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Tango-Fitts: Haptic Interpersonal Coordination

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Tango-Fitts: Haptic Interpersonal Coordination

Lin Nie, PhD

University of Connecticut, [2017]

Interpersonal coordination is sustained by meaningful informational coupling, whether optic, acoustic, haptic or some combination. Such information is specific to the guidance of perception-action in a given activity unfolding at the animal-environment scale. The social dance of Argentine Tango provides a rich interpersonal coordination setting to study such informational coupling with an emphasis, in particular, on haptic coupling. In three experiments, the classic Fitts task was modified to allow a continuous (not discrete) monitoring of error and a treatment of Index of Difficulty as an obtained (rather than imposed) value. Three coordination challenges inspired by tango were investigated: direction of movement, type of perceptual support, and improvisation-like demands arising from unpredictable targets. As expected, dyads were influenced by the direction of movement but solo actors were not (Experiment 1 vs. Experiment 2). Dyadic coupling that involved haptics (with or without vision) provided a better fit to Fitts's law than coupling that was exclusively visual (Experiment 2). Varying target location and limiting the preview of it still preserves Fitts's law (Experiment 3). While solo actors were affected by whether they had a zero or one cycle preview of the target, dyads were not. Results were discussed with respect to the contrast between Claude Shannon's construal of information—limited, syntactic, and inherently meaningless—and James J. Gibson's construal of information—lawful, meaningful, and specific to organism-environment circumstances relevant to perception-action. Implications for the intersection of dance (particularly ensemble improvisation dance), human-computer interaction, and experimental psychology were also considered.

Tango-Fitts: Haptic Interpersonal Coordination

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B.A., Franklin and Marshall College, **[2010]**

A Dissertation

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Doctor of Philosophy

at the

University of Connecticut

[2017]

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[2017]

APPROVAL PAGE

Doctor of Philosophy Dissertation

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The initial idea of this dissertation came from many car discussions with Dobri Dotov when traveling through the Rhodope Mountains in Bulgaria, summer of 2014. I thank Dobri for all the things that we created together.

I save the burden of any shortcoming in this document for my own, and dedicate the thesis to dance and music.

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CHAPTER 1

INTRODUCTION

When people engage in joint actions, the informational coupling can be optic, acoustic, haptic or some combination. As examples, navigating through a crowded airport is primarily visually guided, vocal ensembles are constrained by hearing the other singers, and furniture movers rely on touch transmitted through the object they hold. The rigorous examination of joint action owes much to the pioneering work of R. C. Schmidt and colleagues (e.g., Schmidt, 2007; Schmidt, Carello, & Turvey, 1990; Schmidt & Richardson, 2008) in applying dynamical systems theory to processes of interpersonal synchrony. Research has revealed that stable organization and patterning of interpersonal coordination emerge from the information coupling between individuals and their environment (e.g., Fowler, Richardson, Marsh, & Shockley, 2008). While copious research has highlighted the sufficiency of vision in sustaining interpersonal coordination tasks (e.g., Fine & Amazeen, 2011; Richardson, Marsh, & Schmidt, 2005; Schmidt, Nie, Franco, & Richardson, 2014), information is available in rich acoustic and haptic as well as optic arrays (Turvey & Carello, 2011). Very little attention has been paid to understanding how haptics, in particular, shapes ongoing interpersonal coordination. Haptic coupling provides the focus of the present dissertation. In particular, the research was guided by challenges inherent in the interpersonal coordination setting provided by dance and it exploited the methodology of a classical cyclical aimed-movement task owing to Fitts (1954).

Dance provides a rich interpersonal coordination setting in which optic, acoustic, and haptic information all guide the dancers who see each other, hear the music, and are in physical contact with their partners. Importantly for present purposes, we look at dances by relationships and

rules that can be implemented experimentally. In particular, the tango is a distinct dance practice that shares many qualities with how people act, perceive, and communicate in everyday life: Individuals come together to perform actions in coordination with other individuals and with the environment. What distinguishes tango from other partnering dances (e.g., salsa, ballroom)—and what makes it a unique inspiration for studying interpersonal coordination—is that the primary coupling is haptic. Specific details of tango’s movement grammar are provided in Chapter 2. This dissertation used the coordination challenges of tango to constrain haptic collaboration in a generalized Fitts task to examine novel effects that arise in haptic interpersonal coordination.

One advantage of the Fitts-Tango setting is that it allows haptic interaction research in a real environment. A dominant focus of haptic interaction research has been the utility of haptic feedback that allows individuals located remotely to collaborate in a shared *virtual* space. Within that focus, there is no direct haptic link even when haptics is critical to the tasks (e.g., co-manipulation of an object; Wang, Chellali & Cao, 2016). This is unsurprising given that these experiments tend to stem from the fields of HCI (human-computer interaction), computer-aided design, telemedicine, and virtual environment gaming which historically have embraced a theoretical framework based on old-fashioned computer vision). When the haptic link is either simulated via a teleoperation system (Wall & Harwin, 2000) or mediated by machinery (Reed & Peshkin, 2008), it results in indirect coordination that is not comparable to the zero-lag mechanical feedback available in a partner dance.

In using direct physical contact as the coupling medium, the present experiments examined how classical phenomena in a Fitts task were changed by the real physical demands (e.g., multi-dimensional movements, points of contact, availability of optic/haptic information or a

combination of both, predictability of target locations) observed in a partner dance such as tango.

Generalized Fitts Task

In a common Fitts task, an aiming movement is alternated continuously between two targets whose size and distance can be varied to manipulate the difficulty of the task. Such a precision aiming task was appropriate for the present study because precision is one of the most prominent constraints in everyday coordination (Latash, 1993), such as navigating through animate and inanimate clutter so as to avoid collision. The choice of a generalized Fitts task also stems from the simple recognition that traversing a cluttered environment whether in a partnering dancing or by fundamental bipedal locomotion both require the cyclical “left-right-left-right” stepping motion or the “go-return-go-return” Fitts task motion. The cyclical Fitts task (also referred to as reciprocal aiming in the literature) does not require the pointer to come to pause on the target.

In its simplest form, Fitts’s law characterizes influences on movement time, MT, owing to manipulation of target width, W, and movement amplitude, A, primarily dictated by inter-target distance: $MT = a + b \log_2 (2A/W)$. In particular, it is a prediction of movement time as a function of an index of difficulty, ID, captured by the ratio of A to W. As one of the most robust laws in biological motion, Fitts’s law (Fitts, 1954; Fitts & Peterson, 1964) has been shown to hold for different effectors, on many scales (Guiard, Beaudouin-Lafon, & Mottet, 1999), across differing pointing devices (Fitts, 1954), and to be applicable to hand and foot movements, in air and water, under a microscope, and along with other modifications (Hoffmann, 1981). It also accommodates certain kinds of dyadic interactions, either where one person controls the target while the other controls the pointer (Mottet & Bootsma, 1999; Mottet, Guiard, Ferrand, & Bootsma, 2001) or both people hold a handle that controls a single pointer (Reed, Peshkin, Colgate, & Patton,

2004). In the present study, the dyad individuals moved together, in physical contact, like dance partners. Since Fitts's first model, many modifications have been proposed (see a review in Crossman & Goodeve, 1983) to better fit data. One goal of this dissertation is to examine a recasting of the Fitts task in which error is monitored as a continuous variable as in real-world performance instead of as a binary outcome (Experiment 1, Chapter 3), thereby challenging the long-standing model fit.

