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The Graduate School

Department of Psychology

HAPTIC PURSUIT TRACKING

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ABSTRACT

This set of experiments show that in a novel task – bimanual haptic tracking – neurologically normal human adults can move their two hands independently for extended periods of time with little or no training. Participants lightly touched buttons whose positions were moved either quasi-randomly in the horizontal plane by one or two human drivers (Experiment 1) or in circle and square patterns in the vertical plane by two human drivers (Experiment 2), or at different frequencies in the horizontal plane by two human drivers (Experiment 3). Bimanual contact was maintained equally well in all conditions even though in Experiment 1 the left- and right-hand motions were uncorrelated in the 2-driver condition, and in Experiment 2 the left- and right-hand motions were spatially incongruous when circles and squares were tracked at the same time, and in Experiment 3 the left- and right-hand motions maintained different frequency ratios. Predictability of the position and velocity of a tracked stimulus was manipulated in Experiment 4 through the use of probabilistic abrupt direction reversals. Experiment 4 established that individuals did not benefit from predicting over the long-term either the position or velocity of a target they were haptically tracking. In Experiment 5, haptic tracking was studied in a context of a to-be-tracked stimulus momentarily disappearing by going behind an "occluder". Experiment 5 provided some support for the retention of velocity information over time but not path, and, together with the Supplementary Experiment, established the critical role of discriminable shear forces and slip information for accurate haptic tracking.

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Chapter 1

Introduction to Haptic Tracking

The term ‘haptic’ evokes the idea of active touch: the free manipulation of an object using both cutaneous and kinesthetic information (Gibson, 1966). The activity and movement of haptic perception functions to explore the world over time, in contrast to the view of touch as a passive receptor of sensations imposed upon the skin (Gibson, 1962; 1966). Keeping in the spirit of this sense of haptics, ‘haptic pursuit tracking’ is the active task of keeping a part of the body, such as the hand, in contact with another object that may be moving.

The ability to haptically track a stimulus depends upon the skin’s physical response to a mechanical stimulus, namely the stresses (forces) and strains (deformations) that occur internal to and traveling across the skin. There are two kinds of waves within the skin that produce stress and strains (Oestreicher, 1950). The first is the irrotational compression wave, and it is produced from a normal strain occurring either in parallel or perpendicular to the skin’s surface. The second is the incompressible shear wave, which occurs when an object moves in parallel to the skin. Initially, there is skin stretch (where the object and skin move together), and then, at around three mm of shear displacement, the object will eventually slip across the surface of the skin. Haptic tracking critically depends upon the accurate detection of tangential movements on the skin’s surface.

The concept of haptic tracking came about while considering how one deals with a moving input signal in connection to a theory of motor planning which focuses on the control of manual positioning movements (Rosenbaum, Loukopoulos, Meulenbroek, Vaughan, & Engelbrecht, 1995; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). The posture-based motion planning model is primarily concerned with the planning and execution of single-shot, uninterrupted point-to-point positioning movements (i.e., movements that bring the end-effector from one static position to another). Such movements are similar to saccadic eye movements. Saccades are jumps from one static eye position to the next, whereas smooth pursuit movements are continuous shifts in eye position, usually made in response to seen moving objects. Could the hand smoothly follow a moving stimulus whose input modality is as closely related to the control of the hand as visually perceived motion is to control of the eye?

This question was pursued while wondering whether the specification of goal postures is the only way to move the hand from one place to another. Since the signal that drives the eye in smooth pursuit movement is velocity error whereas the signal that drives the eye in saccadic movements is position error, it can be reasoned that if the hand can only be driven with reference to goal postures (i.e., position errors with respect to current postures), then smooth pursuit hand movements should be impossible. This was a strong prediction of the posture-based motion planning model. The alternative, weaker, hypothesis was that the hand can also be driven with velocity error signals.

To pursue these alternative possibilities, a task was developed in which the error signal was not positional. Participants were asked to close their eyes and maintain contact with a felt moving object whose motion was unpredictable. When the participants' fingertip motion matched object motion, the shear force on the finger was zero, but when the participant was less successful, the shear force on the finger exceeded zero. Thus, haptic tracking relied on nulling of felt shear forces (i.e., participants had to move the hand in directions and with magnitudes exactly opposite the shear forces that were felt). The error signal for haptic tracking was thus defined with respect to a nonzero time derivative of position, not position itself.

While the haptic pursuit task provided a method by which to measure velocity error signals in movement, it leaves one to wonder whether velocity error signals drive movements in real-life. There are many natural situations where one needs to maintain contact with an object to keep track of it without necessarily creating a fixed hold. For example, holding hands with another person allows one to effortlessly track that person's position over time. Similarly, dancers often use light touch to provide instantaneous updates on their partners. Haptic tracking is also used with less animate objects: By carrying a hot pot with one hand (lightly) touching the lid, one can tell instantly when the rattling lid is slipping and needs to be grasped.

Like the real-life examples, haptic tracking was originally postulated to be easy. There was reason to believe this because feedback from touch is direct and automatic. For example, people are able to make changes in their grip based on accidental slips and unexpected perturbations to a grasped object within 65 ms (Johannson & Westling, 1988). Further, contact of the index finger with a stationary surface can greatly attenuate postural sway even when the level of force applied is far below that necessary to provide mechanical support (Jeka & Lackner, 1994). Leonard (1959) also demonstrated that RTs do not increase in relation to the number of S-R pairings (or choices) if movements are signaled with direct deformations of the fingertips.

Haptic tracking has even further advantages when compared to passive touch because tangential movements have been shown to improve the acuity for tactile stimuli (Johnson & Lamb, 1981). There is remarkable acuity for tangential movement, even when a movement is so small that only skin stretch is generated. With just skin stretch, 0.1-0.2 mm of movement can be detected, and with less than 1.0 mm of movement, the direction of movement (from the "pull" of the skin) can be detected (Gould, Vierck, & Luck, 1979).

It was lastly hypothesized that haptic tracking would be easy because it allows the individual's movement to be guided by the stimulus, thus relieving them of engaging in certain kinds of planning. The overall extent, direction, and speed of movement is dictated by the stimulus. However, one's movements are achieved through active force generation. A person who is haptically tracking is not allowing his or her arm to be dragged around by the stimulus; rather, the arm is active as it actively tracks the stimulus.

Haptic Tracking Permits Bimanual Independence

If haptic tracking is so easy, it should not suffer from having multiple targets, such as tracking with both hands simultaneously. This insight lead to the radical hypothesis – radical because it goes against 50 years of research on bimanual coupling – that haptic tracking might provide a special context in which normal, adult participants could move their hands completely independently with little or no practice.

To the author’s knowledge, no previous study has shown that people can move their two hands independently for extended periods of time without extensive practice. Research with split-brain patients has shown that such patients can achieve greater spatial independence between the hands than can normal individuals (Franz, Eliassen, Ivry, & Gazzaniga, 1996), although complete spatial independence between the hands is not evident in these patients. Split-brain patients can achieve greater temporal independence than normal participants do in continuous tasks (Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002) but not in discrete positioning tasks (Franz et al., 1996; Preilowksi, 1972; Tuller & Kelso, 1989). Previous studies with normal populations have shown that after extensive practice with generating polyrhythms, some degree of independence is achieved but only for brief periods of time (Krampe, Kliegl, Mayr, Engbert, & Vorberg, 2000; Pressing, Summers, & Magill, 1996; Shaffer, 1984).

If limb independence was achievable through haptic tracking, not only would it inform us regarding the nature of haptic tracking, but this outcome would also constrain existing models of bimanual coupling which have attributed such coupling to motor output rather than stimulus processing or planning.

Motor Programming Implicated in Bimanual Coordination

Achieving limb independence is a difficult task because of the well-established constraints that come into play when moving both arms. Notably, Fitts’ law, a model of human movement that predicts longer pointing times to targets that are smaller and/or further away, does not hold for each limb when bimanual movements are made to targets of differing difficulty. Instead, movement time is determined unilaterally by the more difficult target, rather than by the index of difficulty for each hand (Kelso, Southard, & Goodman, 1979). Significant spatial incorporations between the hands are also evident when people are asked to simultaneously generate spatially divergent patterns (Franz, Zelaznik, & McCabe, 1991). The constraints in the system occur at many levels (musculoskeletal, perceptual, cognitive, and neural), such that they have been recently described as a ‘coalition of constraints’ that interact to a varying degree as a function of the task at hand (Carson, 2004; but see also the control hierarchy of Heuer, 1993).

One such coordinative structure is an intrinsic constraint, often modeled as a pair of coupled oscillators. However, even modelers who focus on these intrinsic constraints have recognized the cooperative role of extrinsic constraints, such as environmental stimuli (e.g., synchronizing to metronomes; Fink, Foo, Jirsa & Kelso, 2004), and psychological processes (e.g., memory, Schöner & Kelso, 1988). Semjen and Ivry (2001) demonstrated that intrinsic dynamics can be perturbed not only by leaving a preferred coordination pattern, but also when task requirements do not coincide with oscillatory tendencies. For example, exercising intentional control allows participants to reduce the likelihood of switching from an anti-phase pattern to a preferred in-phase pattern (Scholz & Kelso, 1990). Further, coupling can often be reduced in even the most paradigmatic coordination tasks with either enough practice or a reduction in the role of planning (Zanone & Kelso, 1997). The coupled oscillator model was eventually adapted to include intentional influences on coordination (Schöner & Kelso, 1988).

Because bimanual coupling decreases with practice, and is subject to task and environmental demands (see Jirsa, Fink, Foo & Kelso, 2000), coordination cannot be universally described as a solution to the degrees of freedom problem (Rosenbaum, Meulenbroek, & Vaughan, 1996). Coupling may be more accurately viewed as a method by which to deal with learning and attentional constraints when performing a challenging task. Once coupling is recognized as not originating exclusively from a conflict at the level of motor execution, it becomes open to investigation at the level of motor programming.

The following set of experiments was devised as a method of physical guidance or haptic pursuit tracking to bypass certain known coordinative tendencies in favor of direct stimulus-response connections for each hand's movements. Later experiments investigated the involvement of motor planning in haptic tracking by measuring and manipulating predictions about a tracked stimulus.

Chapter 2

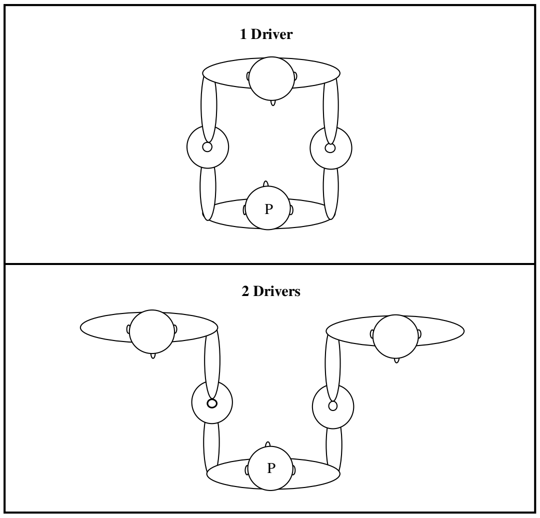
Experiment 1

Rationale

In the first experiment participants pressed the tips of their two middle fingers against two buttons, mounted beneath two vertical shafts whose positions were moved rapidly and quasi-randomly in the horizontal plane. In one condition, the two shafts were displaced by one human driver, whereas in the other condition the shafts were displaced by two human drivers (Figure 1). The participants' task was to keep the tips of both middle fingers in contact with the buttons for as long as possible in each trial while keeping their eyes closed.

The expectation was that the shafts would be moved in a correlated fashion when displaced by one driver and would be moved in an uncorrelated fashion when displaced by two drivers. It was hypothesized that if these expectations were met, and if the motions of the shafts were otherwise comparable, participants would be able to haptically pursue the shafts equally well in the one- and two-driver conditions.

1



1: Experimental conditions experienced by the participant (P) in the 1-driver (top panel) and 2-driver (bottom panel) bimanual haptic pursuit tasks of Experiment 1.

Method

Participants

The participants were 16 healthy, right-handed Penn State University undergraduates. All were tested according to the ethical guidelines of the American Psychological Association and with approval of the Penn State University Institutional Review Board.

Procedure, Design, and Apparatus

The experimenters who drove the shafts were two young women (Penn State undergraduates) of approximately equal height and weight. Each participant was tested in the one- and two-driver conditions in alternation in all possible orders over participants, and with the left/right positions of the experimenters in the 2-driver condition being likewise balanced over participants. Each condition was tested in 4 consecutive trials. Throughout each trial, the participant and driver(s) sat facing each other. Each trial began with the experimenter(s) holding the shafts about 40 cm in front of their own and the participant's torsos. Participants used visual guidance to bring their hands to the start positions and then closed their eyes.

Participants were unaware whether one or two drivers were going to operate the paddles during any given trial. Once the buttons were pressed, the experimenter(s) checked that the participant's eyes were closed and began moving the shafts as quickly as possible, attempting to displace the shafts in random directions and over random distances, subject to the constraints that the manipulanda did not collide, that the shafts remained vertically oriented, that the bases of the manipulanda remained at a height corresponding to the middle of the torso, and that both buttons remained in reach by the participant.

The shafts were made of wood and were 19.69 cm long, 2.38 cm in diameter, and weighed 878.85 g. On top of each shaft were two infrared-emitting diodes (IREDs) whose positions were recorded with an OPTOTRAK motion tracking system (Northern Digital Corp, Waterloo, Ontario, Canada) sampling at 100 Hz. One IRED on each shaft was illuminated throughout the trial. The other IRED was illuminated only when the button beneath it was pressed. The shaft was mounted at the center of a wide circular base that was wide enough (31 cm in diameter) to prevent participants from grabbing hold of the disk when pressing the button. Together, the base and shaft resembled an air hockey paddle. The button had a brass surface that was 2.38 cm in diameter, flush with the bottom surface of the circular base when it was closed, and protruded only 0.16 cm when open.

Closing the button’s switch required 1.75 N of force. The separation between the lateral edge of the button and the inner wall of the wooden disk was so small (0.32 cm) that participants could not press sideways on the button.

The OPTOTRAK began storing the shaft positions when both buttons were closed and continued to do so for 20 s. When the data recording was complete, the participant and experimenter(s) rested.

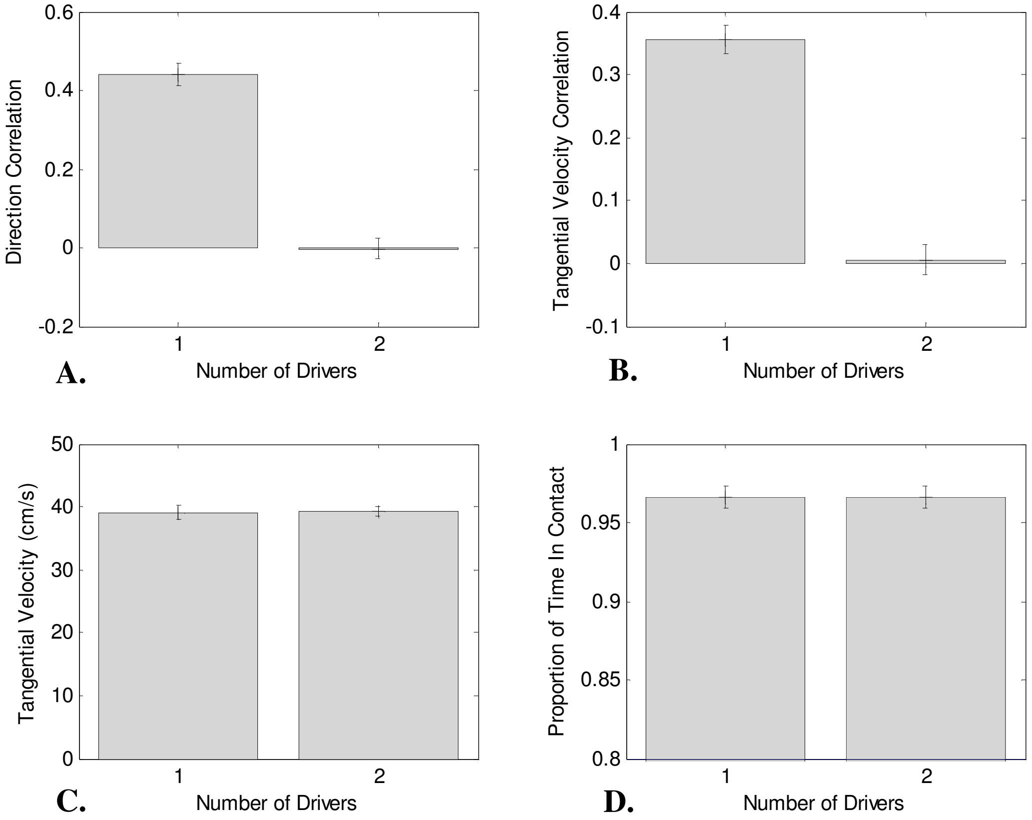
Results and Discussion

As shown in Figure 2A, instantaneous directions of motion in the horizontal plane were correlated in the one-driver condition but were uncorrelated in the two-driver condition. Similarly, as shown in Figure 2B, instantaneous tangential velocities of the left and right shafts were correlated in the one-driver condition but were uncorrelated in the two-driver condition. Finally, as shown in Figure 2C, mean tangential velocities of the shafts in the horizontal plane were statistically indistinguishable in the one- and two-driver conditions.

