leftward scanning motion that repeatedly traversed the width of the workspace, thus encountering forces $f_A = -|f_A|$ (during rightward motion) and $f_B = |f_B|$ (leftward). Changes were effected in the forces between consecutive scans according to the psychophysical procedure that was implemented (see Procedure). The tempo of the motion, and hence average speed, was specified by the experimenters, and enforced via an auditory metronome that indicated when the manipulandum should reach each side of the workspace, and a real-time graphic display that showed the left-right movement trajectory to be followed via a left-right moving ball whose motion was imitated. Each rightward or leftward traversal was specified to occur

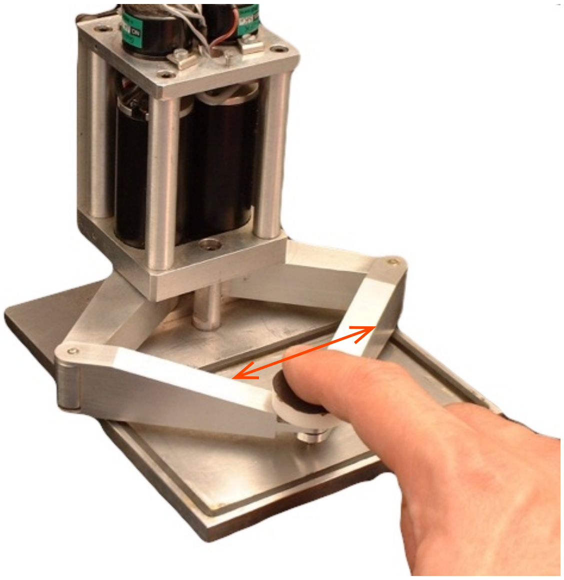

Figure 2: The apparatus consisted of the Pantograph planar haptic interface and the personal computer used to operate and control it. [3]. Stimuli were explored, and forces rendered, in the left-right direction as indicated by the red arrow.

in a time $\tau = d/v$, where $d = 100$ mm was the workspace width and v the mean speed of exploration. Thus, the force and velocity trajectories, $F(t)$ and $V(t)$, were as follows:

$$F(t) = \begin{cases} -|f_A|, & v > 0 \\ |f_B|, & v < 0 \end{cases} \tag{1}$$

$$V(t) = \begin{cases} +v, & 2k\tau < t < (2k+1)\tau \\ -v, & (2k+1)\tau < t < (2k+2)\tau \end{cases} \tag{2}$$
$$\tau = d/v, \quad k = 0, 1, 2, \ldots$$

Here, $V(t)$ represents an idealized velocity trajectory following the indicated tempo. We anticipated that participants would, instead, perform a motion that was non-constant in velocity but that followed the designated mean velocity in each direction, since instantaneous motion reversals are not possible.

A smooth transition from f_A to f_B was insured by switching the force value only when a zero-value of the velocity was detected within a threshold distance from the extremum of motion. (We detected $v = 0$ using a sign detector applied to the adaptive windowing velocity estimator described in [4].)

For each stimulus, participants began at the left side of the workspace and made a rightward-leftward exploratory scanning motion, which they repeated without pause until they responded that the two forces, f_A and f_B felt different (see "Procedure").

2.5 Procedure

At the beginning of each trial, the initial values of movement-opposing forces f_A and f_B were equal and opposite with magnitudes of $f_0 = 0.5$ N. The forces were initially held at these values for a random number n_0 of right-left scans, where n_0 was randomly distributed between 1 and 10 with uniform probability. After the initial, held, portion of the trial, the values of both f_A and f_B were changed by an amount $\Delta f = \pm 0.025$ N after each left-right scan of the workspace. Thus, the difference $|f_A - f_B|$ was held constant, equal to 1.0 N, while the difference in magnitudes, $\Delta F = ||f_A| - |f_B||$ grew by an amount $2\Delta f$ on each left-right scan; See Fig. 3. The change Δf was randomly selected to be positive or negative for each trial (i.e., for each limit procedure), with half the trials in the experiment selected to be increasing (with probability 0.5) and the other half decreasing. After a number $N = n + n_0$ left-right scans, the force values were $f_A = f_0 + \sigma n|\Delta f|$ and $f_B = -f_0 + \sigma n|\Delta f|$, where $\sigma = +1$ or -1 for an increasing or decreasing trial, respectively. The speed for each trial was randomly selected from one of five values, $v = 50$, 100, 150, 200, or 300 mm/s.