Perceptual Coupling in Tango-Fitts

The Fitts formulation was inspired by a direct analogy with Shannon's Theorem 17, $C = B \cdot \log_2(1 + P/N)$ (Shannon & Weaver, 1949) originally developed to characterize telecommunication systems, not animals in the world. In consequence, the term *information* is used in a metrical, technical sense. In the terminology of telecommunication systems, C is the effective information capacity (in bits per sec) for a given communication system of bandwidth B , with signal power P , and noise N . Effective information capacity is a logarithmic expression of the clarity of a transmitted signal P/N (MacKenzie, 1989). Presumably, Fitts's law expresses a similar capacity of human performance where the speed of moving a pointer to a target is traded for accuracy when the difficulty of the task increases. However, this construal of information—as limited, syntactic, and inherently meaningless (Fultot, Nie, & Carello, 2015; Luce, 2003)—does not reflect a natural perspective where the control of movement emerges in dynamic patterns. The latter requires a construal of information as unique and specific to animal-environment relations in a given activity (Gibson, 1966, 1979). Shannon's syntactic information has been distinguished from Gibson's *lawful* information (e.g., Turvey & Carello, 2012), a distinction that was respected here as Information-S and Information-L. In this context,

Fitts's law may be better characterized as a formal organizational principle that captures the perception-action capabilities of an animal in its environment, invariant over various designs and implementations.

One of the key tenets of the ecological, natural perspective to studying interpersonal coordination is its emphasis on the informational basis in the sense of Information-L. As Marsh, Richardson, and Schmidt (2009) put it, the linkages between social-biological systems are not just mechanical, they are informational: “what we take in with a look (or other modalities) can affect our behavior as strongly as a mechanical force” (p. 323). A limb-swinging paradigm was used to study synchrony within this perspective (Schmidt et al, 1990). Synchrony, with all of the hallmarks of within person coordination (e.g., Kelso, 1984; Kugler & Turvey, 1987) occurred between rhythms performed by two individuals linked by merely seeing each other. Since then, two decades of interpersonal coordination research has confirmed that two individuals can perceive and act according to certain phasing relationships via optic or acoustic coupling alone (Richardson et al., 2005). Other experimental tasks have included swinging pendulums, as well as more everyday tasks such as two people rocking chairs, telling knock-knock jokes or playing maracas, all designed to investigate the informational basis of coordination (Nie, Caban, & Marsh, 2015; Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt et al., 2014). As an example, dyads linked by self-generated rocking chair sounds reached more coherence between their rocking rhythms (whether with or not) than with vision alone (Demos, Chaffin, Begosh, Daniels, & Marsh, 2012). This demonstration of the capacity of auditory information to orchestrate coordination of a dyad was echoed in a study showing that the dynamics of breathing sounds effectively guided the actions of a partner during a task where the dyad carries a fragile

object together while traversing a distance (Pellegrini & Ciceri, 2012). By taking inspiration from the touch-enabled dance of tango, the current dissertation begins to fill in the gap of studying how haptic information sustains and constraints a two-person coordination task. Experiment 2 (Chapter 4) designed manipulations that mimicked the haptic and optic support observed in leader-follower tango dancing. Experiment 3 (Chapter 5) continued to explore such haptic connections while adding manipulations that resembled the improvisational aspects of tango.

Summary

The current work straddles (at least) two disciplines, that of partnering dance and experimental psychology. Because dance is a deeply experiential practice, a backdrop for the questions raised by this work is provided in a short overview of tango in Chapter 2. However, directly instantiating the tango in the laboratory would extract a high methodological cost. This work, therefore, is designed as a minimal experimental mimicry of tango that harnesses its haptic coordination challenges in a generalized Fitts task. The description of tango in Chapter 2 was stripped to fundamental principles that are not subject to different readings of tango and are also implementable in a laboratory setting. The present work does not yet aspire to provide a phenomenological understanding of dance or, in particular, how the qualitative experience of dancing or learning the tango might be related to the observable movement parameters uncovered in the experimental setting. Rather, it is designed to pave the way for understanding *haptic* coordination between people from a natural, ecological science perspective. Implications for dance and its related fields at the same time would be a dividend.

The work presented here altered the traditional Fitts task in several ways that challenge the

usual Information-S grounding: (1) Error was monitored continuously rather than discretely; (2) direction of movement was manipulated; (3) dyads were assembled using optic, haptic, or combined coupling; and (4) haptic coupling was direct; and (5) target distances were unpredictable. Together these manipulations served to investigate how solo and dyad performances differ by perceptual coupling, movement direction and improvisation, as well as from each other.

CHAPTER 2

TANGO BASICS

The social dance of Argentine Tango is a distinct dance practice. It is to be distinguished from show tango or ballroom tango, the kind that hollywood images made popular. Unlike stage tango, which is choreographed on an empty floor, social tango is improvised to tango music and executed on a crowded social dance floor. What is improvised is the choice of movement constrained by the spatial (in the sense of navigating the dynamic crowd space) and the rhythmic opportunities for movement in the music. For example, improvisation with tango music can be reflected in the dancers' choosing to add little movements called "adornments," to ornate the rhythm by stepping in double time, syncopating, or playing with the microstructure of the song. Navigating a tango dance floor requires moving on a circle with other couples: The crowd moves in a clockwise or counterclockwise flow with the added proviso not to pass on the right (from the perspective of the leader).

The leader and follower roles in tango have always been subject to the influences of society and culture (Trenner, 2017a). Given the focus of the current thesis, special clarification is required of the lead-follow relationship that is often shrouded in, for example, stereotyped gender readings. Traditionally, the followers sat at the sides of the dance floor, and leaders asked for a dance by signaling from afar. If the follower accepted the invitation, the leader would dance with the follower for a set of three or four songs, and then walk the follower back to the seat and move on to searching for the next follower. Such dictums of tradition, coupled with hollywood show-tango images, portray men as leading submissive women. But it is misleading to think that the leader takes all movement responsibilities or that following is a passive act. The leader and

follower imbalance in the societal and cultural context should not be conflated with the leader and follower behaviors in term of movement coordination. When coordinating, following is never a passive act and the leader is not the only active mover. Consider the extreme case where the follower is completely passive and subject to the forces of the leader: The dance would be tantamount to the leader dancing alone carrying a static object. Careful coordination is what enables two people to move together in tango regardless of the skill level. Because the leader faces the direction of the floor flow in the design of the dance, only the leader can see where the dancers are moving on the dance floor. In fact, the only responsibility that is particular to the leader is navigation, namely, how to move forward and stay in place, how to turn right and left and be aware of where the follower ends up while selecting a step from the tango vocabulary (Trenner, 2017b). Occasionally, even the navigational responsibility is shared, for example, when the follower plays with the direction. The follower might add to a chosen step or stop the leader from issuing a back step when the follower perceives a pending collision.

Careful coordination in tango is enabled by the flow of entangled Information-L via touch, sight and sound. Unlike other partnering dances such as salsa and ballroom, however, where visual and musical entrainment are more dominant and can supplant haptics to enable coordination, the primary coupling in tango is haptic. The haptic communication occurs by means of an embrace at the hands and the chest, a connection that needs to be simultaneously stiff and springy to allow immediate coordination. It is mainly this connection that allows the competition and cooperation of rhythms between a leader and a follower to occur. However, one of the most important exercises in learning to dance tango is where the dance is practiced without any physical contact between the dancers to develop sensitivity to the spatial relationship purely

sustained by optic coupling.