The foregoing results concerned what the drivers did. The remaining data concern what the participants did. Their data appear in Fig. 2D. Here it is seen that there was no difference between the proportions of time within the 20 s trials when participants lost contact with at least one button. The proportions were low, confirming the expectation that this would be an easy task.

Given how well participants did, there was a concern that their hands may have been passively dragged by the manipulanda. To address this concern, a biomechanical model was developed by John Challis to evaluate the possibility of passive drag (see model details in Rosenbaum, Dawson, & Challis, 2006). This model demonstrated that passive drag cannot explain the results. In summary, the model shows that the amount of upward force necessary to permit passive drag would have been a significant hindrance rather than an aid to lateral movement. This outcome, together with the other findings of this experiment, led to the conclusion that the two hands can move independently during haptic tracking.

2



2: Bimanual haptic tracking data from the 1- and 2-driver conditions of Experiment 1. (A) Correlations between instantaneous directions of left- and right-shaft motions. (B) Correlations between instantaneous left- and right-shaft tangential velocities. (C) Mean tangential velocities. (D) Proportion of trial time during which bimanual contact was maintained prior to first loss of contact. Correlations in (A) were computed using circular statistics, a method that prevents spurious numerical jumps associated with discontinuities around 2π radians and integral multiples thereof (Fisher, 1993).

Chapter 3

Experiment 2

Rationale

Although the results of the first experiment were promising, there were concerns about several aspects of the study. First, the argument against the passive drag hypothesis was indirect, being based on a biomechanical model. Second, the measures used may have failed to pick up subtle differences between the patterns of motions of the two target shafts in the one- and two-driver conditions. Thus, even though the correlations between the motions of the two moving targets were significantly different from zero for the one-driver condition and not significantly different from zero for the two-driver condition for the variables considered (instantaneous directions of motion and instantaneous speeds), it is possible that the motions were actually correlated in the two-driver condition for other variables, the number of which is potentially limitless. Third, the measure of the participants' tracking performance was coarse. Because participants could press anywhere on the surface of the button, they could have closed the circuit and illuminated the IRED over a wide range of positions. Fourth and finally, the trials were short, only 20 seconds.

To address these concerns, the apparatus and method were redesigned in several ways for the second experiment. For one, four conditions were used, all of which used two drivers. In one condition both drivers generated squares, in a second condition both drivers generated circles, in a third condition the driver on the left generated a square while the driver on the right generated a circle, and in the fourth condition the driver on the left generated a circle while the driver on the right generated a square.

The simultaneous tracking of a circle and square is of special interest because it is difficult to generate curved lines and straight lines simultaneously (Franz, Zelaznik, & McCabe, 1991) and it is difficult to keep one hand moving when the other hand stops (e.g., Franz, Eliassen, Ivry, & Gazzaniga, 1996). Franz, Swinnen, Zelaznik & Walter (2001) tested whether keeping two goals in mind leads to spatial constraints because of traditional dual-task interference. In their experiment, participants made similar spatial movements that were either two distinct tasks that could not be easily conceptualized as unitary (semi-circle arcs), or two tasks that conceptually formed a unitary pattern (semi-circle arcs oriented to form a circle). Spatial interference between the limbs was greatly reduced in the condition where the two movements could be conceptualized as serving a common goal (a movement forming a circle). Franz et al. attributed their spatial interference effects to maintaining two distinct conceptual representations (semi-circle arcs not forming a circle). If haptic tracking is susceptible to the dual-task effects of keeping two goals in mind, there should be poor performance when tracking different shapes. However, if haptic tracking is independent of conceptual representation of the task, shape similarity should not impact performance.

The apparatus was also changed to eliminate the possibility that passive drag could account for successful tracking. This was accomplished by designing an apparatus whose most important property was that participants could not push on the tracked object with enough force to be passively dragged by it. Details about the apparatus are given in the Methods section.

The third change allowed for a more sensitive measure of performance than was previously possible. Rather than record the buttons' switch closings and openings, as in the first experiment, in Experiment 2 measurements were made of the correspondence between the positions of the to-be-tracked stimulus and the subject's hand. This allowed one to see how well participants could track the shapes when they were different or the same and to see how well participants could track with one hand when the other hand's trajectory had well-defined characteristics. For example, it was now possible to evaluate how well participants tracked a circle with one hand while tracking a square with the other.

Fourth and finally, the duration of observation was extended from 20 s per condition to 2 minutes per condition.

Method

Participants

Ten healthy, right-handed undergraduates at Penn State University participated.

Procedure, Design, and Apparatus

To accommodate the physical requirements of the new apparatus, the plane of paddle motion was rotated from the horizontal plane to the vertical plane and participants and experimenters stood up (Figure 3). The experimenters and participant were separated by an opaque glass pane (76 cm × 92 cm × 3 mm) that prevented them from seeing one another. Each experimenter moved a paddle on his or her side of the glass, which resulted in the movement of a 5.08 cm diameter plastic disc (a target button) on the other side of the glass which was haptically tracked by the subject with one of his or her hands. To couple each target button to its respective paddle, a pair of rare-earth magnets was used (Grade 40 neodymium, National Imports LLC, Fall Church, VA) that attracted each other through the glass. The magnets decoupled when a force greater than 0.3760 N (0.0845 pound) was applied to the target button. This is a low force. Indeed, as one participants said, the force that could be applied to the target button to allow for haptic tracking while not causing the magnets to decouple was "feather-light." Considering that the human arm has a mass of approximately 5% of a human adult's total body mass (Dempster, 1955), causing the arm of a 150 pound adult to have a mass of 7.5 pounds, the forces that could be applied to the target button and still allow it to remain coupled to the driving paddle were insufficient to drag the arm.

The target buttons were made of highly polished polymer, providing a slick, low-friction surface, and thus discouraging participants from establishing a firm finger grip. Seven thin plastic strips were glued to the surface of the target buttons so they radiated from the center of the buttons in a pie-wedge formation (see Figure 3). Participants were instructed to keep the tip of the middle finger as close as possible to the point where the rays converged.

3

3: Setup for Experiment 2. Top panel: Two drivers moving paddles in a square template (left) and in a circular template (right). Curtain between experimenters removed for this photo. Middle panel: A participant haptically tracking the two magnetically driven target buttons. Bottom panel: Target button and participant's index finger without IREDs attached.

IREDs were affixed to the participant's middle and ring fingers of both hands, allowing for measurement of the participant's finger positions. To record the positions of the drivers' paddles, IREDs were affixed to the ends of "antennas" that extended from each paddle.

The antennas extended up by 62 cm and then down by 52 cm over the top of the glass. The antennas enabled the OPOTRAK to record the paddle positions as well as the participants' finger positions from a single vantage point. By knowing the positions of the paddle antenna, it was possible to determine where the paddles were relative to the participant's fingers.

Four young women (three Penn State undergraduates and one graduate student, the author), who were of approximately equal height and weight, alternated responsibility for driving the paddles, monitoring participant's performance, and controlling the OPTOTRAK. Between trials, the two experimenters who drove the paddles switched their own driving positions (left vs. right), as well as the set of templates within which the paddles moved. The inner edge of the templates was either a circle (diameter = 46 cm) or a square (edge length = 46 cm). Because the paddle radius was 15.5 cm, the diameter of the circle described by the moving target was 46 cm – (2 × 15.5 cm) = 15 cm.

Similarly, the length of each side of the square described by the moving target was 15 cm. The templates were cut into square corrugated plastic (edge length = 55 cm) that could be easily attached to and removed from the glass with large clamps. Each driver had a square template and a circular template close at hand. The necessary template was clipped to the glass as needed depending on the condition being tested. The four conditions were administered in a randomized order over participants.

Participants agreed to be blindfolded and to listen to white noise over headphones during the practice and experimental trials. The experimenters could not see participants through the opaque glass. For two minutes prior to the beginning of the first trial, participants were allowed to practice haptically tracking the target buttons as the buttons were moved randomly on the surface of the glass. Then the drivers attached the templates to the glass and brought the paddles into their "home" positions – at 2 o'clock for the left-hand shape and at 10 o'clock for the right-hand shape from the participant's perspective.

The motions of the paddles were mirror-symmetric about the vertical axis. The driver on the left moved clockwise while the driver on the right moved counter-clockwise. The drivers were instructed to align the paddles with marks at each of the four corners of the square template in time with successive clicks of a metronome sounding every 0.5 s. Likewise, the drivers were instructed to align the paddles with "corner" marks at 45, 135, 225, and 315 degrees along the rim of the circle template in time with the same metronome. The drivers listened to the metronome over headphones. The participant could not hear the metronome.

It was anticipated that participants might lose contact with a button or press hard enough on a button to decouple it from its paddle. Accordingly, the experiment was conducted in such a way that if either type of error occurred, the trial was stopped and then started again with both paddles at their home positions. All the time spent in a condition was accumulated until the participant completed 2 minutes of haptic tracking in that condition. The number of trials that a participant needed to complete 2 full minutes of haptic tracking within a condition therefore provided a measure of how hard or easy that condition was.

At the end of the experiment, participants were debriefed.

Results and Discussion

As in Experiment 1, first target motions were evaluated, and then participants' tracking performance was analyzed.

Target Motions

IRED position data from the drivers' paddles were compared to perfectly formed circles and squares (generated from their respective equations). The analysis confirmed that the experimenters generated the necessary shapes correctly. When circles were to be drawn, the mean coefficient of determination between the paddle positions and an ideal circle was $r^2 = 0.9979$. When squares were to be drawn, the mean coefficient of determination between the paddle's positions and an ideal square was $r^2 = 0.9976$. There was no indication that the quality of fit for a circle or for a square was affected by the side on which the shape was traced, by the identity of the experimenter, by the identity of the participant, or whether the other shapes matched or mismatched.

To evaluate the timing of the target motions, two analyses were conducted. The first was concerned with the synchrony of movements on the left and right. Using a repeated measures analysis of variance, a comparison was made between the difference of the mean times that the right paddle and left paddle reached their "corner" positions. Table 1 shows the relatively small mean difference times between the paddles, with an overall time difference between them of only 2.93 ms (SE = 0.25 ms). There was no change in left-right asynchrony depending on whether the left and right target motions followed the same shape or different shapes, $F(1, 9) = 4.939$, $p > 0.05$.

1: Means (and standard errors) of the time differences (in milliseconds) between the left and right paddles to reach the "corners" of their respective shape templates. Data from Experiment 2.

1

	Right Paddle	
Left Paddle	**Circle**	**Square**
Circle	3.02 (.16)	2.96 (.27)
Square	2.78 (.31)	2.97 (.24)
Mean	2.90 (.24)	2.96(.26)

The second analysis of the timing of target motions was concerned with the extent to which the delays between successive arrivals of the targets at their "corner" positions corresponded to the ideal delay of 500 ms (determined by the timing set by the metronome). As shown in Table 2, experimenters were able to keep up with the metronome, on average departing from the ideal delay by only 8.40 ms (SE = 17.86 ms).

The departures from the ideal delay were statistically indistinguishable from zero and did not depend on whether the experimenters generated the same or different shapes, F(1, 9) = 4.129, $p > 0.05$.

2: Means (and standard errors) of the time (in milliseconds) for each paddle to reach the "corners" of the shape templates. The ideal, metronome-specified time was 500 ms. Data from Experiment 2.

2

One Hand's Identity and Shape		**Other Hand's Shape**	
Hand	**Shape**	**Same**	**Different**
Left	Circle	486.64 (21.99)	501.85 (13.45)
	Square	521.13 (20.86)	520.22 (17.07)
Right	Circle	504.83 (28.29)	521.55 (26.15)
	Square	505.28 (7.45)	505.69 (7.65)
Mean		**504.47 (19.65)**	**512.33 (16.08)**

Tracking Performance

The main question of interest was addressed next. How well did participants haptically track the targets? The analyses reported below bear out what was obvious from watching participants and from hearing their reports: It was clear to observers that participants performed the task very easily, and participants reported that the task was simple, no matter what condition they were in.

To provide a more formal, detailed account of participants' tracking, several analyses were conducted. The first concerned the number of trials participants needed to complete 2 minutes of tracking in each condition. The relevant data are shown in Table 3, where it is seen that the mean number of trials required to complete a condition was low, with most participants requiring just one, or at most, two trials. The number of necessary trials did not vary with condition. A repeated measures analysis of variance indicated that the number of trials needed to complete 2 minutes of tracking was not significantly influenced by the shapes being tracked, nor on whether the shapes were same or different (p's > .05).

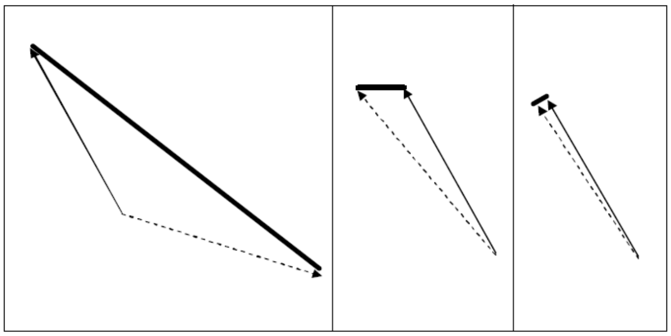
3: Means (and standard errors) of the number of attempts needed to complete 2 minutes of haptic tracking in each combination of shapes. Perfect performance is 1 attempt. Data from Experiment 2.

3

	Right Paddle	
Left Paddle	**Circle**	**Square**
Circle	1.30 (0.95)	1.10 (0.32)
Square	1.10 (0.32)	1.60 (1.90)
Mean	**1.20 (0.63)**	**1.35 (1.11)**

The next analysis of participants' performance concerned their ability to track the positions of the experimenter-driven paddles. To evaluate participants' tracking abilities, the difference between the instantaneous displacement of each paddle's IRED and the instantaneous displacement of the corresponding middle finger IRED was computed (see Figure 4). The measure was the Euclidean distance between the endpoints of the paddle displacements and the endpoints of the corresponding hand displacements after the start positions of both displacements were functionally aligned. This measure could take on a value of zero if tracking were perfect and could grow as the target and hand displacements diverged. The results appear in Table 4, where it seen that, although tracking error was larger when squares were tracked than when circles were tracked, $F(1, 9) = 86.394$, $p < 0.05$, tracking error was statistically indistinguishable when participants tracked the same or different shapes, $F(1, 9) = 0.206$, $p > 0.05$. No other main effects or interactions were statistically significant in this analysis (all $p > 0.05$).

4



4: Target displacements (solid arrows), hand displacements (dashed arrows), and Euclidean distance between the two (heavy lines) in single OPTOTRAK frames. Tracking error is largest in the left panel and smallest in the right panel. Hypothetical data only, for didactic purposes.