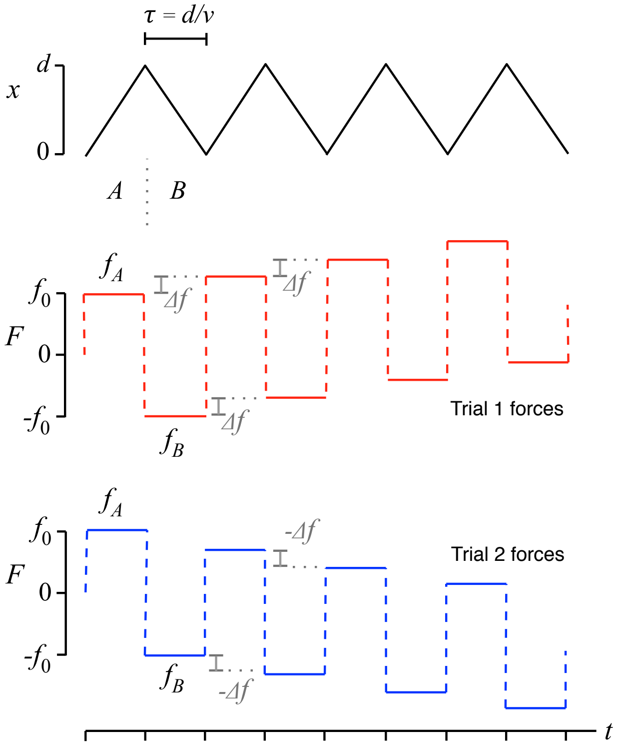

Figure 3: Illustration of two experimental trials, respectively following the "increasing" (red lines, middle plot) and "decreasing" (blue lines, bottom) conditions. Idealized exploratory trajectories for a sequence of four rightward-leftward movements (whose mean velocities were enforced via metronome) are shown in the top plot, with the corresponding displayed forces at middle and bottom. With each left-right movement, the difference magnitude $\Delta F = ||f_A| - |f_B||$ decreases, while the individual forces f_A and f_B grow (shrink) in the "increasing" ("decreasing") condition. The complete trial would continue with further rightward-leftward movements until the participant judged the magnitudes of f_A and f_B to be different. See text for details.

Participants were instructed to respond via keyboard entry as soon as they were sure that the forces felt on successive rightward and leftward scans were unequal. Participants were instructed to avoid guessing. After entering their response, a new trial was begun. If no response was entered after $n = f_0/\Delta f = 20$ scans, the trial was terminated and this event was recorded. n=20 scans were required for one of the two forces to cross the zero-magnitude line, and this is also the point at which the difference in force magnitudes, $\Delta F = ||f_A| - |f_B||$, was maximal, reaching $\Delta F = 2f_0 = 1$ N (i.e., the magnitudes were 0 N and 1 N). Terminating at this point thus ensured that ΔF was increasing throughout the trial and also that all displayed forces were of sufficiently small magnitude that they could be reproduced accurately within device limitations. In order to assess that participants were aware of the forces, the experiment also included catch trials, in which the velocity was randomly selected and no force was displayed. When participants encountered one of these trials, they were required to report that no force was displayed.