Tango steps draw on a simple movement grammar. It is at its core a dance of walking, with two fundamental steps—the *forward/backward step* and the *side step*—from which the rest of the dance’s vocabulary is written. (For a full description of the mechanics of the tango walk, see Castro, 2005, lessons 1 to 5). The coordination challenge for tango dancers is primarily at movement initiation. For a side step, the leader initiates movement by stepping to the left or to the right. In the forward/backward step, the leader initiates the step either towards or away from the follower. Through their embrace, the leader and follower communicate about the speed and timing of changes of direction together (e.g., when the leader stops, goes forward, backward, or from left to right). The tango embrace can have several points of contact between the dancers. In the so-called “open embrace” (Figure 1), the leader’s left palm faces the follower and is in contact with the follower’s right palm (called the open side of the embrace), and the leader’s right hand is in contact with the follower’s left rib cage (called the closed side of the embrace). These points of contact play a critical role communicating the initiation of movement. When initiating a step, force can be applied at the points of contact in the direction that the step is taken. For a sidestep to the leader’s left, the leader’s right arm presses against the left side of the follower’s body. For a sidestep to the leader’s right, the leader’s left hand can press against the follower’s right hand. For forward and backward steps, the leader moves towards the follower, and instead of there being a force applied directly in the direction of movement, friction at the points of contact moving forward or backward communicate the direction.

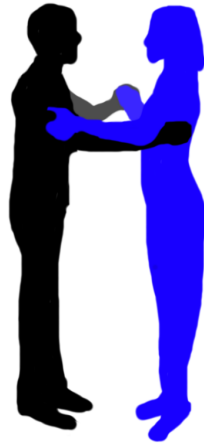


Figure 1. Open Embrace. Note the points of contact of the leader with the follower: The leader's left hand is in contact with the follower's right hand, and the leader's right hand is in contact with the follower's left rib cage.

The ease of step initiation in tango is direction-dependent. Tango dancers commonly observe that stepping towards or away from one's partner is more difficult than stepping sideways with the partner. But directional differences depend on the exercise. For example, it is common to practice with only one point of contact, such as only the leader's left hand and follower's right. In this situation, leaders find initiating a step to the left more difficult than to the right.

In short, tango is a phenomenon of interest to joint action research because when danced in a crowded social dance floor, tango demonstrates the epitome of *coordination via Information-L coupling*: A tango dancer constantly adjusts to the partner, manages quickly appearing and disappearing floor spaces, and adjusts to the other couples moving along the flow of the floor. The current experiments are designed to reflect the beginner's experience of tango. Only the tango basics outlined above will be captured by the experimental design.

CHAPTER 3

EXPERIMENT 1

The vast majority of experiments in six decades of research on Fitts's law has focused on 1-dimensional aiming where the target width and distance are measured along the same axis. Several attempts to extend the Fitts task beyond one dimension vary in the interpretation of "dimension," depending on task and researcher interest. The term "2D" has been used to refer to two-dimensional task space (Mottet & Bootsma, 2001; Mottet, Bootsma, Guiard, & Laurent, 1994), the dimensionality of the targets (e.g, rectangle vs. cube; Hoffman, Drury, & Romanowski, 2011), or to aiming along a tilted linear trajectory with different approach angles (Smyrnis, Evdokimidis, Constantinidis, & Kastrinakis, 2000). Alternatively, some have referred to an extra dimension of input control brought about by resolution-enhancing technology such as zooming in on difficult targets (Guiard et al., 1999). Germane to present interests, MacKenzie and Buxton (1992) showed that movement time along the horizontal and vertical axes did not differ while mean error rates differed significantly. We used this manipulation to implement the 2D setting because it reflects the natural directional constraints in tango.

Experiment 1 was also designed to improve methodological limitations associated with traditional Fitts studies in a way that will anchor subsequent experiments. A careful examination of the Fitts task literature to date reveals two limitations that may arise due to the framing in terms of Information-S: (1) the *ID* manipulation, and (2) the error measurement.

First, absolute inter-target distance D and target width W are often treated as two independent variables to manipulate *ID* (e.g., Accot & Zhai, 1997; Fine & Amazeen, 2011). Guiard (2001) showed that this is problematic, however, because phenomenologically, the only two factors that

can be manipulated to have independent effects on Fitts behavior are D/W and D . Consider the simple observation: If D is varied on its own and ID is kept constant by varying W proportionally (which is tantamount to zooming in/out), then MT (movement time) should not change given that ID stays constant. MT should change, however, simply because it takes more time to traverse the increased absolute distance. The crux of the issue is that, traditionally, the value of W is a characteristic of the measurement apparatus. Data also corroborate this: Fitts's model parameters often diverge noticeably between variations of W while holding D constant and variations of D while holding W constant (Guiard, 2001).

Second, due to technological limitations at the time (e.g., Fitts, 1992), traditional Fitts experiments inherited a legacy of measuring error in terms of hits and misses. An aim is counted as accurate only as long as the hit arrives anywhere within the target width (e.g., Smyrnis et al., 2000; Gentry, Feron, & Murray-Smith, 2005). This Boolean treatment of the error variable is problematic for model prediction. Fitts's law predicts that bigger targets close to each other are supposed to be obtained faster than smaller targets far from each other. However, the strategy of hitting barely inside the target width, thereby consistently undershooting, could bring about real behaviors that the model does not predict. The ideal solution to this problem is to use the *actual* distribution of endpoint coordinates produced by the participant in the model-building stage. Several Fitts experimenters have been unable to do so (see a review in MacKenzie, 1992) because the measurement device typically measures the whole travelled movement distance instead of where the participant actually touches. As a mitigation of the problem, experimenters have calculated the *effective target width* by multiplying the standard deviation of movement distance by a certain factor (four), assuming a normal distribution of the endpoints (Zelaznik &

Forney, 2016). By using a capacitive touch screen for data acquisition and disentangling the influences of D and W , Experiment 1 was directed at solo trials with the intention to demonstrate Fitts's law as a direct consequence of inter-target distances, using a continuous measure of error. From here on, we refer to the traditional width calculation as $W_{E=effective}$ and ours as $W_{A=actual}$.

Method

Participants

Seven University of Connecticut undergraduate and graduate students (Female = 4) served as research participants (in this solo coordination task and, as members of dyads, in Experiment 2). Participants either received credit for participation in introductory psychology or received \$10 compensation for their time. All participants were right-handed, identified by the hand with which the participant preferred doing the tapping. The UCONN Institutional Review Board approved all recruitment and experimental procedures. Oral informed consent was obtained from each participant prior to the start of the experiment.

Procedure

The experimenter introduced the experiment as designed to understand how humans assist each other to complete a movement task involving tapping dots back and forth on a tablet. Participants were told that they would first perform the task alone and then in collaboration with another person. Participants sat in front of a table to read the detailed task instructions for the respective solo or dyad portion of the task. Upon a “ready” signal from the experimenter, the participant initiated data collection by touching the “START” button on the tablet screen.

The basic task environment is schematized in Figure 2. For *solo trials*, the participant repetitively moved the index finger of his or her dominant hand between two circular targets,

without stopping, under the instruction to *touch each target, in alternation, as quickly and as accurately as possible* until the trial ended. The participant always started by tapping on one target, then lifted above the tabletop, moved either in a transverse or medial direction toward the other target, touched down on the other target, and then reversed direction back to the first target.

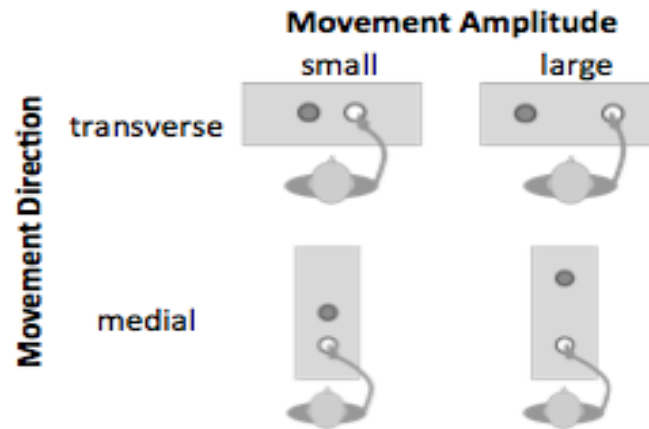


Figure 2. Solo Fitts Task. The participant touched first one circle then the other, repeatedly, as quickly and accurately as possible. Movement direction can be transverse (side to side) or medial (forward and back). Inter-target distance determines whether movement amplitude is small or large.