To provide a more fine-grained analysis of tracking error, performance at the corners was also looked at. The question was whether, when traversing the corners of a square, the other hand would show disruption while making a circle. The kinematic data was used to identify the moments when the square corners were turned and examined performance in the 100 ms before and 100 ms after these critical events. Table 5 shows the tracking error data for these time intervals. The critical comparison was for tracking a circle with one hand while tracking either a circle or a square with the other hand. When the left hand tracked a circle, its tracking error was only .09 mm larger when the right hand tracked a square than when the right hand tracked a circle, and when the right hand tracked a circle, its tracking error was .40 mm smaller when the left hand tracked a square than when the left hand tracked a circle. Neither difference was significant. An analysis of variance confirmed that it did not matter whether the left and right hands tracked the same shape or different shapes ($p > .05$). This outcome was further corroborated in an analysis of tracking in the "straight-aways" (i.e., performance in the 100 ms before through 100 ms after passing through the midpoints between the corners). As seen in Table 6, tracking errors were again statistically indistinguishable if the two hands tracked shapes that were the same or different ($p > .05$).

4: Means (and standard errors) of Euclidean distances (mm) between endpoints of paddle displacements and endpoints of corresponding hand displacements. Data from Experiment 2.

4

One Hand's Identity and Shape		**Other Hand's Shape**	
Hand	**Shape**	**Same**	**Different**
Left	Circle	1.22 (.41)	1.21 (.22)
	Square	1.25 (.30)	1.05 (.37)
Right	Circle	1.86 (.51)	1.88 (.47)
	Square	1.82 (.53)	1.92 (.47)
Mean		**1.54 (.44)**	**1.51 (.38)**

5: Means (and standard errors) of Euclidean distances (in millimeters) between endpoints of paddle displacements and endpoints of corresponding hand displacements at "corners." Data from Experiment 2.

5

One Hand's Identity and Shape		**Other Hand's Shape**	
Hand	**Shape**	**Same**	**Different**
Left	Circle	1.23 (0.50)	1.32 (0.52)
	Square	1.18 (0.54)	1.14 (0.43)
Right	Circle	1.97 (1.44)	1.57 (0.42)
	Square	2.13 (1.17)	1.97 (1.17)
Mean		**1.63 (0.91)**	**1.50 (0.64)**

6: Means (and standard errors) of Euclidean distances (in millimeters) between endpoints of paddle displacements and endpoints of corresponding hand displacements in the "straight-aways." Data from Experiment 2.

6

One Hand's Identity and Shape		**Other Hand's Shape**	
Hand	**Shape**	**Same**	**Different**
Left	Circle	1.21 (.51)	1.09 (.25)
	Square	1.39 (.53)	1.23 (.21)
Right	Circle	1.23 (.21)	2.23 (.56)
	Square	2.64 (.91)	2.59 (1.33)
Mean		**1.62 (.54)**	**1.79 (.59)**

The last aspect of the results concerns participants' comments about the task. As mentioned above, participants said they found the task very easy. Another remark they made, which bears on the interpretation of participants' cognitive states while doing haptic tracking is that, without exception, participants reported that they were aware that they were making circles and squares. Participants were able to report this even though they never saw the templates nor were told that circles or squares were part of the experiment. Participants were also asked whether some trials seemed more difficult than others. Most participants said they found it harder to track squares than circles, but none reported that it was harder to track squares and circles at the same time than to track two circles or two squares at the same time, though they also expressed surprise that they were able to make a circle and a square simultaneously in this context.

Chapter 4

Experiment 3

The comments of the participants in Experiment 2 raise the concern that, because they were aware that they were tracking circular and square motions, their success in the tasks may have relied on strategic attention allocation (see Franz, 2004). In particular, they may have paid special attention to the squares' corners when they made circular arcs with the other hand. If this strategy were used, it would not vitiate the main finding of bimanual independence in those conditions but would raise questions about the need for special attentional strategies at critical points in those conditions.

This is a particular concern because some think that coupling may be due entirely to attentional capacity limitations: it is difficult to represent and assign two different goals to the two hands (Monno, Temprado, Zanone, & Laurent, 2002). If interlimb interference is due to capacity limitations, one would expect to find traditional dual-task interference effects. In one dual-task experiment, Kunde & Weigelt (2005) had participants move a pair of objects with instructions that focused on making movements that were either a) symmetric or asymmetric, or b) ending up in matching or disparate orientations. When participants were provided with an external goal to focus on, like orienting the objects, they demonstrated less interference on the goal-congruent movement task as compared to the goal-incongruent movement task or even the motor-symmetric movement task. However, when no external goals were provided, and participants simply made the same movements, a typical motor symmetry effect dominated. In Kunde & Weigelt's experiment, spatial interference effects were attributable to representing the movement rather than a conceptual goal.

To address this concern and, more importantly, to further evaluate the generality of the capacity for bimanual independence in haptic tracking, one of the most robust phenomena in the study of bimanual performance was exploited – the tendency of the two hands to veer toward simple frequency ratios when both hands generate cyclic movements. The simplest frequency ratio, and the one toward which the hands gravitate the most as driving frequencies increase, is 1:1. A frequency ratio that is very hard to maintain, except at very low driving frequencies or with extensive practice, is 3:4 (3 cycles of the left hand for every 4 of the right) or 4:3 (4 cycles of the left hand for every 3 of the right) (Peper, Beek, & van Wierengen, 1995; Zanone & Kelso, 1997). In Experiment 3, it was asked whether 3:4 and 4:3 frequency ratios are harder to produce than 1:1 frequency ratios in haptic tracking.

Participants in the third experiment were asked to make circular haptic tracking movements with the two hands simultaneously such that the left hand moved at .500 Hz or .375 Hz and the right hand moved at .500 Hz or .375 Hz. Pairing the left- and right-hand frequencies in all four possible ways led to frequency ratios of 1:1 (.375 Hz paired with .375 Hz or .500 Hz paired with .500 Hz), 3:4 (left .375 Hz paired with right .500 Hz), or 4:3 (left .500 Hz paired with right .375 Hz). An important feature of the resulting motion patterns was that the phase lags of the two hands changed continuously in the 3:4 and 4:3 frequency ratios. Thus, for these ratios, and also for the 1:1 frequency ratios, there was no critical point in the circular motions when it would have been a priori especially advantageous to attend to one hand rather than another. Consequently, if strategic attention allocation to critical points was responsible for bimanual independence in Experiment 2, one would expect performance to suffer in the complex frequency ratios (3:4 and 4:3) as com-pared to the simple frequency ratio (1:1). By contrast, if bimanual independence in Experiment 2 reflected some inherently easy feature of haptic tracking which permits bimanual independence, then one would expect participants to do just as well at bimanual haptic tracking with complex frequency ratios as with simple frequency ratios.

Method

Participants

Twelve healthy, right-handed undergraduates at Penn State University participated.

Procedure, Design, and Apparatus

The apparatus originally designed for Experiment 2 was used in Experiment 3. IREDS were used to record the positions of the driver paddles and the middle and ring fingers of the participants. Participants attempted to keep the tips of their fingers as close as possible to the middle of the tracked stimuli. Participants performed the tasks blindfolded and while listening to white noise over headphones, as before.

Four young women and one young man (four Penn State undergraduates and one graduate student, the second author), of approximately equal height and weight, alternated as paddle drivers, performance monitors, and computer operators. Each driver used a circular template and placed his or her paddle into the beginning “home” positions, which were identical to those used in Experiment 2, namely, at 2’oclock for the left-hand shape and 10 o’clock for the right-hand shape, from the participant’s perspective.

Participants tracked clockwise motions with the left hand and counterclockwise motions with the right hand. Each of the four frequency conditions was administered twice in two separate blocks and in a randomized order over participants. Successful completion of a condition required one full minute of accurate haptic tracking. (The time was reduced down from 2 minutes in Experiment 2 in order to reduce fatigue and to provide multiple trials in any one condition. Total time spent in a condition across the two blocks was still two minutes.) Time spent in a condition was accumulated across multiple trials if a condition's trial had to be discontinued because of an error (i.e., the participant lost contact with the target or decoupled the magnets between the target button and paddle).

Results and Discussion

Target Motions

The first analysis concerned the target motions generated by the human drivers. Cycle completion times were measured based on successive times of arrival of the paddles at key points on the circumference of the left and right circles. As shown in Table 7, the times to complete the revolutions were close to the required periods of 2000 ms when the target frequency was .5 Hz, although the left-circle periods were somewhat shorter on average than the right-circle periods. The times to complete revolutions were also close to the required period of 2670 ms when the target frequency was .375 Hz, although cycle times were generally shorter than the required periods in this condition and again tended to be shorter for the left circle than for the right. The generated periods were significantly different when the target periods were 2000 ms versus 2670 ms for a given hand, $F(1,12) = 8903.78$, $p < 0.01$, but the period generated for a given hand was not statistically affected by the other hand's required period.

7: Means (and standard errors) of obtained periods (ms) when the target periods were 2000 ms (.500 Hz) and 2670 ms (.375 Hz). Data from Experiment 3.

7

One Hand's Identity and Target Period (ms)		**Other Hand's Target Period**	
Hand	**Target Period**	**Same**	**Different**
Left	2000	2007 (22)	2006 (7)
	2670	2607 (8)	2602 (11)
Right	2000	1958 (15)	1954 (15)
	2670	2599 (11)	2585 (11)

From the mean obtained periods of each hand, the mean obtained frequency ratios in the four conditions of the experiment can be calculated. These were 1.025 when both hands' target period was 2000 ms (.500 Hz), 1.003 when both hands' target period was 2670 ms (.375 Hz), .7761 when the target periods were 2000 ms (.500 Hz) for the left hand and 2670 ms (.375 Hz) for the right, and 1.331 when the target periods were 2670 ms (.375 Hz) for the left hand and 2000 ms (.500 Hz) for the right. These values are close to the ideal values of 1.000, 1.000, .7500, and 1.333.

Tracking Performance

Next participants' haptic tracking performance was evaluated. In the first analysis the number of trials participants required to complete one full minute of any given condition was tallied, with one trial being the minimum required and a larger number of trials corresponding to greater difficulty. The number of trials required to complete a condition was low, with most participants needing only one trial. Although, as shown in Table 8, there was a tendency for more trials to be needed when the target periods mismatched than when they matched, the interaction between target period and match or mismatch of target period was not statistically significant (p > .05).

8: Means (and standard errors) of number of attempts needed to complete 1 minute of haptic tracking in each combination of frequencies. Perfect performance is 1 attempt. Data from Experiment 3.

8

	Right Target Period (ms)	
Left Target Period (ms)	**2000**	**2670**
2000	1.21 (.12)	1.29 (.14)
2670	1.36 (.15)	1.07 (.07)

To get a more detailed picture of performance in the four conditions of the experiment, the mean Euclidean distance between vector endpoints of the paddle and corresponding hand was analyzed, as in Experiment 2. The results appear in Table 9. Quality of tracking performance, as revealed by displacement errors, was very good. The displacement errors were very small and there was no main effect of whether the two hands' frequencies matched or mismatched, F(1,12) = 0.283, p > 0.05. No other main effect or interaction approached statistical significance.

9: Means (and standard errors) of Euclidean distances (mm) between endpoints of paddle displacements and endpoints of corresponding hand displacements. Data from Experiment 3.

9

One Hand's Identity and Target Period (ms)		**Other Hand's Target Period**	
Hand	**Target Period**	**Same**	**Different**
Left	2000	2.56 (.90)	1.65 (.68)
	2670	2.03 (.78)	1.46 (.29)
Right	2000	1.99 (.50)	1.86 (.53)
	2670	1.56 (.58)	2.51 (.72)
Mean		**2.04 (.69)**	**1.87 (.55)**

Participants in this study successfully tracked pairs of objects rotating at a difficult frequency ratio. This outcome contrasts with the classic observation that only simple integer ratios can be reliably performed. It is worth noting that in order to accurately track, participants had to move their arms in continuously changing phase relations. This outcome is also in direct contrast to the previous observations that people can only produce phase relations other than 0º and 180º if they have extensive training on those other phase relations (Zanone & Kelso, 1997).

Chapter 5

Experiment 4

Rationale

The results of Experiments 2 and 3 as a whole support the idea that people are highly proficient at haptic tracking. While haptic tracking had a marked impact on bimanual coordination, it remained unclear whether that impact was at the level of motor planning. It was earlier proposed that haptic tracking reduced dependence on motor planning. Conceivably, however, plans for haptic tracking movements extend beyond immediately forthcoming, instantaneous hand displacements. Consistent with this possibility, participants in Experiment 2 said they knew they were moving in circles and squares.

The primary methodological goal of the next set of experiments was to directly address the hypothesis that haptic tracking reduces bimanual interference by limiting the role of prediction in movement. This hypothesis stands in contrast to typical tracking performance, which benefits from repetitive or structured inputs compared to irregular or unstructured inputs, suggesting that prediction plays a role in tracking (Epelboim et al., 1995; Fuller, 1992; Nelson, Staines & McIlroy, 2004). The previous haptic tracking experiments in this paper, however, suggest that prediction plays a relatively minor role in haptic tracking. Excellent tracking performance was demonstrated regardless of the fact that in Experiment 1 the motions to be tracked were quite unpredictable, and in Experiments 2 and 3 the motions to be tracked were quite predictable. However, caution is required in reaching this conclusion because the methods of both studies were less sensitive than they might have been. So far, haptic tracking had not been studied in situations where participants potentially form predictions that are either fulfilled or violated. The next experiment was designed to compare these situations and also to refine the means of delivering the motions to be tracked, to create conditions in which participants fail in haptic tracking, and to obtain more sensitive measures of haptic tracking performance than have been obtained so far.

Similar to previous experiments, participants performed bimanual circling movements by means of haptically tracking target stimuli. However, they were confronted with an abrupt direction change in one hand either placed quasi-randomly in the circular space or at a particular spatial location with a fixed probability (25, 75 or 100%) (see Figures 5 and 6). It is well established that interlimb interference occurs when different specifications are generated simultaneously by both limbs (e.g., a shorter amplitude in one limb's movement compared to the other) (Swinnen, Dounskaia, Levin, & Duysens, 2001; Franz, Zelaznik, & McCabe, 1991). Between-limb disruptions are also found when one limb reverses direction during an initially symmetric movement

(Byblow, Lewis, Stinear, Austin, & Lynch, 2000; Spijkers & Heuer, 1995). What is unknown, however, is whether these between-limb disruptions would occur if there was a unimanual direction reversal during bimanual haptic tracking.

Further, this experiment was designed to address the impact of participants' preparation for the perturbation. In a series of experiments, Heuer and colleagues demonstrated that interference effects stemming from differences in movement amplitude, direction, and force diminish when participants are given adequate time to prepare before initiating their movements (Heuer, 2006; Heuer, Spijkers, Kleinsorge, van der Loo, & Steglich, 2004; Steglich, Heuer, Spijkers, & Kleinsorge, 1999; Heuer, 1993). Because Heuer and colleagues found interference to be "transient", it lead them to hypothesize that cross-talk occurs during the concurrent specification processes of motor programming rather than at motor execution. If advance motor planning is also a benefit to haptic tracking, then participants in the present experiment who are in a highly predictable transition condition (e.g., the transition occurs in the same place and at the same time 100% of the time) should be less susceptible to between-hand interference. If, however, haptic tracking diminishes dependence on specification planning then the transition predictability should have no effect, such that even the most random transitions should not result in between-hand interference.

Participants in the present experiment came in for three sessions distributed over separate days, with two days scheduled consecutively and the third session occurring one week later. This practice manipulation was added to Experiment 4 because predictions take time to develop. Typically, with sufficient time for planning, training, or expertise, bimanual interference effects can be overcome. The fact that practiced bimanual movements can achieve independence is part of what lead Klapp and colleagues to the conclusion that coordination is related to the planning of movements (Klapp, Nelson, & Jagacinski, 1998; Klapp et al., 1985; Jagacinski, Klapp, Nelson, & Jones, 1988). Klapp et al. found that participants have difficulty when asked to attend to one rhythm while tapping another, and that this interference is similar to the one demonstrated when trying to tap a 3:2 rhythm between hands. However, Klapp et al. showed that the difficult 3:2 tapping frequency between hands can be made easy by repeating a mnemonic phrase "not-dif-fi-cult" while tapping the "not" "dif" and "cult" syllables with the index finger of the left hand and the "not" and "fi" syllables with the index finger of the right hand. On the basis of these experiments, Klapp et al. concluded that at least some of the interference found in 3:2 rhythm tasks was not due to motoric constraints, but from the inability to form a unified perception by which to shape motor output (see also Mechsner, 2001; Franz et al., 2001; Neilson and Neilson, 2003).