Participants completed an instructional phase at the outset of the experiment, during which they practiced with several stimuli in trials that did not produce recorded data. The training period was continued (typically for fewer than 10 test trials) until participants could reliably track the specified trajectory with the specified speed v. During the subsequent, main, experiment, stimuli were presented in block-randomized order, with all five speed values presented in each direction (increasing or decreasing). There were a total of ten stimuli together with one zero-force catch trial in each randomized block of eleven stimuli. The experiment consisted of five such blocks, for a total of 50 stimulus-trials (i.e., 50 limit procedures). Participants were required to pause and rest their hand between blocks of trials. The entire experiment lasted between 20 and 30 minutes.

2.6 Results

For those trials where the magnitudes of the forces f_A and f_B were, after $n+n_0$ trials, judged to be different, the data consist of the minimum change in force, $\Delta F = n|\Delta f|$, that was detected by participants at each given speed value v. Recall that at the end of a trial, the difference in force magnitudes was $||f_A| - |f_B|| = \Delta F$. Trials such that f_A and f_B were not judged to be different in magnitude after $n = 20$ scans (see "Procedure") were marked as such; in the latter case, the magnitude difference $\Delta F = n|\Delta f| = 1$ N was used to provide a lower bound on the required force magnitude difference for that trial. This manifestly underestimated the required force magnitude difference for the affected trials. Since more than 75% of these "not different" trials occurred at the highest two velocities (Fig. 6), our measurement can be regarded as a conservative estimate of the differential force threshold at those velocities, and a conservative evaluation of the effect we report on here.

Each participant was also presented with 5 "no force" catch trials during the course of the experiment, and reported when one of these trials was encountered. These trials were detected at a mean rate of 87%, indicating that participants were mostly, but not always, alert to and aware of the displayed forces.

We analyzed the mean differential threshold in force, ΔF, at each velocity level as a function of speed using a polynomial regression analysis. A linear least-squares fit yields $\Delta F = p_0 + p_1 v = 0.35 + 0.0018v$ and an R-squared value of 0.94. Here, v is measured in mm/s. The fitted curve is shown in Fig. 4. The 95% confidence intervals for $p_1 = 0.0018$ are $(1.0e\text{-}2, 2.6e\text{-}2)$, which confirms a significant dependence of ΔF on v. A further quadratic term was rejected in the fit, since it yielded a coefficient that did not exclude zero with 95% confidence.

On many of the higher speed trials, participants did not report any difference between the magnitudes of f_A and f_B before the trial was terminated – recall that this occurred when one force magnitude was 0 N and the other 1 N, which maximized the force magnitude difference for our procedure. The proportions of times this condition was reached without participants reporting any difference at each value of v are shown in Fig. 6. A logistic regression analysis indicated that this "no-difference" response frequency increased with velocity at a significant level ($p < 0.001$). The fitted logit is $z(v) = -2.22v + 0.082$, where v is expressed in mm/s (with t-values > 8.0). The model correctly predicts 79.5% of the data.

3 DISCUSSION

The results of this experiment demonstrate a basic asymmetry in the perception of force magnitudes contingent on a reversal of the direction of motion. We have demonstrated that this effect manifests at force magnitudes and differences on the order of 1 N, far

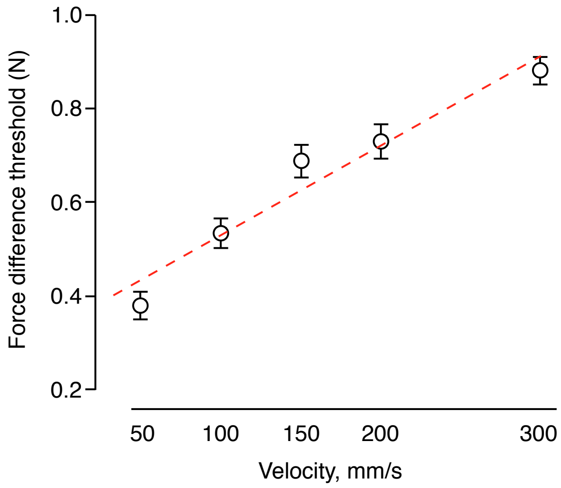

Figure 4: Mean measured differential force thresholds between forces f_A and f_B as a function of speed v for all trials. The value $\Delta F = 1.0$ N, corresponds to a situation in which one of the force magnitudes was zero and the other equal to 1.0 N. The line corresponds to the fit described in the text. Error bars: ±1 standard error of the mean (SEM).