Movement amplitude was manipulated through four inter-target distances (40, 60, 80, and 100 mm). The distances were randomized within each direction. The two sets of direction trials were counterbalanced. Each participant began with one practice session of 4 sets of 10-sec trials in each of the four difficulty conditions (i.e., the four inter-target distances). After each trial, average error (compared against the radius of the target circle) was displayed to participants as feedback to ensure that they moved in compliance with the speed-accuracy constraints of the task. Although participants were invited to rest for as long as they needed, they expressed no

interest or need to rest.

Each individual participated in 24 experimental trials resulting from a 4 inter-target distances \times 2 directions of movement (medial and transverse) \times 3 repetitions within-subject design. Each trial lasted 30 seconds. The solo portion of the experiment lasted 40 minutes.

Apparatus and Data Preparation

As already noted, the canonical categorical *target width* manipulation was considered redundant for yielding Fitts behavior. Hence, the target circles were intentionally made very small so the question of hitting inside or outside the circle was avoided. Both targets were 5 pixels in radius (60 pixels = 10 mm for the tablet), that is, smaller than the average adult fingertip size. They were of equal brightness, one blue and the other reddish-purple given by the RGB triplet (0, 0, 255) and (155, 0, 100). The background of the tablet was set to black.

Data were collected using a customized Web-App from a pressure sensitive tablet. Appendix A describes the details of the measurement device. Movement time (MT) was determined as the time interval from one reversal point to the next; that is the length of time the participant took between touching one circle on the tablet and the next, which indicates a reversal in the direction of their movement. Precise endpoint coordinates were collected for every tap and absolute distance traversed between target center and tap for each target circle was computed. Error was determined as the distance between the location touched by the participant and the target center (in pixels, converted to mm). Higher values indicate that taps were farther from the target center. Endpoint variability was determined as the standard deviation of error.

Very occasionally participants mis-tapped on the side of the tablet with their elbow while working above the tablet; this resulted in erroneous error values. The MT values were severely

inflated when participants occasionally renegotiated their connection mid-air and resulted in longer MT. These extreme outliers were tracked and accounted for by deleting the top 5% (2-3 taps) of error and MT values. The first 5 transient taps of each trial were also deleted before data analysis. The obtained index of difficulty, *Obtained ID*, was treated as a dependent variable in the model-building stage. Obtained ID = $\text{Log}_2(2D/W_A)$ was computed as the logarithm to the base two of the ratio of twice the target amplitude and the actual distance to center for each trial.

W_A . The calculation of W_A is a major contribution of the current thesis. The actual width W_A was determined as the 95th percentile value from the distribution of distances to the centers of both circles. Three W_A were extracted from every trial: W_A based on the distribution of errors produced in the direction where the participant was moving, W_A based on the direction perpendicular to the direction of movement, and W_A based on the distribution of absolute errors.¹ We used absolute errors instead of dimension-specific displacement errors (Appendix A) to extract W_A and calculate ID. It should be noted that there is a strong positive correlation between W_A calculated based on the absolute errors and the trial average error values (i.e., mean distance to target), $r = .96, p < .0001$. This is not surprising considering the way W_A is calculated but it bolsters the validity of the apparatus capturing the actual distribution of taps' distance to target. Using the capacitive web-app we were able to record and replot a visualization of each and every tap of a participant's in the task space (Appendix B). This also illustrates how W_A was determined. Appendix B shows that in the solo performances, the errors produced along the x -axis (Appendix A) when moving side to side (transverse) and the errors produced along the

¹ Note that, in principle, W_A based on absolute errors is always indistinguishable from W_A based on the errors that are larger, in whichever direction. In Experiment 1, the correlation between W_A based on absolute errors and W_A in the direction of movement is 0.997, $p < .0001$.

y-axis (Appendix A) when moving forward and back (medial) seemed representative of the respective absolute errors. In other words, the direction where the errors dominated was the direction that the participant was moving. Significance testing further corroborated this. Within each trial, the mean of the errors is significantly larger in the direction of movement than in the direction perpendicular to the direction of movement (Appendix B). Furthermore, the spread (*SD*) of the mean of errors is also larger in the direction of movement ($M = 4.23$, $SD = 3.22$) than in the other direction ($M = 2.04$, $SD = 1.63$), $t(167) = 8.70$, $p < .0001$. Note that the spread of the mean of errors is what will be examined as endpoint variability. Here we are specifically interested in how they vary with the direction of travel.

Results

Obtained ID. Table 1 provides the range of average ID values that each solo participant produced in Experiment 1, separated by the movement orientation. The Obtained IDs did not significantly differ by direction, $t(167) = .957$, $p > .10$ (medial: $M = 3.89$, $SD = 0.81$; transverse: $M = 4.01$, $SD = 0.82$). Traditionally, the effective ID computed using W_E that some (e.g., MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Zelaznik & Forney, 2016) used to approximate the obtained ID employed here were generally seen as an expression of movement precision. On first pass, movement orientation seemed to not impact precision in solo performance. In Gentry et al.'s (2005) Fitts dyad experiments, the IDs were deliberately kept in the low range of 2.5 to 4.5 where cyclical motion in dyads was possible. The produced IDs in the present experiment were in a comparable range to theirs.

Table 1

Summary of Average Obtained ID by Each Participant as a Function of Movement Direction in Experiment 1.

	Transverse		Medial	
	Max	Min	Max	Min
P1	5.27	3.55	5.42	3.32
P2	3.12	2.13	4.06	2.37
P3	4.67	3.07	4.64	2.64
P4	4.84	3.51	4.91	2.77
P5	5.27	3.07	5.23	3.21
P6	5.27	3.55	4.77	3.74
P7	5.27	2.13	5.42	2.37

Fitts's law behavior. A linear least-squares fit between Obtained ID and MT and the associated r^2 value was calculated for each solo participant to determine if our data obey Fitts's law. The MT and error across all IDs were averaged for each participant also. A summary of these results appears in Table 2. A linear relationship between MT and ID as a function of movement orientation is shown in Figure 3. The overall correlation, ignoring movement direction, was significant, $r = .85$, $p < .0001$. Further, a reasonably strong negative correlation characterizes the relation between movement time and error, $r = -.65$, $p < .0001$. This directly captures the speed-accuracy trade-off of the Fitts phenomenon. Fitts's law was observed with respect to our solo data.

Table 2

Average Movement Times (MT), Error, and Fitts Line Fits (r^2) for Each Solo Participant as a Function of Movement Direction (T = Transverse; M = Medial).

Participant	Direction	MT	Error	r^2
P1	T	287.1	3.44	.98
	M	306.3	3.17	.96
P2	T	189.1	10.25	.66
	M	196.6	9.84	.89
P3	T	217.5	5.15	.79
	M	222.9	6.88	.93
P4	T	348.7	3.38	.48
	M	289.8	4.54	.87
P5	T	325.8	3.30	.90
	M	339.5	3.22	.90
P6	T	429.2	2.58	.63
	M	360.6	3.23	.38
P7	T	319.0	3.95	.68
	M	284.0	5.12	.54

Movement Time. Figure 3 seems to suggest that the relation between Obtained ID and the MT is different in the transverse and medial directions. An interaction term between Obtained ID and movement orientation was entered into a stepwise regression. However, regression results indicated that the overall model significantly predicted movement time independent of movement orientation, $R^2 = .723$, $F(3, 165) = 143.7$, $p < .0001$, $\beta = .87$; neither orientation nor the interaction term was a significant predictor, $t < 1$ in both cases. Only Obtained ID significantly contributed to the model.