While the present experiment did not teach an explicit method by which to overcome interference, participants were exposed to statistical regularities that could be learned over time. The ability of participants to learn predictable transitions was assessed through measures of improvement in the disrupted hand's ability to maintain contact with its driven stimulus, improvement in the non-disrupted hand's ability to maintain contact with its driven stimulus, and general haptic tracking performance as assessed over several days, and after a week delay. If performance was found to improve during the disruption training trials or during general haptic tracking tasks (i.e., better maintenance of positional accuracy and fewer errors), it would be safe to conclude that prediction had some role in the previous, predictable experiments, and that some type of representation was being formed even while haptically tracking. The present experiment's assignment of participants to different levels of movement reversal predictability was designed to give a sense of the complexity of patterns that can be reliably predicted, while distributed practice allowed investigation of immediate, short-term, and long-term practice effects.

Method

Participants

Fifteen healthy, right-handed undergraduates at Penn State University participated.

Procedure, Design, and Apparatus

The apparatus was slightly redesigned for Experiment 4 in that the separating pane of glass was rotated from a vertical plane to a horizontal plane (similar to the horizontal plane of Experiment 1). This adjustment was made to extend the generalizability of haptic tracking movements, increase testing time by reducing arm fatigue in participants, improve IRED visibility, and allow for possible future experiments with individuals who have a limited ability to lift their arms.

In the new configuration, the glass was replaced with a "tabletop" of two panes of opaque acrylic (each at 28 cm x 28 cm x 6 mm thick) resting on a pair of saw horses 91.44 cm high. The templates were also scaled down to fit within the newly sized acrylic panes (diameter = 22.6 cm) as were the paddles (radius = 3.5 cm). Because the paddle radius was 3.5 cm, the diameter of the circle described by the moving target was 22.6 cm – (2 × 3.5 cm) = 15.6 cm. With the new paddles and acrylic panes, the target button magnets decoupled when a force greater than 0.3744 N (0.0841 pound force) was applied.

Five young women and two young men (six Penn State undergraduates and one graduate student, the second author) alternated responsibility of driving the paddles and operating the OPTOTRAK system. Two drivers sat underneath the elevated acrylic panes, separated from one another by a divider, and separated from the standing participant by a divider (see Fig. 5).

5

5: The setup for Experiment 4. Two drivers under the tabletop moved the paddles connected to magnetized targets while the subject haptically tracked the targets. The driver on the far left side of the picture abruptly changed directions according to a computerized tone that only she could hear.

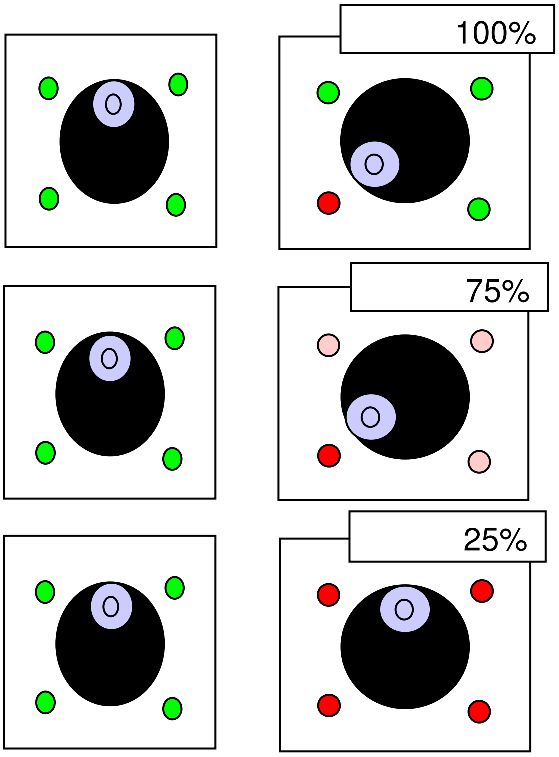
Participants came in for three sessions distributed over separate days with two days scheduled consecutively, and the third session occurring one week later. On their first visit, they were allowed thirty seconds of unblindfolded practice smoothly tracking bimanual symmetric movements. They were then blindfolded and headphones playing white noise were placed on their ears. Participants then performed in succession (a) a baseline haptic tracking task for two aggregated total minutes of accurate tracking, (b) two blocks of four one-minute trials of abrupt direction changes, and, finally, (c) a probe trial of haptic tracking for two aggregated total minutes of accurate haptic tracking. On the second visit, participants again received two blocks of four trials of abrupt transitions, and concluded with a two minute probe of haptic tracking. On the third visit, a week later, they received only the two minute probe of haptic tracking.

The baseline and probe haptic tracking tasks were identical, differing only in name based on when they occurred in a given session. In the baseline/probe haptic tracking task, the paddles began in the standard symmetric home positions of 2 o'clock for the left-hand shape and 10 o'clock for the right-hand shape (from the participant's perspective), and they moved mirror-symmetrically about the horizontal axis. Each paddle driver listened to a shared metronome set at a frequency of 0.5 Hz over a pair of headphones. If the participant lost contact with the button or decoupled the magnets, the trial was stopped and then started again with both paddles at their home positions. All the time spent in a condition was accumulated until the participant completed 2 minutes of haptic tracking in that condition.

For the abrupt transition training trials, drivers listened to independent metronomes, with the metronome on the right-hand side (from the driver's perspective) set at 120 bps (0.5 Hz), and the metronome on the left-hand side set at 140 bps (0.58 Hz). The driver on the right-hand side (driving the stimulus tracked by the left hand of the participant) always generated continuous, smooth, clockwise movement. However, the driver on the left-hand side reversed the direction of the paddle when signaled by a special tone embedded in their metronome program. Transitions always occurred at one of four possible marker points, set at 45, 135, 225, and 315 degrees along the rim of the circle template. Further, the tone always sounded after two full cycles of movement around the circle plus a defined number of beats after those cycles dependent upon the assigned condition.

Participants were randomly assigned to either a 100%, 75%, or 25% predictability condition (see Fig. 6). In the 100% predictability condition, the transition signal always sounded at exactly the same point in time after the two full rotations, i.e., drivers always reversed direction at the same marker point on the circle template. In the 75% predictability condition, drivers reversed direction at the same point 75% of the time, with the other 25% of reversals randomly (but equally) distributed among the three remaining points. In the 25% condition, the tone signaling the direction transition occurred at all four markers an equal number of times, randomly ordered.

6



6: Experiment 4 between-subject conditions from the participant's perspective. The left hand maintains a smooth, symmetric pattern while the right hand changes path direction at a particular corner with differing levels of predictability. At 100%, the stimulus changes direction in the same place and time on each trial. At 75%, the stimulus changes direction in the same place 75% of the time, with the other 25% equally distributed across other potential change points. At 25%, the stimulus is equally likely to change direction at any point along the circular workspace.

The abrupt transition trials were administered in two blocks of four one-minute trials, and each trial had a different randomization order for the 25 and 75% predictability conditions. If the participant made an error during the trial, by losing the target or decoupling the target, the trial was stopped and restarted at the same point it had been discontinued at in the original randomization order. At the end of the third session, participants were debriefed.

Results

Target Motions

The first set of analyses concern the target motions generated by the human drivers. Cycle completion times were measured based on successive times of arrival of the paddles at the “corner” positions on the circumference of the left and right circles. As shown in Table 10, during perturbed haptic tracking trials, the times to complete the revolutions varied around the left hand required period of 1700 ms when the target frequency was .58 Hz and around the right hand required period of 2000 ms when the target frequency was .5 Hz. The generated periods were significantly different for the left hand target period of 1700 ms versus the right hand target period of 2000 ms, $F(1, 12) = 23.03$, $p < 0.05$, but the periods generated were not statistically affected by the assigned predictability condition, $F(2, 12) = 0.19$, $p > 0.05$, or by the day and block of the trial, $F(4, 9)=1.73$, $p > 0.05$ (with Huynh-Feldt adjustment). No interaction approached statistical significance.

10: Means (and standard errors) of obtained periods (ms) when the target periods were 1700 ms (0.58 Hz) for the left hand, and 2000 ms (0.50 Hz) for the right hand. Data from Experiment 4.

10

		Day 1			**Day 2**	
	Condition	**Baseline**	**1st block**	**2nd block**	**1st block**	**2nd block**
Left	**25%**	1648 (81)	1715 (59)	1901 (123)	1618 (120)	1637 (91)
	75%	1657 (81)	1719 (59)	1843 (123)	1942 (119)	1849 (91)
	100%	1498 (81)	1556 (58)	1695 (122)	1652 (119)	1749 (91)
	Total	1601 (47)	1663 (34)	1813 (71)	1737 (69)	1744 (52)
Right	**25%**	1958 (179)	2157 (183)	2112 (160)	2392 (312)	2290 (252)
	75%	2150 (179)	2340 (183)	2191 (160)	2338 (312)	2223 (253)
	100%	2107 (179)	2249 (183)	2212 (160)	2410 (312)	2203 (252)
	Total	2072 (104)	2248 (105)	2172 (92)	2380 (180)	2238 (146)

Similarly, an analysis was conducted on the target motions generated by the human drivers during unperturbed haptic tracking. As shown in Table 11, the times to complete the revolutions were quite variable around the required period of 2000 ms when the target frequency was .5 Hz. The generated periods were not significantly different between hands, $F(1, 12) = 4.12$, $p > 0.05$, between predictability conditions, $F(2, 12) = 1.43$, $p > 0.05$, or by the day and block of the trial, $F(3, 10) = 0.25$, $p > 0.05$ (with Huynh-Feldt adjustment). No interaction approached statistical significance.

11: Means (and standard errors) of obtained periods (ms) when the ideal, metronome-specified period was 2000 ms (0.50 Hz). Data from Experiment 4.

11

		Day 1		**Day 2**	**Day 3**
	Condition	**Baseline**	**End probe**	**End probe**	**End probe**
Left	**25%**	1763 (152)	1852 (188)	1824 (215)	1710 (149)
	75%	1720 (152)	2116 (188)	2187 (215)	1924 (149)
	100%	1714 (152)	1820 (188)	1855 (215)	1658 (149)
	Total	1733 (88)	1930 (109)	1955 (124)	1764 (86)
Right	**25%**	2270 (393)	1967 (222)	2948 (483)	2713 (308)
	75%	2261 (393)	1926 (222)	1730 (483)	1557 (308)
	100%	2084 (393)	2194 (222)	1670 (483)	1873 (308)
	Total	2205 (227)	2029 (128)	2116 (279)	2048 (178)

Tracking Performance

The following data address participant performance. The mean number of trials participants needed to complete one minute of tracking in each perturbation block is shown in Table 12. A repeated measures analysis of variance indicated that there was a main effect of time such that the number of trials needed to complete one minute of perturbed tracking was significantly higher for the initial baseline perturbation measure (the first perturbation order that participants experience) ($\bar{x}$ = 2.6) compared to all subsequent blocks ($\bar{x}$ = 1.40, 1.90, 1.32, and 1.45), $F(4, 9) = 8.51$, $p < 0.05$ (with Huynh-Feldt adjustment). The number of required trials was not significantly different across the different levels of predictability, $F(2, 12)=1.18$, $p > 0.05$. No interaction approached statistical significance.

12: Means (and standard errors) of the number of attempts needed to complete 1 minute of haptic tracking in each condition for the first perturbation order experienced and for the first and second blocks of Day 1 and 2. Perfect performance is 1 attempt. Data from Experiment 4.

12

	Day 1			**Day 2**	
Condition	**Baseline**	**1st block**	**2nd block**	**1st block**	**2nd block**
25%	3.60 (.62)	1.15 (.15)	2.30 (.29)	1.20 (.18)	1.40 (.28)
75%	1.80 (.62)	1.20 (.15)	1.60 (.29)	1.25 (.18)	1.65 (.28)
100%	2.40 (.62)	1.85 (.15)	1.80 (.29)	1.50 (.18)	1.30 (.28)
Total	2.60 (.36)	1.40 (.09)	1.90 (.17)	1.32 (.10)	1.45 (.16)

The mean number of trials participants needed to complete two minutes of unperturbed haptic tracking is shown in Table 13. A repeated measures analysis of variance indicated that there was an effect of practice, irrespective of condition, such that the number of trials needed to complete two minutes of unperturbed tracking was significantly higher for the initial baseline measure of haptic tracking ($\bar{x} = 2.47$) compared to all subsequent probes ($\bar{x} = 1.40$, 1.33, and 1.60), F (3, 10) = 5.09, $p < 0.05$ (with Huynh-Feldt adjustment). The number of required trials was not significantly different across the different levels of predictability, F (2, 12)= 0.47, $p > 0.05$. No interaction approached statistical significance.

13: Means (and standard errors) of the number of attempts needed to complete 2 minutes of unperturbed haptic tracking in each condition for the Day 1 baseline and for the end-of-day probes of Day 1, 2, and 3. Perfect performance is 1 attempt. Data from Experiment 4.

13

	Day 1		**Day 2**	**Day 3**
Condition	**Baseline**	**End Probe**	**End Probe**	**End Probe**
25%	2.20 (.65)	1.80 (.27)	1.20 (.22)	1.40 (.29)
75%	2.20 (.65)	1.20 (.27)	1.20 (.22)	1.80 (.29)
100%	3.00 (.65)	1.20 (.27)	1.60 (.22)	1.60 (.29)
Total	2.47 (.38)	1.40 (.16)	1.33 (.13)	1.60 (.17)

To further assess the impact of predictability on performance the mean Euclidean distances between vector endpoints of the paddle and corresponding hand were analyzed. The results appear in Table 14. There were no significant differences in average displacement errors between hands, $F(1, 12) = 1.08$, $p > 0.05$, between predictability conditions, $F(2,12) = 0.10$, $p > 0.05$, or based on the amount of practice, $F(4, 9) = 0.67$, $p > 0.05$ (with Huynh-Feldt adjustment). No interaction approached statistical significance.

14: Across-trial means (and standard errors) of Euclidean distances (mm) between endpoints of paddle displacements and endpoints of corresponding hand displacements during perturbed tracking blocks. Data from Experiment 4.

14

		Day 1			**Day 2**	
	Condition	**Baseline**	**1st block**	**2nd block**	**1st block**	**2nd block**
Left	**25%**	3.04 (.79)	2.63 (.36)	3.38 (.43)	3.04 (.76)	3.44 (.81)
	75%	2.93 (.79)	2.61 (.36)	3.52 (.43)	3.41 (.76)	2.76 (.81)
	100%	2.35 (.79)	3.07 (.36)	3.25 (.43)	3.41 (.76)	2.62 (.81)
	Total	2.77 (.50)	2.77 (.21)	3.38 (.25)	3.29 (.44)	2.94 (.47)
Right	**25%**	2.32 (.90)	2.71 (.36)	3.62 (.63)	2.94 (.75)	3.34 (.63)
	75%	3.32 (.90)	2.86 (.36)	3.69 (.63)	3.74 (.75)	3.22 (.63)
	100%	3.29 (.90)	3.02 (.36)	3.47 (.63)	3.14 (.75)	2.41 (.75)
	Total	2.98 (.52)	2.86 (.21)	3.59 (.36)	3.27 (.43)	2.99 (.36)

To better assess the impact of an abrupt reversal in the context of the three conditions of the experiment, a 1000 ms window of data for the period that occurred immediately after the signal tone to reverse right hand target direction was analyzed. The results appear in Table 15. Quality of tracking performance, even at the time of perturbation, was comparable to non-perturbed performance. The average displacement errors at the time of the right hand target reversal were very small and there were no significant differences between hands, $F(1, 12) = 2.77$, $p > 0.05$, between predictability conditions, $F(2,12) = 0.75$, $p > 0.05$, or based on the amount of practice, $F(4, 9) = 1.69$, $p > 0.05$. No interaction approached statistical significance.