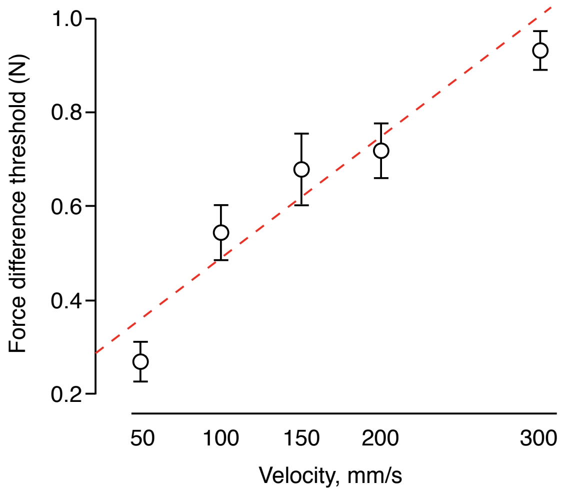

Figure 5: Results from one participant in the study, with linear least-squares fit to the data (Error bars: ±1 SEM).

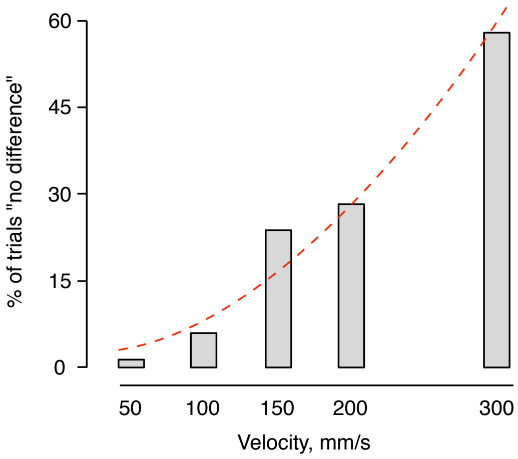

Figure 6: Percent of trials (among all participants) at each velocity such that f_A and f_B were not discriminated at any values tested. Dashed line: logistic regression fit.

above perceptual thresholds, and equalling half of the maximum force that our apparatus is capable of exerting. At low speeds, the threshold for detection of force changes increased monotonically over the range of speeds studied. In addition, participants were significantly less likely to detect a change in force magnitude at high speeds than at low speeds. The speeds tested were, nonetheless, within a range that is relevant to many everyday manual tasks.

While participants had little difficulty in following the specified tempo, and therefore mean velocity, one limiting factor in this experiment was related to the fact that, consistent with basic considerations of motor control, it is not generally possible for subjects to reproduce constant-speed motion trajectories while freely controlling their own motion, as we desired for them to do.

A number of potential explanations for the effect observed here suggest themselves, including the following, not necessarily mutually exclusive, possibilities:

- Temporal adaptation to the mean force magnitude: As in the hypothesis represented in Fig. 1, this could, in the simplest case, constitute a high pass filter that would emphasize transient aspects of the felt signals. Here, "transient" could refer to either the force magnitude, or to its consistency with prior expectations. However, the effect observed here seems to depend crucially on the coincidence between directional change and force magnitude change. Indeed, in informal testing, we failed to elicit an effect when the force transition was not coincident with the motion reversal (we will attempt to demonstrate this in future work).

- Open-loop control of position. Participants may have ignored sensory input, hence force information, at higher speeds, if they switched to an open-loop movement control model that focused on following a high-speed movement trajectory with specified times for motion reversal at its extrema.