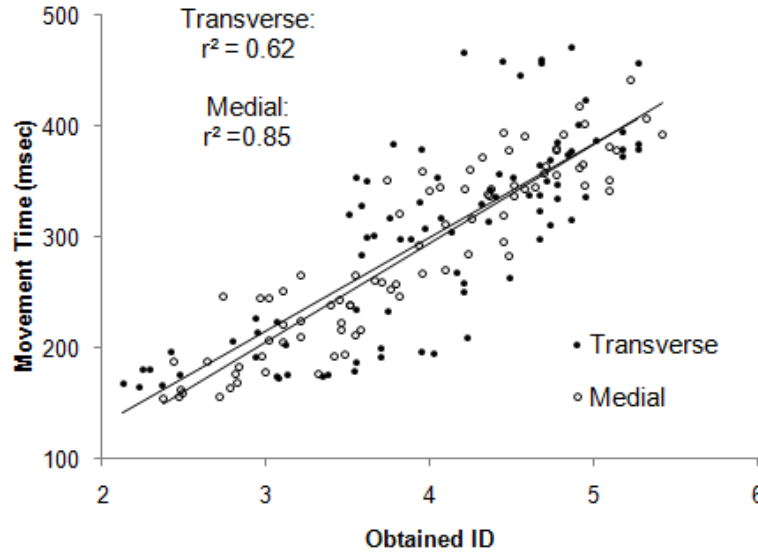


Figure 3. The relation between MT and obtained ID for seven solo participants (i.e., not averaged) as a function of medial and transverse movement direction. Each dot represents a trial.

Error and Endpoint Variability. Traditionally, the percentage of target misses and endpoint *SD* together express movement precision in Fitts tasks. Error is tracked continuously in our experiment. Recall that error stands for the distance from each tap to the center of its target. The targets were both 5 pixels in radius (approximately less than 1 mm, 60 pixels = 10 mm). In light of the strong relationship observed between MT and Obtained ID, the true relationship between error and MT is better observed in separate distance conditions (Figure 4), as a participant also took longer to travel longer distances, a result that is trivial. Figure 4 shows that the speed-accuracy trade off that is a hallmark of Fitts law behavior is present within each distance condition. As expected given the relation between MT and error, a somewhat strong negative linear correlation is also observed between endpoint variability and MT, $r = -.47$, $p < .0001$.

Standard multiple regressions were conducted to determine the effect of Obtained ID, movement orientation and their interaction term on error and endpoint variability, respectively. Regression results indicated that no predictor contributed to either model significantly other than Obtained ID, $p < .0001$, for both error and endpoint variability. The coefficient tables are omitted here considering no significant contribution from movement orientation or its interaction with ID was observed.

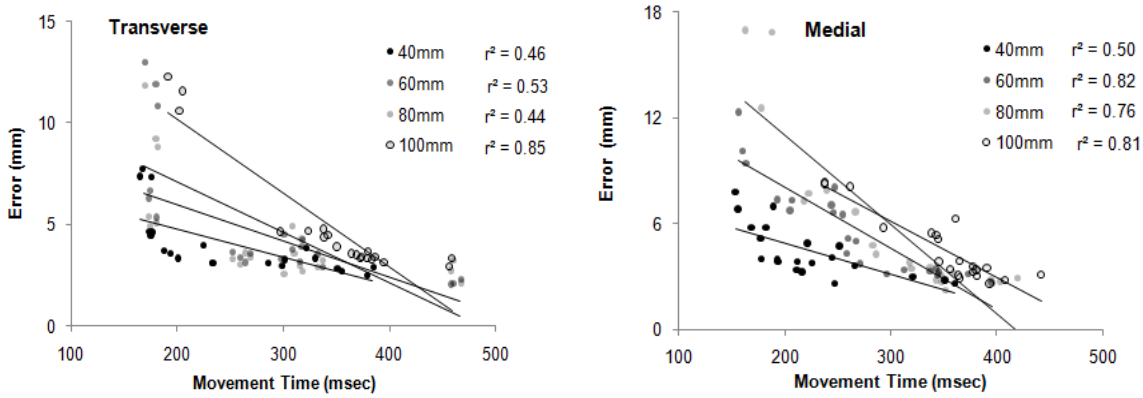


Figure 4. The relation between MT and error as a function of target amplitude in transverse (left) and medial (right) directions for seven solo participants (i.e., not averaged).

The average movement time, error and least-squares fit between ID and MT for all solo trials are summarized in Table 7 when the dyad context is also provided in Experiment 2. Discussion comparing solo and dyad performance will be deferred until the next chapter.

Discussion

Experiment 1 had two key purposes. One was to test if the refined measure of W_A demonstrates Fitts's law as a direct consequence of a continuously obtained ID. The success of the model fit (Figure 3) and the multiple correlation results supported this. Interestingly, based on

the actual spread of taps, we found that participants' produced errors are specific to the direction they are moving in the Fitts task. This result agrees with the key finding in Hoffman et al. (2011) where the most important variable in constraining multi-dimensional Fitts performance is the tolerance in the participant's direction of movement. Hoffman et al. (2011) used three targets to implement the different dimensions: a long flat strip of paper where the dimension orthogonal to the direction of movement is much larger than the target width (1D), a square flat paper where the target width and the other dimension are comparable (2D), and a cube (3D). Their findings showed that MTs remained relatively unchanged as these dimensions changed; the ID in the direction of movement consistently accounted for the most variance in MTs. Our results further corroborated this even when the target geometry is circular. This implies that ID can be defined by the accuracy of the tap in the direction of the movement and the inter-target distances (amplitude), in addition to the traditional, scalar definition of ID as a combination of target width and amplitude.

The second purpose of Experiment 1 was to assess Fitts performance differences in the two main movement directions in tango: transverse (sideways) and medial (forward-backwards). The regression results showed no effect of movement direction on movement time (neither as a main effect nor in an interaction). However, participants' speed is somewhat faster and the accuracy is lower moving forward (Table 7), resulting in a better model fit (Figure 4). It is of particular interest to the current thesis to show that the putative information processing capacity, traditionally quantified as the inverse of the slope of the model (bits/sec), is always subject to influences from meaningful constraints such as the biomechanical limits of the body. For inter-target distance higher than 5.08 cm, both forearm and upper arm movements are involved

in the Fitts task (Langolf, Chaffin, & Foulke, 1976). Our tapping task and the distance manipulation (4 to 10 cm in 2 cm increment step) required participants to engage multiple muscle groups spanning arm, wrist and finger during movement. Perhaps Cisek and colleagues' recent work can shed light on our discussion of the movement direction effect. Cisek's central thesis is that voluntary behavior such as arm reaching is not just kinematic but also subject to biomechanical properties of the movement. It was shown that when presented with multiple movement trajectory choices, participants' movement trajectory naturally reflects one that is better aligned with the major axis of the arm's mobility² ellipse (Cos, Belanger, & Cisek, 2011; Cos, Medleg, & Cisek, 2012). Perhaps in our experiment, participants are biomechanically constrained to reach with greater difficulty forward than sideways and they are proprioceptively aware of that when making forward and sideways reaching movements. Hence, the constraint could be affecting their performance in the Fitt's task, and the awareness could be coming into play that resulted in bigger errors but faster movement in the forward direction.

² Mobility is a metric that captures the biophysical properties of the arm that muscle energy is derived from (Cos et al., 2012).