15: Means (and standard errors) of Euclidean distances (mm) between endpoints of paddle displacements and endpoints of corresponding hand displacements for a 1000 ms period anchored on the signal to reverse directions in the right hand. Data from Experiment 4.

15

		Day 1			**Day 2**	
	Condition	**Baseline**	**1st block**	**2nd block**	**1st block**	**2nd block**
Left	**25%**	3.05 (.40)	3.27 (.34)	3.06 (.36)	2.60 (.33)	2.75 (.29)
	75%	3.03 (.40)	2.91 (.34)	2.97 (.36)	2.68 (.33)	2.72 (.30)
	100%	2.79 (.40)	3.08 (.34)	3.50 (.36)	2.38 (.33)	2.76 (.30)
	Total	2.96 (.23)	3.10 (.20)	3.18 (.21)	2.53 (.19)	2.72 (.17)
Right	**25%**	3.49 (.56)	3.60 (.34)	3.19 (.25)	3.58 (.29)	3.66 (.41)
	75%	3.37 (.56)	2.94 (.34)	3.03 (.25)	2.84 (.29)	3.23 (.41)
	100%	2.37 (.56)	2.71 (.34)	3.05 (.25)	2.84 (.29)	2.69 (.41)
	Total	3.07 (.32)	3.09 (.20)	3.09 (.15)	3.09 (.16)	3.19 (.23)

Lastly, Table 16 displays the average displacement errors during unperturbed haptic tracking. Analysis of the unperturbed mean errors did not yield a significant difference between hands, F (1, 12) = 0.06, $p > 0.05$, between predictability conditions, F (2, 12) = 2.45, $p > 0.05$, or based on the amount of practice, F (3, 10) = 0.27, $p > 0.05$ (with Huynh-Feldt adjustment). No interaction approached statistical significance.

16: Means (and standard errors) of Euclidean distances (mm) between endpoints of paddle displacements and endpoints of corresponding hand displacements during unperturbed tracking. Data from Experiment 4.

16

		Day 1		**Day 2**	**Day 3**
	Condition	**Baseline**	**End probe**	**End probe**	**End probe**
Left	**25%**	2.34 (1.30)	1.80 (1.00)	1.61 (1.10)	1.44 (.52)
	75%	2.79 (1.30)	3.40 (1.00)	4.41 (1.00)	3.32 (.52)
	100%	3.55 (1.30)	3.55 (1.00)	2.39 (1.10)	2.65 (.52)
	Total	2.90 (.75)	2.91 (.58)	2.80 (.64)	2.47 (.30)
Right	**25%**	2.61 (.90)	1.44 (.97)	2.9 (1.12)	1.45 (.57)
	75%	2.86 (.90)	3.28 (.97)	3.29 (1.12)	2.85 (.57)
	100%	4.56 (.90)	3.15 (.97)	2.39 (1.12)	2.90 (.57)
	Total	3.34 (.52)	2.62 (.56)	2.85 (.65)	2.40 (.33)

Other methods were also used to attempt to verify that there was no improvement in performance. First, Euclidean distance error data was subjected to a time series impact analysis designed to assess the impact of intervention inputs on an ordered series of responses. The impact response model was formulated as a regression function with Euclidean distance error varying over time as function of the pre-intervention AutoRegressive Integrated Moving Average (ARIMA) noise model plus the input function of the deterministic intervention indicator for each of the perturbations. The ARIMA time series analysis did not reveal that the series level underwent any shift at the time of the intervention. Second, haptic tracking performance error was also calculated using root mean squared error (RMSE). When the RMSE data was subjected to the same analyses, a similar pattern of results emerged, where there was no difference in tracking performance across hand, predictability condition, or time.

Between-Hand Coordination

The direction reversal method of Experiment 4 also provided a unique context by which to evaluate coordination tendencies between the two hands. As mentioned earlier, Spijkers and Heuer (1995) found that when one hand alternates between long and short movements and the other hand is maintaining a constant amplitude, performance in alternating hand suffers, and further, its error translates to the constant amplitude hand (Spijkers and Heuer 1995). Based on this finding, one might expect an increased correlation in the error between the two hands when unimanual transitions occur. However, if participants use foreknowledge about the time or location of the transition, and so have time to complete movement planning before the transition, they may be able to attenuate cross-talk (Spijkers, Heuer, Steglich, & Kleinsorge, 2000).

To measure possible fluctuations in between-hand cross-talk, a Pearson’s r was computed for the average error between the two hands across every 1000 ms of data for every testing block and predictability condition. Each r was converted to a Fisher's z to compute confidence intervals and perform significance testing. The values of Fisher's z in the confidence interval were then back-transformed to Pearson's r's.

Error in the left hand was not associated with error in the right hand (at the .05 level) during the unperturbed tracking blocks (Table 17), nor were errors associated during the unperturbed portions of the perturbation tracking blocks (Table 18 and Fig. 7), nor were errors associated even during the perturbed portions of the perturbation blocks (Table 19 and Fig.8). The polar plots of Fig. 7 and Fig. 8 reveal that the correlation in error between the hands fluctuates over time and across the workspace. Primarily, between-hand correlations are weak, varying between –0.2 and +0.2, but occasionally achieving moderate or even strong (-0.6, 0.6) correlations. However, these transient correlation spikes were not cyclical nor were they identifiably systematic.

17: Pearson correlation coefficients (and 95% CI for $\mu 1 - \mu 2$) of between-hand error as measured by the Euclidean distance (mm) between endpoints of paddle displacements and endpoints of corresponding hand displacements during unperturbed tracking blocks. Data from Experiment 4.

17

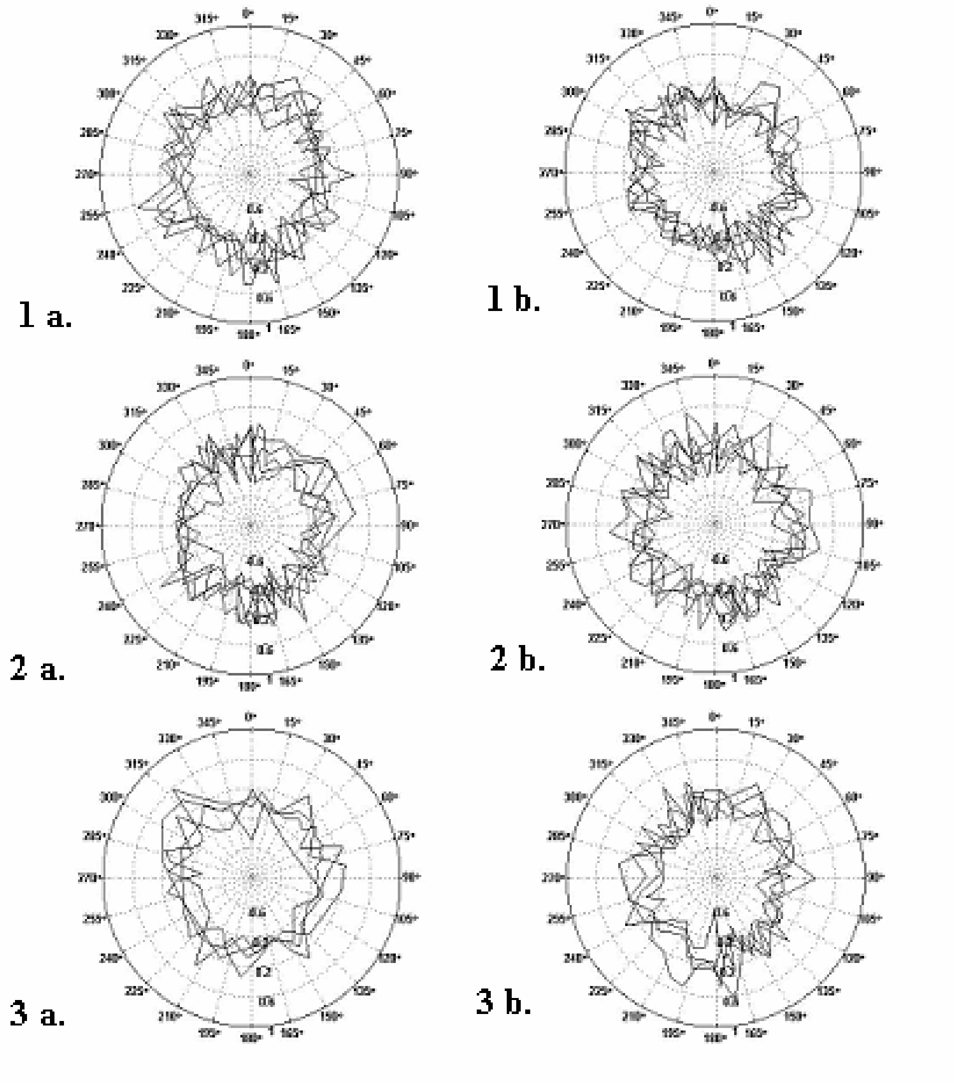
	Day 1		**Day 2**	**Day 3**
Condition	**Baseline**	**End Probe**	**End Probe**	**End Probe**
25%	.053 (-.06,.17)	.003 (-.12,.12)	-.014 (-.10,.08)	.025 (-.07,.11)
75%	-.013 (-.11,.08)	-.038 (-.12,.05)	-.001 (-.08,.08)	.023 (-.07,.12)
100%	.012 (-.08,.10)	.054 (-.03,.13)	.003 (-.09,.09)	-.035 (-.12,.05)
Total	.017 (-.08,.12)	.006 (-.09,.10)	-.004 (-.09,.08)	.004 (-.09,.09)

18: Pearson correlation coefficients (and 95% CI for $\mu 1 - \mu 2$) of between-hand error as measured by the Euclidean distance (mm) between endpoints of paddle displacements and endpoints of corresponding hand displacements during the unperturbed portions of perturbation tracking blocks. Data from Experiment 4.

18

	Day 1			**Day 2**	
Condition	**Baseline**	**1st block**	**2nd block**	**1st block**	**2nd block**
25%	-.001 (-.18,.18)	-.011 (-.15,.13)	-.010 (-.13,.11)	.012 (-.11,.13)	-.031 (-.16,.10)
75%	-.018 (-.13,.10)	.011 (-.11,.13)	.013 (-.10,.13)	.008 (-.10,.12)	.026 (-.08,.13)
100%	.026 (-.10,.15)	.049 (-.07,.17)	-.023 (-.14,.09)	.008 (-.10,.12)	.028 (-.08,.14)
Total	.002 (-.14,.14)	.016 (-.11,.14)	-.007 (-.12,.11)	.009 (-.10,.12)	.008 (-.10,.12)

7



1 a.

1 b.

2 a.

2 b.

3 a.

3 b.

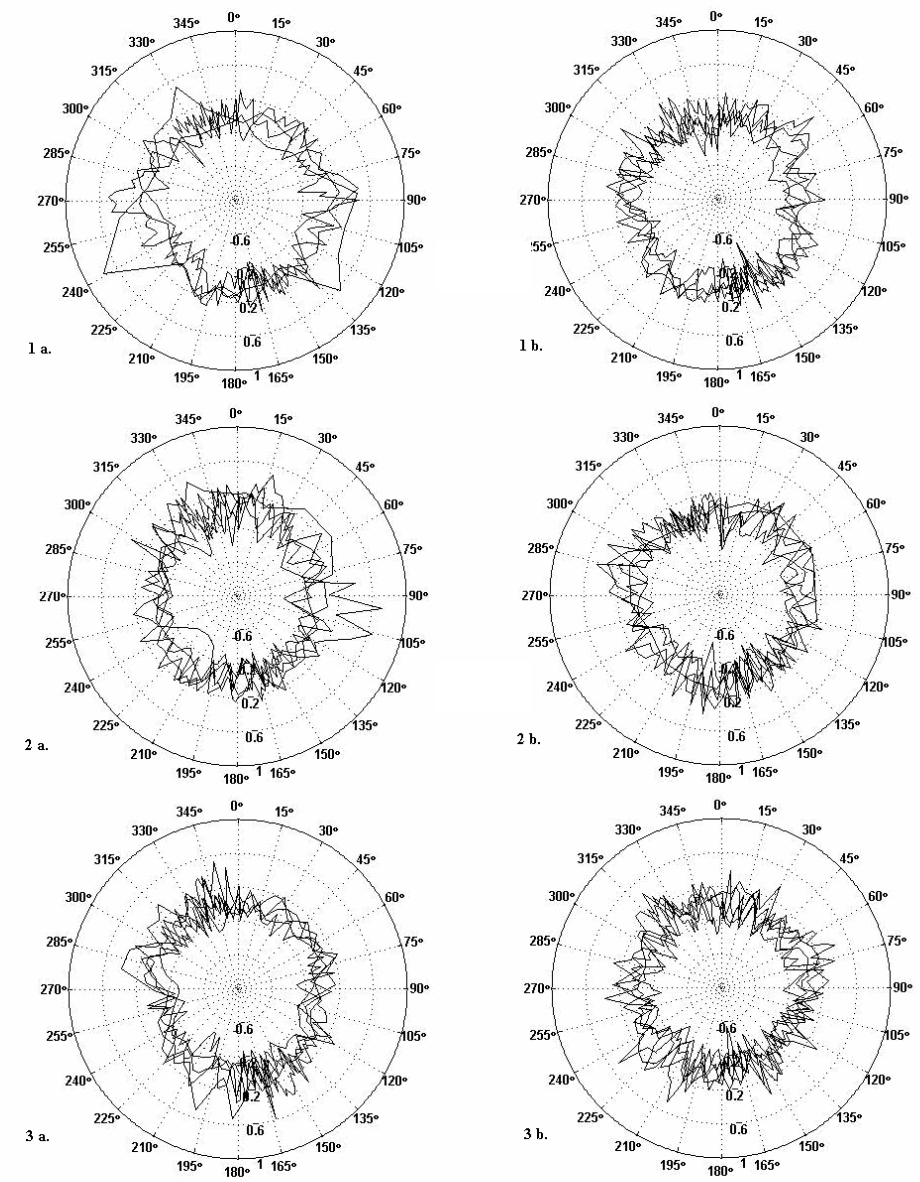
7: The correlation in errors of the left and right hands on the unperturbed portions of the perturbation tracking blocks. In this polar plot, Theta is defined at the angles of the circular tracking workspace, and Rho is defined by the Pearson correlation of the between-hand error at that angle across participants. 1a. Baseline 25%; 1b. Final trial 25%; 2a. Baseline 75%; 2b. Final trial 75%; 3a. Baseline 100%; 3b. Final trial 100%. Data from Experiment 4.

19: Pearson correlation coefficients (and 95% CI for $\mu_1 - \mu_2$) of between-hand error as measured by the Euclidean distance (mm) between endpoints of paddle displacements and endpoints of corresponding hand displacements during the perturbed portions of perturbation tracking blocks. Data from Experiment 4.

19

	Day 1			**Day 2**	
Condition	**Baseline**	**1st block**	**2nd block**	**1st block**	**2nd block**
25%	-.001 (-.47,.47)	-.028 (-.38,.34)	.019 (-.29,.33)	-.002 (-.31,.31)	.153 (-.20,.47)
75%	-.083 (-.37,.22)	-.036 (-.34,.28)	.042 (-.26,.33)	.045 (-.24,.32)	.034 (-.25,.31)
100%	.070 (-.26,.39)	.049 (-.27,.36)	.071 (-.23,.36)	.020 (-.26,.30)	.049 (-.23,.32)
Total	-.005 (-.37,.36)	-.005 (-.33,.33)	.044 (-.26,.34)	.021 (-.27,.31)	.079 (-.23,.37)

8



8: The correlation in errors of the left and right hands during the perturbed portions of the perturbation blocks. In this polar plot, Theta is defined at the angles of the circular tracking workspace, and Rho is defined by the Pearson correlation of the between-hand error at that angle across participants. 1a. Baseline 25%; 1b. Final trial 25%; 2a. Baseline 75%; 2b. Final trial 75%; 3a. Baseline 100%; 3b. Final trial 100%. Data from Experiment 4.