- Arm impedance modulation: At higher speeds, the periodic changes in force direction provided a strong disturbance capable of destabilizing the motor program. As a result, the limb seems to have stiffened (through muscular co-contraction), perhaps limiting undesired deflections of the phalangeal or other joints. This could have led to decreased proprioceptive input or other sensory input yielding lower force estimates.

- Tactile afference suppression: Prior research has indicated that tactile sensations in the hand are suppressed during some movement tasks (e.g., [8, 11]). However, the demonstrated suppression effects involve weak stimuli near sensory thresholds, thus do not seem significant enough to explain the results reported here, which involve signals that are far above previously reported force detection thresholds.

- Prior expectations for movement-opposing forces: A prior expectation, possibly in the form of an internal model for resistive friction, may have led participants to assume that the displayed forces were equal in magnitude, as would be more consistent (modulo normal force variations) with a Coulomb-type friction law. While this doesn't provide a direct explanation for the velocity-dependence of the observed effect, it is conceivable that at low velocities, the parameters of such an internal model would have had time to adapt to better reflect the changing physical situation.

- Viscous force priors: Alternatively, one could may have a prior for viscous forces that increase in magnitude with speed. If one assumed Weber's law to hold, one might expect individuals to be less sensitive to force differences felt at higher speeds, all other factors being equal. However, given the wide range of other factors that affect movement-opposing forces (e.g., normal force, material properties, etc), it seems questionable whether a simple viscous force prior could explain the observed dependences.

- Inertial forces: At higher speeds, inertial forces can become significant, potentially contributing substantially to the net force that was felt, and masking contributions due to the forces displayed by the device. A rough estimate of the order of magnitude of such an effect can be made as follows. The effective moving mass at the manipulandum might be taken to be on the order of 40 grams. If we approximate the motion as sinusoidal, at the highest frequencies Newton's second law, $F = ma$, yields a force magnitude on the order of 0.2 N. At the lowest velocity, the corresponding magnitude is just 0.03 N. While inertial forces forces of this magnitude might be insufficient to fully explain the observed effect, this rough calculation at least suggests that their effect can't be entirely neglected in this setting.

- Sensory integration: In the slower conditions, participants experienced each force level for longer, which could aid them in forming better sensory estimates. individuals with better sensory estimates

- Force neglect: A simple, alternative hypothesis to the foregoing is that higher speed motion has a tendency to impair force perception. However, our results do not support the notion that participants could not detect the presence of the forces, since participants had no difficulty identifying catch trials in which no force was displayed. Due to the limited number of catch trials (just 5 per participant, or one per participant per speed value, v), we have insufficient data to fully rule out this hypothesis in the conditions of our experiment, but are not aware of comparable results in the literature.

The experiment presented here is not able to fully distinguish between these potential explanations, beyond the arguments given above. However, the effect uncovered is perceptually prominent, relevant to normal haptic interaction, and surprising enough to suggest that further research is needed and merited. Several of these hypotheses are aligned with the idea that the effect is mainly one of temporal integration or adaptation, and is not dependent on the fact that there is an executed motion. Based on informal testing in which the effect seemed to disappear if the force change did not coincide with motion reversal, we believe that this is not the case. However, such a hypothesis could be ruled out in a second experiment in which we presented force stimuli to the finger pad without motion. Certainly, this is a setting that has been studied much more extensively, however.

From an engineering standpoint, the present study suggests that some unusual changes might be needed in design requirements for force rendering and display in haptic simulation. For forces and interaction speeds that are sufficiently large (e.g., large enough to evoke a significant increase in the stiffness of the finger or limb), the haptic perceptual system may be insensitive to changes in movement-opposing forces that are contingent on motion-reversal. This may ultimately point to perceptually-motivated compromises that could be made in the interest of improving future haptic display devices.

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