CHAPTER 4

EXPERIMENT 2

The success with Fitts modeling using our refined metrics in Experiment 1 formed the basis for the dyad experiments. The first goal of Experiment 2 was to compare solo and dyad Fitts task performance as a function of movement orientation. Managing the movement direction is key to tango technique that starts from the principle of two dancers, a leader and a follower, facing each other. The ease of initiating a dyadic movement in tango is dependent on the point of physical contact and the direction of force that can be exerted. In the laboratory implementation, participants guided or were guided by another individual via their fingers.

Two tango observations inspired the hypotheses in Experiment 2, namely, movement in tango can be led by:

1. exerting force into the point of contact, toward the follower in the direction the leader intends to move. In the present experiment, this is when the index and middle finger press into the follower's finger; or
2. decreasing pressure (i.e., depending only on friction) to move the follower in a direction away from the point of contact, for example, the leader takes a backstep perpendicular to the follower's front. In the present experiment, this is when the index and middle move either left or right, or away from the follower's finger. Coordination depends on the follower's maintaining contact with the leader in order for the follower to move appropriately. In other words, it requires the follower to be active, pushing into the leader so as to coordinate his/her own movement.

The Tango-Fitts movement task in Experiment 2 embodied these coordination challenges.

Dyad performance was expected to differ significantly from solo performance as a function of movement direction. The predicted difference reflects the suggestion that Fitts performance is not only about constraints on sensory information processing, viz. IP (the rate of information processing) = ID/MT, but also evinces biomechanical limitations of the moving, interacting bodies coordinating in two directions in the dyad case.

The second goal of Experiment 2 was to investigate the importance of haptic versus optic coupling in supporting dyadic coordination. Studies of solo Fitts tasks have been dominated by manipulations of visual constraints. For example, an intermittent obstruction to visual contact with the moving cursor revealed that the change in Fitts kinematics associated with levels of task difficulty is a result of changes in the available optic structure (Bootsma, Boulard, Fernandez, & Mottet, 2002). Specifically, participants moved so as to harness more optic structure at the end and beginning of each aiming cycle. Relatedly, a manipulation of display size (Kovacs, Buchanan & Shea, 2008) revealed that the larger visual display enabled participants to achieve successful harmonic aiming motion beyond the critical index of difficulty level where such movements had been shown to break down, becoming discrete (i.e., ID = 4, Guiard, 1997).

As previously discussed, there are very few studies that extended the solo Fitts task to a two-person cooperative setting. There is no prior study that examined a dyadic Fitts task with direct haptic coupling. The study closest to the situation in Experiment 2 is provided by Gentry's (2005) dissertation, which also applies Fitts to the context of dance. In particular, the Fitts task was intended to implement haptic communication during American Swing, another partnering dance (see Chapter 2). Gentry (2005) followed Reed et al. (2004) to construct a haptic-coupled device that attempts to mimic a simultaneously stiff and springy connection. Two people

controlled a pointer via a driving wheel fixed to a desk to complete a 1-D, cyclical Fitts task on the screen. The two people were haptically coupled by a 4 ft long wooden dowel attached to the wheel, embodying a kind of lever. Previous results for a discrete Fitts task (Reed et al., 2004) were replicated for a cyclical Fitts task: Dyads achieved lower movement time on average and committed higher error rates than individuals only at higher difficulty levels (Gentry, 2005). Gentry and colleagues (see also Gentry et al., 2005) modeled American swing dance as a finite state machine.

The second goal of Experiment 2 thus explored not only how haptic coupling alone sustains a dyadic Fitts task but how haptic and optic coupling interact in the Fitts task. Three variants of dyad connections—visual haptic, blind haptic, and purely visual—allowed a comparison of the various impacts of haptic versus optic coupling.

Method

Participants

A subset of participants from Experiment 1 were paired amongst themselves to create the dyads for Experiment 2 ($N = 7$ pairs). Due to scheduling difficulties, not every solo participant was able to be matched with every other to form a perfect permutation. Of the seven pairs, five pairs were opposite-sex dyads and two were female-female dyads. Dyads included strangers and acquaintances but none had any prior experience with partnering dance.

Task Design

For *dyad trials*, one participant guided or was guided by the partner's dominant hand to touch the targets in the same fashion as outlined in Experiment 1. The target size and measurement device attributes remained the same. Movement amplitude was manipulated through 4 target

distances (40, 60, 80 and 100 mm) as in the solo trials.

Each dyad task consisted of two roles, follower and leader. To minimize participants' personal interpretations of the "leader" and "follower" responsibilities, we opted for the neutral language of "navigator" for the leader and "tapper" for the follower; these terms are used interchangeably from now on. The navigator was able to see the targets and was responsible for guiding the tapper's finger to touch the targets; the tapper touched the targets but was unable to see them. An occlusion screen ensured that only the navigator could see the targets. (This restriction reflects a feature of the lead-follow reality in tango; Chapter 2)

In addition to the speed and accuracy instructions, dyad trials included a few additional variants that characterize the nature of the haptic and visual relationship between the participants.

The first dyad variant, referred to as the *haptic + visual task*, allowed the follower to both touch and see the leader's hand (but not see the targets). It required participants to maintain a point of contact (the tip of the index and middle fingers of the leader touch the proximal interphalangeal, or PIP joint, of the follower), and assist each other achieving the movement goal (Figure 5a and b). To reinforce the constraint that participants maintain contact throughout the trial, the dyad received an audio beep of 500 Hz lasting 0.25 s whenever the fingers broke contact during the trial. Real-time touch feedback was enabled by installing *MakeyMakey* from the MIT Media Lab. During each trial, an alligator clip that served as part of a conductance circuit connected to the tablet was affixed to each participant's off-hand. The Web-application registered the absence of touch as a keyboard stroke that triggered a tone and recorded the event in the program log of events.

The second dyad variant, *the blind haptic task*, required the follower to closing his or her

eyes and rely only on haptic contact with the leader. This restriction reflects the common practice in tango for followers to close their eyes. The perceptual support that was removed in this case is the followers' ability to see the leader's hand.

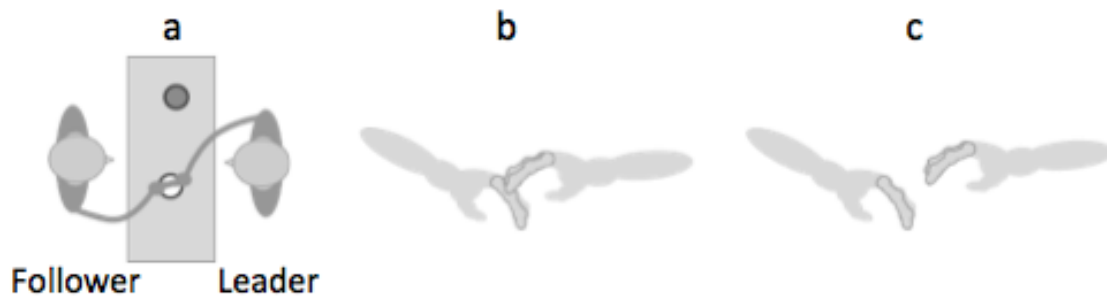


Figure 5. (a) Positions of participants in the Fitts dyad task. The hands of follower and leader either (b) touch, for *haptics + vision* and *blind haptics* conditions, or (c) do not touch, for *purely visual* condition.