The present experiment failed to yield any evidence that individuals actively use long-term prediction when haptically tracking. None of the measures of tracking error revealed a change in performance based on the level of predictability of the abrupt transition. Tracking error did not increase significantly even at the time of the perturbation itself. Learning was only evident in the number of trials it took to complete a trial, and that effect was relegated to the improvement made after the first baseline trial. Furthermore, the investigation of continuous changes in between-hand error failed to yield a consistent timepoint or location of increased interlimb interference.

These results complement the performance of participants in a compensatory haptic pursuit task developed by Gentry and Murray-Smith (2003). In their experiment, participants tracked forces reflecting error from a path. Sudden direction reversals occurred at both unpredictable and learned, predictable points in a rhythm. There were no reliable differences in tracking performance between predictable and unpredictable reversals, leading Gentry and Murray-Smith to conclude that participants fell back to a closed-loop response rather than engage in prediction.

Chapter 6

Experiment 5

The results in Experiment 4 point to a lack of planning during haptic tracking. However, participants in that experiment had to form predictions that spanned across several rotations and many seconds. This method did not address the moment-by-moment online prediction that individuals may use to improve their tracking. Experiment 5 was designed to investigate whether participants are wholly reliant on the online detection of shear forces to make their responses, or whether they also engage in short-term prediction of either a target's position or velocity.

These issues about the nature of the signal used for haptic tracking are reminiscent of the analogy to smooth pursuit eye movements made early in the paper. In review, visual smooth pursuit is thought to be driven by three inputs: a direct retinal slip signal, an internal representation of target velocity in space (Robinson, Gordon, & Gordon, 1986), and predictions of the future location of the target in space (Keller & Heinen, 1991). In Experiment 5 the apparatus was redesigned to specifically address these inputs in the haptic domain, by minimizing the skin stretch and slip signals and by assessing predictions about velocity and position.

Similar to visual smooth pursuit, haptic smooth pursuit is informed by a slip signal. In the previous experiments, participants were reacting to shear forces felt along the underside of their fingertips as they maintained contact with a self-propelled stimulus. In the present experiment, participants tracked along a large, continuous canvas surface, stretched taut, and the presence of the stimulus was only signaled by a traveling change in the surface's elevation. Because the taut canvas is completely smooth, it is expected that participants will find it difficult to differentiate between movement that only produces skin stretch and movement that also causes slippage across the surface of the skin. This prediction is based on the results of Srinivasan, Whitehouse, and LaMotte (1990) who moved glass plates along participants' fingerpads and discovered that in order for participants to be able to distinguish the actual movement of an object relative to the skin from skin stretch alone, there needed to be some surface feature present.

If accurate perception of shear force information is critical to haptic tracking, one would expect to find poorer performance in this experiment compared to all of the previous experiments. However, if haptic tracking error in previous experiments was low because of the direct stimulus-response characteristics of touch, one would not expect a perceptible stimulus moving behind a plane, as opposed to in front of it, to necessarily impair tracking ability.

The apparatus was further reconfigured to assess the representation of velocity and position during haptic tracking. It is known that individuals are very accurate at estimating perceived velocity, and estimates are comparable for both skin indentation (between 0.1-10 cm/s) and surface parallel brushing of either the index finger or the volar forearm (between 1.0-100 cm/s; Franzén, Thompson, Whitsel, & Young, 1984). Because the psychophysical functions are equivalent for different body parts it suggests that the estimation of velocity is not based on the absolute sensitivity or receptor density of the skin, but instead is the result of a central mechanism (Greenspan & Bolanowski, 1996). Also, as mentioned earlier, perception of the direction and distance of movement across the skin is highly accurate. One can detect the direction of skin stretch on the forearm with as little as 1.0 mm of shear displacement (Gould, Vierck, & Luck, 1979).

While it is known that individuals can estimate velocity and position when asked to, the question remains as to whether individuals naturally use this information to form predictions during haptic tracking. To investigate this question, the apparatus was reconfigured to parallel the design of a classic visual experiment called the occluder paradigm. In occluder experiments, a participant visually tracks a smoothly moving stimulus that momentarily goes “behind” an occluder. In these experiments it is typically found that participants are able to maintain smooth visual tracking of the target even while the target is not visible, and notably, their eye maintains the previously viewed velocity of the target for up to four seconds after the target has disappeared from view (Becker & Fuchs, 1985). The maintenance of velocity in the absence of the target has been termed ‘predictive pursuit’ and is thought to be part of other open-loop responses like anticipatory smooth tracking of a highly predictable target motion. Over time the eye’s adherence to the target velocity declines, unless the participants expect to meet up with the target again once it reappears from behind the occluder. In that case, the eye either quickly saccades to the expected reappearance location, or quickly increases its velocity right before the time the participant expects the target to reappear (Barnes & Asselman, 1991; Becker & Fuchs, 1985; van den Berg, 1988).

Just as in the visual occluder paradigm, participants in this experiment tracked a stimulus that ‘disappeared’ for a period of time before reappearing in a position that could be predicted by the target’s previous velocity and path. The question at hand is whether haptic tracking will be sensitive to velocity errors, similar to the smooth pursuit visual system, or if it will use position error information, similar to the saccadic system. In the former case, one would expect to see a maintenance of the target’s velocity for a period of time after the target disappearance. In the latter case, path would be accurately recreated for a time. If haptic tracking represents both velocity and position then one might expect that participants could meet back up with the target once it reappears, if the length of its disappearance did not exceed the maintenance of the representations.

Method

Participants

Fifteen healthy, right-handed undergraduates at Penn State University participated.

Procedure, Design, and Apparatus

Participants followed a pair of small metal shafts attached to robotic arms that moved in symmetric circles. A 60.96 cm x 91.44 cm artist canvas, consisting of a cloth covering stretched taut on a frame of wood, served as the tabletop. Two servo-controlled rotary motors powered by a variable voltage power supply sat underneath the canvas. Attached to each rotary motor was a 38.10 cm horizontal aluminum arm. In motion, the right and left arms described symmetric 33.02 cm diameter circles, with the left-handed arm swinging clock-wise and the right-handed arm swinging counter-clockwise (from the participant's viewpoint). The left-handed motor consistently ran at 10v, which translated to an arm movement at 0.0625 Hz (one full rotation every 16 seconds). The right-handed motor could run at either 10v, with the same parameters as above, or it could run at 15v, which translated to an arm movement at 0.095 Hz (one full rotation every 10.5 seconds).

Set back 2.54 cm from tip of each arm was a 7.62 cm high block that served as housing for a 25.4 mm vertical metal shaft. When a shaft was extended outside of its housing it pressed against the overhead canvas, thereby providing a small bump of canvas for the participant to follow. The right-handed metal shaft could rapidly retract, by virtue of a computer-controlled solenoid, allowing the bump stimulus to disappear underneath the canvas for a prescribed period of time. Both shafts were designed to not retract upon pressure, and the tension between the taut canvas and shaft was adjusted such that participants could not use further pressure to maintain contact with a shaft that had been retracted. To achieve both these properties, the right-handed vertical shaft was 5 mm in diameter and could extend to 3.3 mm outside of its housing, while the left-handed vertical shaft was 10 mm in diameter and could extend 12.7 mm outside of its housing. The canvas distention provided by each shaft was both the diameter of the shaft, at the center, encircled by a graded slope that extended nearly 4 cm in circumference around the center target.

Participants were introduced to the task with a single 30 second practice trial in which they were told to haptically follow the targets moving under the canvas with both hands. After this orientation to the task demands, participants were blindfolded and listened to white noise over a set of headphones. They received two thirty second practice trials at the 10v velocity of 6.48 cm/s across both hands. In these trials both the right and left-handed shafts were always extended and available for direct haptic contact.

After the practice trials, participants underwent two blocks of randomized trials where the right-handed shaft would disappear 15 seconds into the trial and then either remain retracted (a “no return” trial), or would extend again after 3 seconds, 5 seconds, or 10 seconds. Each trial lasted 30 seconds, and the left-handed shaft always remained extended. Participants were told before each trial that when the right-hand target “disappeared” to continue tracking the invisible target as if it was still there. They were also informed before each trial whether they could expect the right-hand stimulus to “reappear” or not. If it was to reappear, they were told to try to pace and position themselves such that they would be able to meet back up with it once it reappeared. Participants were given a break before the second block began. The second block featured a change in the motor velocity of the right-hand stimulus to 15v or 9.88 cm/s, with the left-hand motor velocity remaining at 10v or 6.48 cm/s. To acquaint the participants with the new velocity requirements, they were once again given two practice trials, where no drop occurred in the right-handed solenoid, and only then received a randomized set of disappearing right-hand stimulus trials.

One may note that the velocities used in this experiment were much slower than those in previous experiments in this thesis. However, in contrast to the previous experiments, participants must demonstrate a target's path in its absence. The target velocities in the present experiment were set to match those needed for participants to verbally indicate direction. The perceived travel distance of a tangentially moving stimulus is most veridical within only a small range of velocities (5-20 cm/s). Even more specifically, for the fingertip, the mean optimal velocity for directional discrimination is 5.4 cm/s (Essick, Bredehoeft, McLaughlin & Szaniszlo, 1991). Furthermore, the critical length for the fingertip (the length skin that needs to be traversed to correctly identify the direction of movement at least 75% of the time) is between .46 and .50 cm for the velocities used in the present experiment (Whitsel, Dreyer, Hollins, & Young, 1979). These threshold distances are appropriate for the skin surface available on the fingerpad.

Results

Hand Velocity

The first assessment was of the participants' ability to haptically track at the required target velocities. As shown in Table 20, the times to complete the revolutions were fairly well-matched to the robotic arms, where the required velocity at 10v was 6.48 cm/s and at 15v was 9.88 cm/s. Table 20 displays the means for both the practice and experimental trials, however only the experimental trials were entered into a repeated measures MANOVA. The generated velocities between the hands were similar when the voltages matched (left hand $\bar{x}$ = 6.50 cm/s; right hand $\bar{x}$ = 6.57 cm/s), but significantly different from one another when the voltages mismatched (left hand $\bar{x}$ = 6.47 cm/s, right hand $\bar{x}$ = 9.79), F (1,14)=169.57, p< .05. There was no effect of condition on velocity, F (3,12)=2.20, p > .05. However, there was a substantial increase in variability for the right hand when tracking and replicating the speed produced by a 15v motor.

20: Means (and standard errors) of obtained velocities (cm/s) when the target velocities were 6.48 cm/s (.0625 Hz) for the 10v conditions, and 9.88 cm/s (.095 Hz) for the 15v condition. Totals do not include practice trials. Data from Experiment 5.

20

	1st Block		2nd Block	
Condition	**Left (10 v)**	**Right (10 v)**	**Left (10 v)**	**Right (15 v)**
Practice 1	6.50 (.04)	6.56 (.06)	6.44 (.07)	10.30 (.26)
Practice 2	6.46 (.04)	6.55 (.05)	6.51 (.03)	10.34 (.22)
3 seconds	6.46 (.03)	6.61 (.07)	6.44 (.06)	10.31 (.18)
5 seconds	6.52 (.02)	6.56 (.04)	6.52 (.05)	9.71 (.18)
10 seconds	6.51 (.03)	6.51 (.07)	6.40 (.07)	9.60 (.33)
15 seconds	6.50 (.05)	6.58 (.07)	6.51 (.03)	9.55 (.23)
Total	6.50 (.02)	6.57 (.03)	6.47 (.03)	9.79 (.15)

Each trial in the 2nd block was divided into two fifteen second segments in order to further evaluate the frequencies produced by the right hand (see Table 21). The experimental trials were entered into a repeated measures MANOVA. In the first fifteen seconds of a trial the stimulus was always extended and available to the hand for haptic tracking. The position of the stimulus in the second fifteen seconds of a trial depended upon the condition: It was either extinguished for 3, 5, 10, or 15 seconds. No difference was found in the right hand's frequency between the two trial segments, F(1,14) = .132, p > .05, nor across conditions, F(3,12) = 1.37, p > .05, nor for the interaction of trial segment and condition, F(3,12) = 1.84, p > .05. However, between-subject variance proved to be high across both blocks, indicating that there were a number of participants who were struggling to successfully track the available stimulus when the right-hand was moving at the 15v speed.

21: Means (and standard errors) of obtained periods (ms) for each half of a trial when the target velocity was 9.88 cm/s (.095 Hz) for the right hand 15v condition. Totals do not include practice trials. Data from Experiment 5.

21

	2nd Block	
Condition	**1st 15 s**	**2nd 15 s**
Practice 1	10.59 (.30)	9.51 (.35)
Practice 2	10.37 (.18)	9.76 (.28)
3 seconds	10.66 (.30)	9.84 (.19)
5 seconds	9.69 (.23)	9.91 (.43)
10 seconds	9.33 (.36)	10.46 (.66)
15 seconds	9.55 (.37)	10.46 (.66)
Total	9.81 (.24)	9.99 (.33)

Hand Position

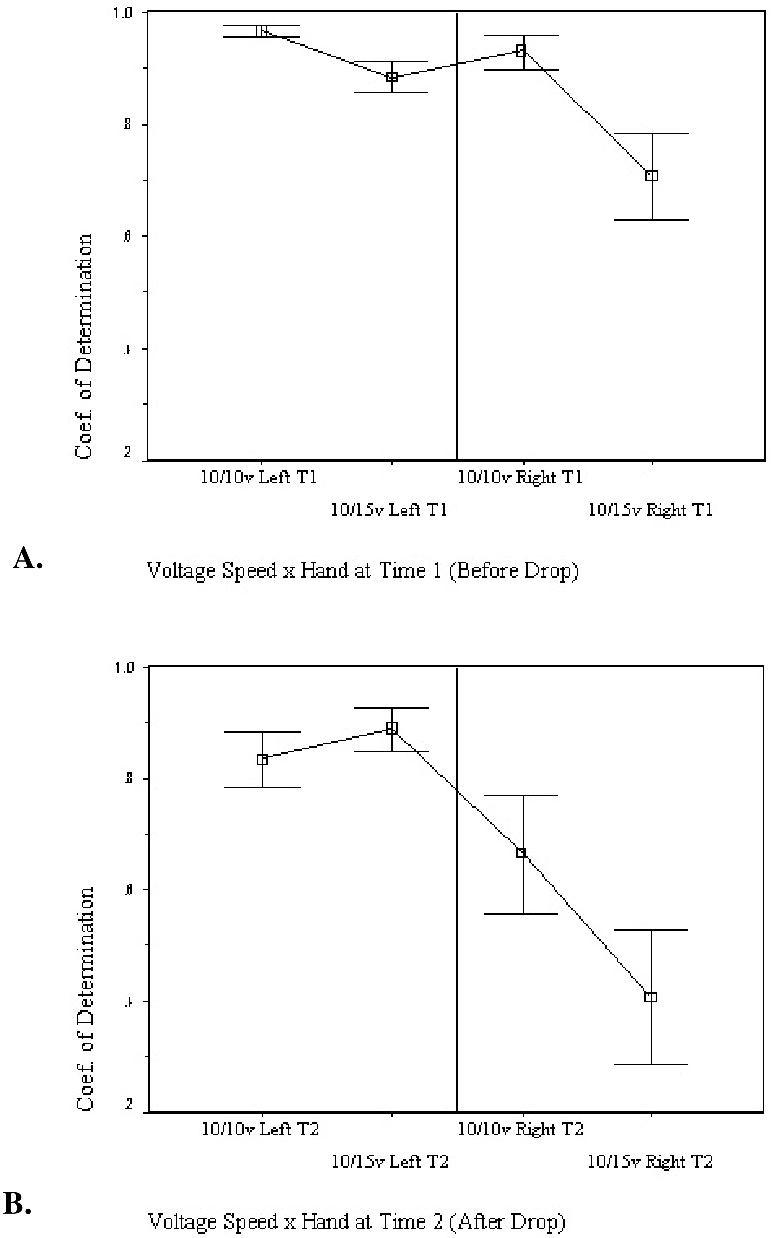
Participants' hand path was also compared to the perfectly formed circles generated by the servo motors. Coefficients of determination between the positions of the hands and the positions of the robotic arms are displayed in Table 22. Participants formed better circles in the first block of trials ($r^2 = .87$) than in the second ($r^2 = .70$), $F(1,14) = 33.37$, $p < .05$, and left hand performance was significantly better than right hand performance (left $r^2 = .89$, right $r^2 = .68$), $F(1,14) = 71.85$, $p < .05$. The interaction between the hands, motor speed, and segment of the trial (before or after the drop at fifteen seconds) was significant, $F(1,14) = 5.22$, $p < .05$. As depicted in Fig. 10, when the two motors produced different speeds, the right hand, which was required to follow a faster speed, was differentially impaired in positional accuracy during both the first and second halves of the trial. Further, the right hand's positional accuracy suffered in the second half of the trial, corresponding to the right-handed stimulus retracting, regardless of whether the hands were in a 1:1 frequency ratio or not. There was no main effect or interaction that involved the length of time that the stimulus was retracted, F(3,12) = .03, p > .05.

22: Coefficients of determination between the participants' hands and the corresponding robotic arms. The 10v speed corresponded to a velocity of 6.48 cm/s and the 15v speed corresponded to a velocity of 9.88 cm/s. Data were separated by the first and second halves of each 30 second trial, with the first 15 seconds representing tracking to an available stimulus and the second 15 seconds corresponding to the solenoid disappearance and return (after a period of time described by the condition). Data from Experiment 5.

22

	1st Block				**2nd Block**			
	1st 15 s		**2nd 15 s**		**1st 15 s**		**2nd 15 s**	
Condition	**Left (10v)**	**Right (10v)**	**Left (10v)**	**Right (10v)**	**Left (10v)**	**Right (15v)**	**Left (10v)**	**Right (15v)**
Practice 1	.965 (.009)	.887 (.057)	.869 (.030)	.692 (.081)	.882 (.034)	.584 (.090)	.892 (.047)	.473 (.088)
Practice 2	.969 (.006)	.944 (.013)	.828 (.034)	.720 (.057)	.886 (.013)	.721 (.045)	.881 (.051)	.619 (.084)
3 seconds	.960 (.007)	.904 (.041)	.826 (.040)	.717 (.070)	.855 (.042)	.692 (.056)	.823 (.064)	.446 (.068)
5 seconds	.964 (.009)	.926 (.015)	.849 (.024)	.679 (.071)	.862 (.024)	.740 (.048)	.900 (.029)	.342 (.085)
10 seconds	.971 (.006)	.950 (.011)	.853 (.022)	.698 (.050)	.922 (.008)	.679 (.056)	.843 (.063)	.378 (.064)
15 seconds	.971 (.007)	.930 (.024)	.753 (.069)	.559 (.059)	.896 (.017)	.715 (.045)	.924 (.031)	.459 (.088)
Total	.966 (.004)	.923 (.017)	.830 (.025)	.677 (.053)	.884 (.011)	.689 (.039)	.877 (.026)	.453 (.060)

9



9: The coefficients of determination between each hand and the circle produced by the motor arm. 10/10v corresponds to the first block of trials where the left and right motors both run at 10v (or 6.48 cm/s), while 10/15v corresponds to the second block of trials where the left motor continues to run at 10v (or 6.48 cm/s) but the right motor runs at 15v (or 9.88 cm/s). A. The coefficients for tracking performance during the first 15 second segment (T1) of each trial before the solenoid drop in the right hand. B. The coefficients for tracking performance during the second 15 second segment (T2) of each trial after the solenoid drop in the right hand. Data from Experiment 5.

In summary, when the right hand tracked a faster stimulus that differed from the frequency of the left hand, the right hand suffered in tracking, both in terms of velocity and path. From this experiment alone it is impossible to tell whether the difficulty lay in tracking a faster stimulus or whether it lay in the differing frequency ratio between the hands. Just looking at the first block of trials, where the frequency between the hands was 1:1, both the left and right hand produced appropriate mean velocities across the trial, but the right hand differed significantly from the appropriate circle description once the haptic stimulus was retracted. The degradation in pathway in the right hand was irrespective of the length of time that the stimulus was retracted, even occurring for a three second “blip”. This suggests that once the haptic stimulus was gone, participants were immediately unable to produce the correct path and likely never met up with the stimulus once it was extended again. Lastly, instructions regarding stimulus reappearance or lack of reappearance did not influence participant performance. The overall conclusion made was that participants were unable to internally model the path of the target.

However, there were some indications that participants in the present experiment modeled a target’s velocity. Participants were able to generate the correct velocity when motor speeds matched. However, participants may have used reafferent information from the tracking limb to dictate the velocity at which they moved their generating limb. Thus, it is necessary to look at the performance when frequency ratios differed. Velocity was again not significantly different between the tracking and generation portion of each trial, however, between-subject variability was high and thus tracking accuracy was questionable. High variability in this task is not surprising because there are large intersubject differences in tactile intensity (Greenspan, 1984; Knibestöl & Vallbo, 1980) and the perceived intensity of stimulation changes with the velocity of tactile stimuli (Greenspan & Bolanowski, 1996). However, despite uneven tracking and variable generation, participants took in enough information that they were, on average, able to generate a velocity appropriate for the motor speed. They were also able to retain this velocity across the longest stretches measured, in this case fifteen seconds. These results suggest that participants were able to model the velocity of the haptic stimulus such that they could reproduce it across time and even in the face of interlimb interference.

While the velocity-based results are generally concordant with smooth pursuit eye movement occlusion studies, there are a number of notable differences. Participants in this study maintained the correct target velocity up to the longest retention interval of fifteen seconds, a significantly longer period of time than the four seconds after stimulus offset that has been achieved with visual smooth pursuit tracking (Becker & Fuchs, 1985). Further, anticipation of meeting up with the haptic target again did not seem to result in the kind acceleration that is observed for smooth pursuit eye movements (Churchland, Chou, & Lisberger, 2003), nor in saccade-like position corrections towards the anticipated target reappearance position (Xivry, Bennett, Lefevre, & Barnes, 2006; DeBrouwer, Yuksel, Blohm, Missal, & Lefevre, 2002). However, large accelerations may be less likely in limb motions due to the limitations imposed by limb inertia, which are less of a constraint in eye movements.

The last aspect of the results concerns the dramatic and consistent reduction in tracking accuracy in this experiment compared to all previous experiments. A number of factors likely contributed to this difference. For one, using a taut canvas allowed for stress (force) information from the targets, but minimized available strain (displacement or depth of skin indentation). It was noted that even when the targets were available for touch, participants were frustrated with the information they were getting through the canvas and attempted to press harder to achieve better skin indentation. Strain is more relevant to accurate perception than stress (Greenspan & Bolanowski, 1996). Further, the tracking portions of this experiment differ from previous haptic tracking experiments in terms of how distinguishable shear forces were from slip signals. The results of this experiment validate that not only is skin stretch and slippage important to haptic tracking, but also the ability to distinguish between the two sources of movement. The excellent performance witnessed in previous experiments was not simply due to the task being in the domain of touch, but instead was based on the rich information available in the error signal. In the following Supplementary Experiment, a collaboration was formed with another set of researchers interested in the shared hypothesis that in previous haptic tracking experiments participants were responding to felt shear forces, and that to be able to respond to these forces, it required some elementary planning.

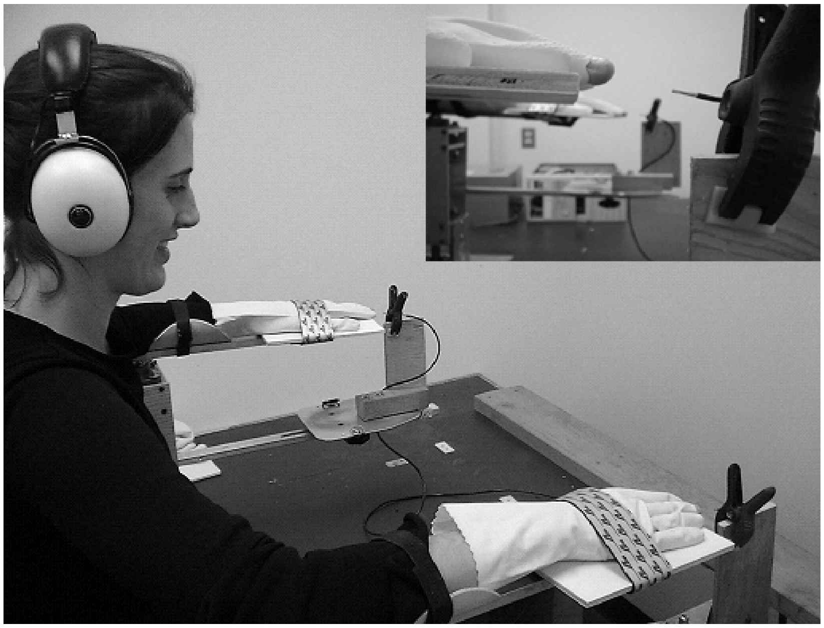
Chapter 7

Supplementary Experiment (Summary)

In an ongoing collaboration with the University of British Columbia (UBC), the physical cues used by participants to guide their haptic tracking were investigated. To test the physical cues directly, Nagelkerke, Chua, Dawson, Rosenbaum, and Franks (2006) measured how well participants could haptically track moving air jets rather than moving mechanical contacts. It was reasoned that if touch alone was sufficient for skilled haptic pursuit tracking, participants would be able to track the air jets with low error, regardless of the way the air jets moved. By contrast, if shear forces in particular provided the critical input for haptic pursuit tracking, participants would only be able to accurately track the air jets' movements when those movements conformed to the participants' natural movement preferences – in-phase and anti-phase movements, but not the 90-degree-relative-phase movements.

Participants' arms were attached to two manipulandua which allowed the horizontal inward flexion and outward extension movements of each forearm about the elbow (Fig. 10). Each manipulandum's angular displacement was measured via optical encoders. Immediately below and co-axial with each of the manipulanda holding the participant's forearms were servo motor controlled arms carrying the haptic pursuit tracking stimulus, which was a small jet of compressed air. Each air jet used a blunt-tipped 18 gauge needle sharing an air supply from a low pressure air compressor The air jet needle was placed 2.5 cm away from the tip of the participant's middle finger, aiming approximately 15 degrees upward (see inset of Figure 10). This position maximized stimulation of low threshold fast and slow adapting mechanoreceptive units in the participant's fingertips. The fingertips have the highest density of mechanoreceptors of the sort thought to promote spatial acuity, approximately 241 units per square cm (Johannson & Vallbo, 1979).

10



10: Experimental set-up with inset detail of non-contact air-jet stimulus. Data from Nagelkerke et al. (2006)

The results favored the shear force hypothesis. Participants were able to track simple in-phase and anti-phase movements, making mostly in-phase corrections during in-phase movements and anti-phase corrections during anti-phase movements. Any gross movement errors were corrected quickly, but by both hands rather than only the hand that was removed from the air jet. Moreover, participants had great difficulty tracking the air jets in the 90-degree-relative-phase condition. Here participants resorted to tracking predominantly with their right hand, moving their left hand either in-phase or anti-phase (as evidenced by lower right than left hand tracking error). Expert participants already capable of voluntarily producing the 90 degree relative phase movement tended to make in-phase or anti-phase corrections, and some had difficulty successfully performing under the additional tracking demands of synchronizing with the non-contact air jet. (Similar to the results of Navas-Mutis (1964), whenever the participants had foreknowledge of a periodic, predictable stimulus, they had difficulty abstaining from prediction of the input.) Without physical guidance, participants relied on voluntary control of movement, limited to in-phase or anti-phase movements or previously learned 90 degree movements.

Because the participants in the studies of Nagelkerke et al (2006) tracked poorly compared to previous participants, it was concluded that shear forces, in particular, were the cues that allowed for skilled haptic tracking in the current studies. However, one must be careful when comparing haptic tracking to air jets to haptic tracking to a tactile target. There may be different mechanisms for directional perception based on the different means of producing tactile movement. For example, directional discriminability of an air jet is not dependent on the force applied, while force improves directional discriminability of a probe drawn across the skin (Norrsell & Olausson, 1992; Olausson & Norrsell, 1993).

Chapter 8

Discussion

Summary of Findings

The present set of experiments first tested the hypothesis that haptic tracking might provide a special context in which neurologically normal human adults could move their hands independently for extended periods of time with little or no practice. The results confirmed this hypothesis. Participants excelled at haptic tracking even when it required making difficult bimanual motions.

In Experiment 1 participants haptically tracked two horizontally moving objects that were driven either in a correlated fashion by one human driver or in an uncorrelated fashion by two human drivers. Participants tracked the two objects equally well in these two conditions.

In Experiment 2 participants haptically tracked two vertically moving objects that followed circular or square patterns. The participants tracked the two patterns equally well regardless of whether the patterns were the same (two circles or two squares) or different (a circle and a square). The apparatus in Experiment 2 made it impossible for participants' arms to be passively dragged by the moving objects. Because participants in Experiment 2 could haptically track as well as they did with no possibility of being passively dragged, their fine performance argues against the possibility that participants in Experiment 1 did as well as they did because their hands were passively dragged.

In Experiment 3 a further check was made on the capacity for bimanual independence in haptic tracking by exploiting one of the most robust phenomena of bimanual movement generation – the tendency of the two hands to be drawn toward simple frequency ratios such as 1:1 when the task requires a more complex frequency ratio such as 3:4 or 4:3. When participants in Experiment 3 haptically tracked circular motions with 3:4 or 4:3 frequency ratios, they did just as well as when they haptically tracked circular motions with 1:1 frequency ratios.

Bimanual haptic tracking was possible with both quasi-random motions and patterned motions that are hard to generate without moving input stimuli, such as producing a square with one hand together with a circle with the other hand. Careful control of the apparatus and experimental procedure ruled out the possibility that participants' hands were being passively dragged or that participants were merely predicting motions so well that their performance approached perfection.

Subsequent experiments were planned to discover the basis for such accurate haptic tracking, focusing on the necessity of prediction at the psychological level and the necessity of shear force information at the stimulus level. Previous experiments had used both unpredictable (Experiment 1) and predictable (Experiments 2 and 3) target motions. Predictability of the position and velocity of a tracked stimulus was manipulated in Experiment 4 through the use of probabilistic abrupt direction reversals. Experiment 4 established that individuals did not benefit from predicting over the long-term either the position or velocity of a target they were haptically tracking. Based on these results, and based on the excellent tracking performance in Experiment 1 with quasi-random stimuli, the conclusion was made that it is unlikely that long-range movement plans are necessary for haptic tracking.

In Experiment 5, haptic tracking was studied in a context of a to-be-tracked stimulus momentarily disappearing by going behind an "occluder". This procedure is analogous to one popular paradigm in the smooth pursuit eye movement literature where the stimulus to be visually tracked disappears for a brief period but can be smoothly "pursued" by the eye nonetheless. Another way of conceptualizing this experiment is that it allowed us to monitor participants' performance as they transitioned between haptic tracking and the generation of a movement. In this experiment there was some support for the retention of velocity information but not path information over time. Further, changes to the discriminability of the slip signal and shear force signal proved detrimental to haptic tracking performance.

The Supplementary Experiment was conducted in collaboration with the University of British Columbia (UBC). In that experiment, participants' ability to track moving felt air jets rather than felt mechanical contacts was evaluated. Participants in the UBC study tracked poorly, consistent with the idea that shear forces were the cues that allowed for skilled haptic tracking in the current study. This conclusion complements the confusable error signal results of Experiment 5.

Overview of Claims

Continuous tracking movements of the hand have been studied, but only in connection with eye-hand coordination, where the error signal is visually mediated. Moving the hand so it remains in physical contact with a moving object has not been studied before, at least to the author's knowledge. There have been a number of compensatory tactile tracking experiments, where participants respond to an error signal, presented either with an air jet display (Hill, 1970), or the protrusion of a button (Jagacinski, Flach, & Gilson, 1983). However, in compensatory experiments, visual tracking is usually superior to tactile tracking. This difference between compensatory and pursuit haptic tracking is perhaps unsurprising because many studies show that human performance is better with pursuit tracking than compensatory tracking (Briggs and Rockway, 1966).