The third dyad variant, *the purely visual task*, required the follower to maintain a one-inch separation between their PIP joint and the leader's extended index finger (Figure 5c). (This third variant of the dyad task reflects one of the most important exercises in learning to dance tango; Chapter 2)

Procedure

Upon taking turns to finish the solo trials, dyad members were gathered and seated opposite each other (Figure 5a). They drew lots to be assigned their roles and remained in their role throughout the dyad trials. The experimenter gave specific instructions on the navigator and tapper responsibilities:

In the conditions that involve touch, the navigator was instructed to:

1. be in charge of initiating directions without losing contact with the tapper's finger; and
2. make sure the extended index and middle fingers stay on top of the tapper's PIP joint but not fall on either side of the joint, which would greatly reduce the coordination challenge by treating the tapper's finger as if it were a passive object.

In tandem with the navigator's role, the tapper was instructed to:

1. strive to maintain finger contact with the navigator throughout a trial; and
2. give pressure back to the navigator's fingers so as to help maintain contact and enable coordination when the direction changed.

In the *purely visual* condition, to ensure that the same approximate distance was maintained between the tapper's and navigator's fingers, the tapper was asked to estimate the distance, and the experimenter measured it before and after each trial. Additionally, when visual inspection detected that the distance increased overtly during the trial, the experimenter intervened by verbally reminding the participants of the constraint. This reduced the degree of error in the distance estimation.

In pilot studies, several participants deviated from the distance constraint for the *purely visual* task. As a result, instructions were elaborated. The navigator was asked specifically, when arriving above each target, *not* to use a tapping motion to signal the follower to tap on the target. They were told that doing so would change the distance to the partner's fingers, thereby disrupting their connection while increasing movement variability. This instruction was also instrumental in respecting the analogy to tango training where the follower and leader learn to move together while maintaining a fixed distance from each other. In particular, they learn to move together by observing each other's body movements, in which case, the leader and

follower develop an awareness of their spatial relationship without the leader's issuing any special movement signal at the stopping points (Chapter 2). To ensure consistency of the task, the tapper was asked to follow the navigator in a fingertip-to-fingertip fashion: keeping the tapper's fingertip right underneath the navigator's fingertip. This means that the tapper was not supposed to anticipate the navigator by moving ahead of the finger. These instructions were reinforced by the experimenter's visual inspection.

The dyad experiments all began with a practice session consisting of 4 blocks of 10-sec trials for each of the four difficulty conditions. Every dyad told the experimenter they were ready by the end of the practice session. The practice session was very important in establishing partnership. Some dyads referred to it as the "calibration phase." Particular instructions were given regarding verbal negotiation. During practice, participants were encouraged to talk and puzzle out their coordination. A distinct learning phase was observed. During the experiment, verbal negotiation was only allowed when encountering severe struggles. Occasional verbal negotiation did occur during the experiment. Most of the conversations surrounded touch feedback (e.g., "A little more pressure;" "I can't feel the pressure;" "When going forward towards me, you have a tendency to slide down on your own. Touch down only when you feel the pressure from me") or dialogs (e.g., "Can you feel my lead?" "Yes. We can actually do it even faster.").

Each dyad performed a total of 48 trials: 4 inter-target distances \times 2 directions of movement \times 3 coupling conditions (purely visual, visual + haptic, blind haptic) \times 2 trial repetitions. Each trial lasted 30 s. Each dyad lasted on average 2 hours including the time they practiced and rested. Some dyads shook their hands in between trials to rest the finger joints. No one

complained about fatigue.

Apparatus and Data Processing

The apparatus was the same as in Experiment 1. As explained before, the top 5% of error and MT values (2-3 taps) were counted as outliers and deleted from data analysis. The first 5 transient taps of each trial were also deleted from data.

W_A . Similar to the solo case, within each trial, the mean of the errors (mm) is significantly larger in the direction of movement ($M = 4.87$, $SD = 2.48$) than in the direction perpendicular to the direction of movement ($M = 1.89$, $SD = .92$), $t(167) = 9.92$, $p < .0001$ (cf. Appendix B). Likewise, the spread (SD) of the mean of errors is also larger in the direction of movement ($M = 4.23$, $SD = 3.22$) than in the other direction ($M = 2.04$, $SD = 1.63$), $t(167) = 8.70$, $p < .0001$.

Statistical Considerations

For the statistical analyses, Huyuh-Feldt adjustments for violations for sphericity were made when necessary. To further investigate main effects and interaction effects in the post hoc analyses, simple effect F -tests were run with the Bonferroni correction to adjust statistical significance.

Results

Obtained ID. ID was calculated based on the distribution of absolute errors instead of displacement-specific errors. Table 3 summarizes the average ID values produced by the seven dyads for the three coupling conditions, averaged over movement direction.

Table 3

Average ID Produced by Each Dyad as a Function of Perceptual Coupling and Orientation.

	Haptic	Haptic + Visual	Visual	Transverse	Medial
Pair 1	4.48	4.09	4.29	4.38	4.19
Pair 2	3.45	3.26	2.79	3.36	2.98
Pair 3	4.06	4.30	4.22	4.20	4.19
Pair 4	3.79	4.12	3.36	3.65	3.86
Pair 5	3.96	3.91	3.70	3.96	3.76
Pair 6	3.01	3.53	3.69	3.39	3.44
Pair 7	3.38	3.48	3.21	3.46	3.24

Fitts's law behavior. First of all, we investigated the validity of Fitts's law with respect to dyad data aggregated over all coupling and orientation conditions. The correlation between MT and ID is positive, such that the higher values of movement time are related to higher IDs, and significant ($r = .20, p < .0001$); however, as the scatterplot (Figure 6) shows, it is quite weak. Separating the plots by movement orientation did not yield a stronger profile of Fitts behavior (Figure 7; $r = .20$ for the transverse direction and $.24$ for the medial direction). Separating the plots by coupling condition, however, yielded a more distinctive trend where haptic coupling,

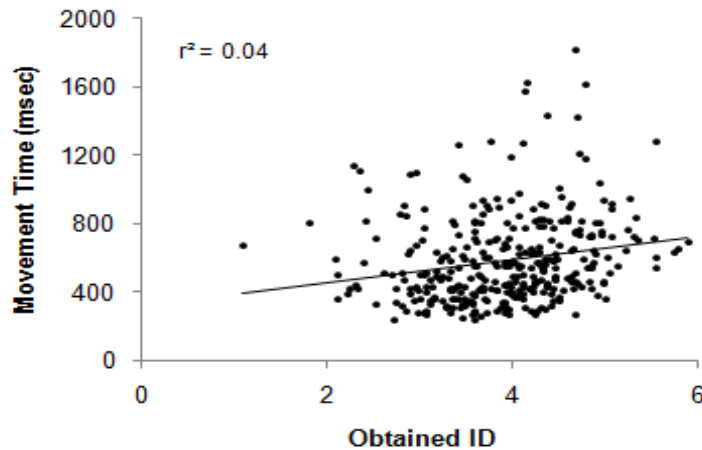


Figure 6. Data for the seven dyad (not averaged) showing the relation between MT and obtained ID.

$r = .40$, seemed to outperform haptic + visual, $r = .11$, and visual coupling, $r = .18$, in terms of yielding Fitts behavior (Figure 8).