Owing to the novelty of the methods, it is important to be as clear as possible about what is and is not being claimed. Four claims are being made. One is that bimanual independence is easily achieved with haptic tracking. Second, bimanual coupling, when it has been observed in previous studies that required similar arm movements, cannot be ascribed to interactions at the level of movement execution per se (e.g., interactions at the level of the spinal cord), contrary to the suggestion made by some that this may have been the case (Cattaert, Semjen, & Summers, 1999; Rosenbaum, 1991). The present experiments indicate that people are physically capable of moving their two hands independently. Third, a claim is being made that haptic tracking's movement planning differs from normal manual positioning and so, by implication, the primary source of the strong intermanual coupling that has been observed in previous studies, which involved normal manual positioning, was in the planning of those positioning behaviors. The proposed planning differences include haptic tracking's reliance on direct stimulus-response cueing, a favoring of velocity over positional information, and a reduction in long-term prediction. Fourth, successful haptic tracking requires the reception of target-relevant shear forces, and, to a lesser degree, the discrimination of shear forces from a slip signal.

One claim not being made is that planning is the only source of coupling. Some physical coupling surely exists, and such coupling may explain why certain movements are hard or easy to make simultaneously (Carson, 2004; Ridderikhoff, Peper & Beek, 2005).

Further, claims are not being made about a complete lack of planning during haptic tracking. Some local planning is required to be able to respond to a velocity error signal. Some plan, however mundane, must be formed to permit the hand to cover the direction and distance needed to nullify the shear force. Biomechanically, this plan (or its corresponding computation) is nontrivial, especially considering the changing muscle forces needed to compensate for shifting joint angles and lengths of the mechanical lever arms. The period of time that occurs between the proprioceptive system's detection of the target's movement and the motor output to correct the error creates an intermittency in response as well as a "refractory" period between responses (Telford, 1931; Hick, 1948; Vince, 1948; Welford, 1952; Craik, 1947). This refractory period can be reduced by the effects of training, grouping of stimuli, and predictability (Hyman, 1953; Halliday, Kerr & Elithson, 1960; Licklider, 1960; Adams, 1961). For example, Jagacinski and Hah (1988) found that participants who used a joystick to track the same segment over and over in a compensatory tracking task reduced the delay in their responses from 126 ms to 32 ms. A 32 ms delay is physiologically impossible for visuomotor loops, thus indicating that the remaining delay was the result of learning the input signal. Excluding outright drag, haptic pursuit tracking would have the lowest error if there was no need to wait to detect each successive velocity error signal, and if responses were not subject to the delay of a full refractory period. In other words, haptic tracking would be best with some prediction.

Interpretation of Findings

In this section the basis for bimanual coupling in previous studies is spelled out in detail, and connections are made between this paper's model and other emerging theoretical concepts in the analysis of bimanual control.

How to interpret the finding that bimanual independence is possible in haptic tracking but is basically impossible in more conventional two-handed movement tasks? The results point to three important differences between haptic tracking and typical voluntary movements: reduced long-term planning, direct stimulus-response cueing, and a sensitivity to velocity rather than positional information.

The first proposal is that long-term planning is the locus of bimanual coupling in more conventional two-handed movement tasks. The idea is that haptic tracking obviates the planning of large-scale movement plans, and this idea rests upon the result that haptic tracking was insensitive to statistical regularities in the environment (Experiment 4). This interpretation also fits with the fact that in each of the experiments participants exhibited bimanual independence with essentially no practice. This result stands in contrast to experiments on the generation of polyrhythms, where only a modicum of independence is achieved between the hands in neurologically normal individuals and only for very brief periods and only in people who are very highly practiced (Krampe, Kliegl, Mayr, Engbert, & Vorberg, 2000; Pressing, Summers, & Magill, 1996; Shaffer, 1984).

The proposal that haptic tracking obviates prediction and long-term planning agrees with other emerging views of bimanual coupling as being mainly due to cognitive factors (Diedrichsen, Hazeltine, Kennerley, & Ivry, 2001; Franz, Zelaznik, Swinnen, & Walter, 2001; Kunde & Weigelt, 2005; Mechsner et al., 2001). For example, Kunde and Weigelt (2005) concluded that asymmetric object-placing movements were easier to perform when the goal positions were symmetric than when they were asymmetric. Kunde and Weigelt attributed this outcome to the greater difficulty of pursuing different goals with the two hands than to pursuing a single goal with both hands. Similarly, Franz, Zelaznik, Swinnen, and Walter (2001) showed that interference between movements of the two hands is reduced if the motions are conceptualized as forming a unitary pattern rather than as forming two distinct patterns. In these experiments, manipulations that reduced the conceptual demands of the dual-task also reduced bimanual interference. Likewise, each of the present paper's experiments required participants to simultaneously track two stimuli, and quality of performance was indistinguishable across the various symmetric and asymmetric conditions. This set of results suggest that cognitive factors play a key role in determining the ease or difficulty of making simultaneous movements

The second proposal is that direct stimulus-response cueing is critical to the reduction of prediction and long-term planning in haptic tracking. This property of haptic tracking is proposed because of previous work demonstrating that the somatosensory cortex directly affects active motor behaviors (Jones et al., 1978). Often implicated in this relationship are the dense ipsilateral connections between motor cortex and primary somatosensory cortex (Jones et al., 1978; Stepniewska et al., 1993). Motor cortex responses to cutaneous stimulation may arrive through several pathways, including the abundant, somatotopically organized connections with somatosensory cortex area 1, or from connections with the dominant cutaneous somatosensory cortex area 3b (Burton & Fabri, 1995).

There is also evidence from the bimanual literature that tasks which provide more direct and automatic connections between the stimulus and response also result in less bimanual interference. Ivry and colleagues (2004) have pursued a theory that coupling is the result of interference between abstract spatial codes as they are perceived, generated, and assigned to each hand. The overlap between target trajectories and effectors cause the interference. In support of this theory, Diedrichsen, Ivry, Hazeltine, Kennerley, and Cohen (2003) found that movements represented in terms of the movement amplitude itself (e.g., making a long or short movement when receiving a symbolic cue of 'L' or 'S') create far more interference between the limbs than when movements are directly cued by the target goal (e.g., moving to a red or green target). Using this representational theory, Diedrichsen et al. were successful in attenuating the typical bias for initiating a symmetric compared to an asymmetric movement by providing a direct cue to the target. When participants were cued to move simultaneously to congruent colored targets, initiation time was improved, as compared to cueing participants to make a symmetrical movement.

Another way to conceptualize the direct stimulus-response cueing of haptic tracking is to consider it to be an extrinsic constraint, similar to environmental stimuli (e.g., synchronizing to metronomes) and psychological processes (e.g., attention, task representation; Amazeen, Schmidt & Turvey, 1997; Temprado, Zanone, Monno, & Laurent 1999), that reduces typical intrinsic constraints, like afferent phase entrainment. If haptics can provide a special instance of coupling to the environment (Kelso, Fink, DeLaplain, & Carson, 2001), then it would come as no surprise to dynamicists that haptic tracking can overcome internal coupling. An extension of the HKB model already accounts for the coupling of sensory information to movement with a parametric stabilization term (Jirsa, Fink, Foo & Kelso, 2000). This extension was developed to explain the influence metronomes have on participants' rhythmic behavior, not only in terms of pacing, but also on observed dynamics. At a local level, metronomes 'anchor' bimanual coordination by decreasing spatial and temporal variability at the points when the metronome sounds. Further, global coordination patterns are more stable, and phase transitions between in-phase and anti-phase patterns are delayed.

Though Jirsa et al.'s model was developed in relation to periodic auditory stimuli, it stands to reason that other sources of environmental information, like haptics, may have similar effects upon bimanual coordination. This possibility was tested by Kelso, Fink, DeLaplain and Carson (2001) with an experiment pairing active touch and a metronome. When haptic contact synchronized to a stop with the metronome, coordination between the fingers stabilized, however when haptic contact did not synchronize with the metronome, coordination destabilized causing transitions.

Jirsa et al.'s parametric stabilization term was also originally developed for the discrete influence of a metronome click, but could be adapted to account for a continuous effect. A continuous information source, like haptics, may continuously improve pattern stability, and decrease variability, that participants could perform movements requiring independence between oscillators. Buchanan and Ryu's (2005; 2006) exploration of tactile bimanual tracing provides support for the continuous stabilizing effect of haptic information. In their studies, participants bimanually traced circles at a given frequency using either their fingertips or a plastic stylus. Buchanan and Ryu found, in general, that tactile feedback stabilized the production of bimanual coordination patterns, such that participants were less likely to transition between anti-phase and in-phase patterns.

The last proposal is that haptic tracking movements are generated in response to velocity or acceleration error signals, unlike typical hand movements, which are generated in response to position error signals. This proposal is based on the fact that the hand is often moved from one static position to another, but also, and more importantly, by the fact that participants in the bimanual haptic tracking experiments could move their hands independently, whereas in conventional bimanual tasks independence of the two hands is out of the question (Kelso, 1984; Swinnen et al., 1998). In conventional bimanual tasks, participants direct their hands from place to place without a velocity (or acceleration) error signal to guide them. Instead, they rely on position error signals.

Evidently, then, use of position error signals cannot be escaped in conventional manual positioning tasks, judging from the fact that when such tasks are bimanual, coupling of the hands sets in, whereas in bimanual haptic tracking tasks, coupling of the hands is all but absent. Insofar as positioning movements are driven by position error signals, it is likely that there is a representation of a goal position, as assumed in the posture-based motion planning model, whose central tenet is that positioning movements are planned first and foremost with respect to goal postures.

This last proposal was at least partially substantiated by the results of Experiment 5, where participants were unable to maintain positional accuracy when the between-hand frequency deviated from a simple 1:1 ratio, and were also unable to reproduce previously tracked paths upon stimulus offset. However, participants were better able to maintain the average velocity needed to track the stimulus, and upon stimulus offset, they maintained the stimulus' average velocity across the longest measured times of the experiment. The results of Experiment 4 also suggest that participants are less sensitive to positional information. In that experiment, participants were able to accurately track during abrupt transitions and this accurate tracking proved independent of the predictability of the position of a transition. Of note, even when the predictability of a transition location was low, participants still had access to the acceleration changes that necessarily accompanied a direction reversal. The deceleration accompanying the start of a reversal may have afforded participants an "absolute prediction" of the upcoming direction shift. If direction reversals can be prepared for by, say, reducing the hand's effective mass, participants could ready for even the "unpredictable" reversals.

The work by Navas-Mutis (1964) also provides some support for a proposed distinction between velocity and position error signals in tracking tasks. As in the present paper, Navas-Mutis was interested in the possible parallel between hand movements and eye movements. In his experiments, participants rotated a handle to visually match a pointer to a target that moved in either a predictable or unpredictable manner. Navas-Mutis expected manual tracking to behave like an intermittent, saccadic, position servo. However, he was also interested in whether it could, in some cases, perform like a smooth pursuit velocity servo. His results fundamentally separated along the lines of the predictability of the input. Manual tracking of unpredictable input generated saccade-like position error adjustments, whereas tracking of predictable input generated a reduced delay response, or even absolute prediction, that Navas-Mutis attributed to either a velocity error servo or preprogrammed movements. He concluded that in a complete model of manual pursuit tracking "the psychological nature of the signal, in particular its predictability, the error criterion, and other factors should be given as much importance as its frequency domain representation."

Future Endeavors and Applications

An interesting future direction for haptic tracking research is to pair one-handed haptic tracking to other sorts of tasks performed simultaneously with the other hand. For example, the other hand may be involved in a tracking task that uses another modality, such as tracking a moving visual target. There are presently two studies that speak to the possible results of such an experiment. In an experiment by Burke, Gilson, & Jagacinski (1980) participants using one hand to track a visual target performed better when the other hand tracked a kinaesthetic-tactual target as compared to another visual target. Similarly, Diedrichsen et al. (2003) found stronger interference between limb movements when relevant distractors (e.g., experimentally relevant colors in a different location than the target location) were paired with targets compared to irrelevant distractors (e.g., irrelevant colors). The results of these studies emphasize that in designing dual-task haptic tracking experiments, the competing task must be considered in terms of how similar the information used in the task is to that used in haptic tracking. Tasks that have similar informational sources are much more likely to produce interference.

Haptic tracking could also benefit from a kinetic analysis of changes in force related to bimanual movements. For example, an interesting comparison could be made between forces generated while tracking compared to voluntarily pushing a stimulus either freely or in a position-directed fashion along a grooved pathway. It would also be beneficial to document the involvement of short- and long-loop reflexes in haptic tracking by measuring multi-joint kinematics at the level of the stimulus, fingers, hand, wrist, forearm, and elbow. Lastly, it would be valuable to further explore adaptation and flexibility in using shear force information for haptic tracking. For example, one could design a simple experiment that provides conflicting shear force information through a set of bearings that rotate in the opposite direction of the overall moving target.

The are also some compelling real-world applications for haptic tracking. For instance, designers of human-machine interactions have also long been interested in techniques that allow humans to reduce the error between a tracked signal and an output position. Haptics are particularly attractive to human factors research because of the relatively fast reaction times to proprioception compared to other input modalities. As one example, Nissan has been developing techniques to generate pulses of haptic feedback on a foot brake pedal, that is being haptically tracked with light touch, to induce quicker reactions in drivers to slow down for an impending intersection. Haptic brake pulsing is uniquely effective as a cue because it provides an omni-directional alert that is consistent with the braking action it is intended to elicit from drivers (U.S. Department of Transportation, National Highway Traffic Safety Administration, Office of Advanced Safety Research, 2000). Robotics engineers are also keen to develop robots that can benefit from physical interaction to facilitate human-robot coordination. Kazuhiro Kosuge and colleagues (Wang, Takano, & Kosuge, 2003) have designed a series of robots that use force/torque sensors to realize compliant physical interaction between robots and humans. Based on the force-moment applied to the human, these robots are able to do things like ballroom dance and coordinate the two-handed movement of furniture.

Lastly, haptic tracking has a number of properties that recommend it as a candidate rehabilitative tool. For one, haptic tracking reduces a task's motor planning demands, particularly the planning of large-scale movement plans over long time scales. Yet, it still requires the generation of active forces (see Hogan & Krebs, 2004 for a similar, but more passive rehabilitative approach). Further, haptic tracking can retain the frequency of a guided movement to use in a subsequent self-directed movement. Based on the above features, haptic tracking may be a useful rehabilitation tool in clinical populations who have difficulties in typical movement planning or control (e.g., stroke patients, or children with coordination problems).

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- Don A. Trumbo Psychology Department Student Research Fund, Research and Graduate Studies Office, Penn State University, 2006
- Alumni Dissertation Award, Penn State University, Alumni Association, 2006
- Graduate Fellow, Penn State University, Graduate College, 2003
- Outstanding Graduate Teaching Assistant Award, Social Behavior Sciences, University of Arizona, 1999

GRANTS

Co-Investigator, "Online Learning Environment Interface to Oracle," 2000-2001, $25,000 total direct costs, New Learning Environments and Instructional Technologies Grants Program, Learning Technologies Partnership, University of Arizona, Tucson, AZ.

PUBLICATIONS

Rosenbaum, D. A. & Dawson, A. M. (2004). The motor system computes well but remembers poorly. *Journal of Motor Behavior, 36*, 390-392.

Rosenbaum, D., Dawson, A., & Challis, J. (2006). Haptic tracking permits bimanual independence. *Journal of Experimental Psychology: Human Perception and Performance, 32,* 1266-1275.

Rosenbaum, D., Cohen, R., Dawson, A., Jax, S., Meulenbroek, R., van der Wel, R. & Vaughan, J. (2006). The posture-based motion planning framework: New findings related to object manipulation, moving around obstacles, moving in three spatial dimensions, and haptic tracking. In D. Sternad (Ed.) *Progress in Motor Control*. Springer. In press.

Dawson, A., Nagelkerke, P., Chua, R., Franks, I., & Rosenbaum, D. (2006). Pursuit tracking signals in haptic tracking: The role of shear forces and stimulus predictability. Manuscript under submission.