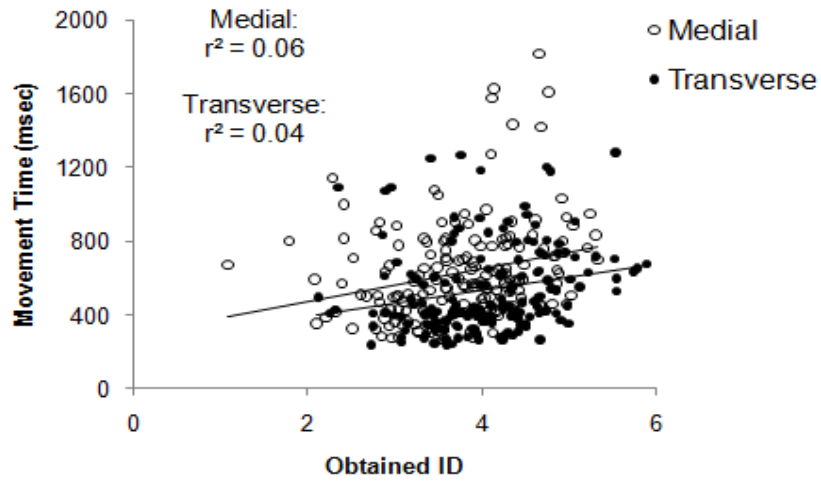


Figure 7. Data for the seven dyad (not averaged) showing the relation between MT and obtained ID for medial and transverse directions.

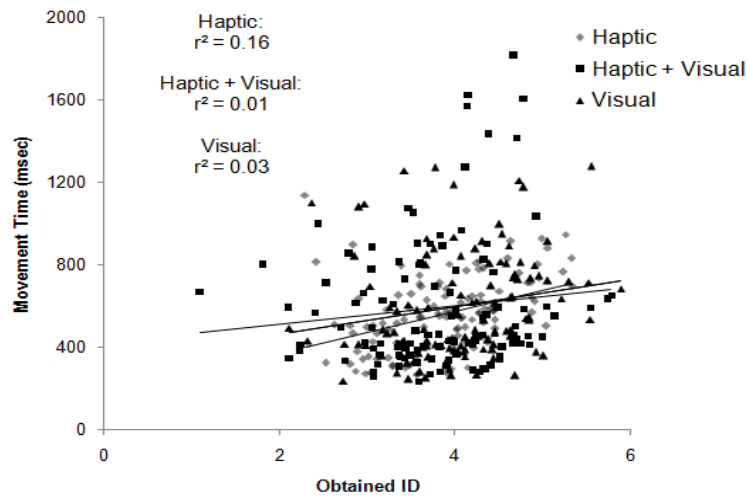


Figure 8. Data for the seven dyad (not averaged) showing the relation between MT and obtained ID for the three coupling conditions.

The scatterplot characterization of aggregated dyad data (Figure 6, 7 and 8) suggests that the overall behavior does not obey Fitts's law, nor do the Fitts parameters vary dramatically by condition. However, the plots also suggest that there was much larger skill variance among dyads than solo individuals. Data inspection showed that the slopes (msec/bit) not only vary from dyad to dyad, but also vary from the previous solo performances where Fitts's law was observed. The different slopes finding agrees with Gentry et al. (2005) who also did not find identical slopes between solo and dyads, a finding that has also been reported for a dyadic discrete aiming Fitts task (Reed et al., 2004). This motivated treating each dyad as an independent unit for data analysis (as did Gentry et al., 2005). A scatter plot between ID and MT, along with an r^2 value was created for each dyad in every unique condition. The r^2 value for the line fit between MT and ID for each dyad is shown in Table 4 for every condition. To evaluate what brings the dyads to act more in line with Fitts's law, that is, how the goodness of model fit varies by condition, the individual r^2 values were submitted to a two-way repeated-measures ANOVA with within-subject variables coupling (haptic, haptic + visual, and visual) and orientation (transverse and medial). The line fit is best in the blind haptic condition ($M = .42$, $SD = .29$), followed by the haptic + visual condition ($M = .36$, $SD = .25$) and pure visual condition ($M = .28$, $SD = .24$); however, the main effect of coupling condition is not significant, $p > .10$, $\eta_p^2 = .16$. The line fit is numerically better in the medial direction ($M = .40$, $SD = .28$) than in the transverse direction ($M = .33$, $SD = .24$), though the difference is not significant either, $p > .10$, $\eta_p^2 = .14$. There is no significant interaction between orientation and coupling condition, $p > .50$, $\eta_p^2 = .08$.

Table 4

Average Fitts Line Fits (r^2) as a Function of Movement Direction (T = Transverse; M = Medial) and Coupling for Each Dyad.

Participant	Direction	Haptic	Haptic + Visual	Visual
Pair 1	T	.15	.06	.49
	M	.55	.81	.06
Pair 2	T	.40	.27	.02
	M	.34	.32	.03
Pair 3	T	.68	.77	.45
	M	.46	.43	.64
Pair 4	T	.27	.03	.21
	M	.70	.30	.09
Pair 5	T	.76	.44	.52
	M	.92	.39	.12
Pair 6	T	.03	.60	.24
	M	.57	.21	.16
Pair 7	T	.01	.26	.18
	M	.00	.22	.77

Movement Time The average movement time for each dyad is shown in Table 5. To evaluate if dyads' movement time is affected by orientation and coupling, the trial averages were submitted to a three-way repeated-measures ANOVA with the within-subject variables coupling, orientation, and distance. The analysis revealed three main effects. As expected, dyads slowed down as distances increased (40 mm $M = 547.23$, 60 mm $M = 554.61$, 80 mm $M = 597.80$, 100 mm $M = 633.76$), $F(1.75, 20.39) = 7.32$, $p = .005$, $\eta_p^2 = .36$. Importantly, dyads were significantly faster (about 100 ms) in the transverse direction ($M = 534.9$, $SD = 212.3$) than in the

Table 5

Average Movement Time (msec) for Each Dyad As a Function of Movement Direction (T = Transverse; M = Medial) and Coupling.

Participant	Direction	Haptic	Haptic + Visual	Visual
Pair 1	T	564.0	625.3	793.8
	M	724.6	618.6	460.6
Pair 2	T	386.6	382.6	514.3
	M	537.4	644.3	665.9
Pair 3	T	344.4	443.3	1016.0
	M	481.1	712.9	1445.6
Pair 4	T	396.0	379.6	948.8
	M	392.6	585.1	901.6
Pair 5	T	446.5	513.4	797.1
	M	683.1	571.2	741.6
Pair 6	T	441.7	443.6	779.0
	M	552.0	723.0	811.5
Pair 7	T	299.2	263.3	455.2
	M	308.1	291.5	434.8

medial direction ($M = 629.7$, $SD = 246.9$), $F(1, 13) = 10.57$, $p = .006$, $\eta_p^2 = .45$. Lastly, dyads moved fastest in the blind haptic condition ($M = 463.8$, $SD = 131.1$), followed by the haptic + visual condition ($M = 514.1$, $SD = 149.2$), and the visual only condition ($M = 769.0$, $SD = 270.8$), $F(1.06, 13.76) = 17.10$, $p = .001$, $\eta_p^2 = 0.57$. Pairwise post hoc tests highlighted the unique contribution of a haptic connection to speed: Moving with only visual coupling is significantly slower than any other condition that contains haptic coupling, namely, haptic + visual coupling ($p = .004$) and haptic coupling alone ($p = .001$), while haptic coupling did not differ significantly from haptic + visual coupling, $p > .50$. In addition, there is a significant three-way interaction:

distance \times coupling \times orientation, $F(4.77, 62.04) = 2.74, p = .03, \eta_p^2 = .14$. Figure 9 shows that in the medial direction, the haptic coupling is faster than visual + haptic coupling which is faster than visual coupling alone, however, this pattern is true for shorter distances only (40 mm and 60 mm, $ps < .05$); as the distance increases, the visual addition to haptic coupling no longer affects speed, $ps > .50$) while the haptic coupling speed persists over visual coupling alone, without or without visual addition $ps < .01$. In the transverse direction, the separation among the three kinds of coupling only occurs at the lowest distance level (40 mm); as distances increases, movement speeds with haptic coupling (with and without vision) are nondifferentiable from each other while being dramatically faster than visual coupling alone ($ps < .01$).

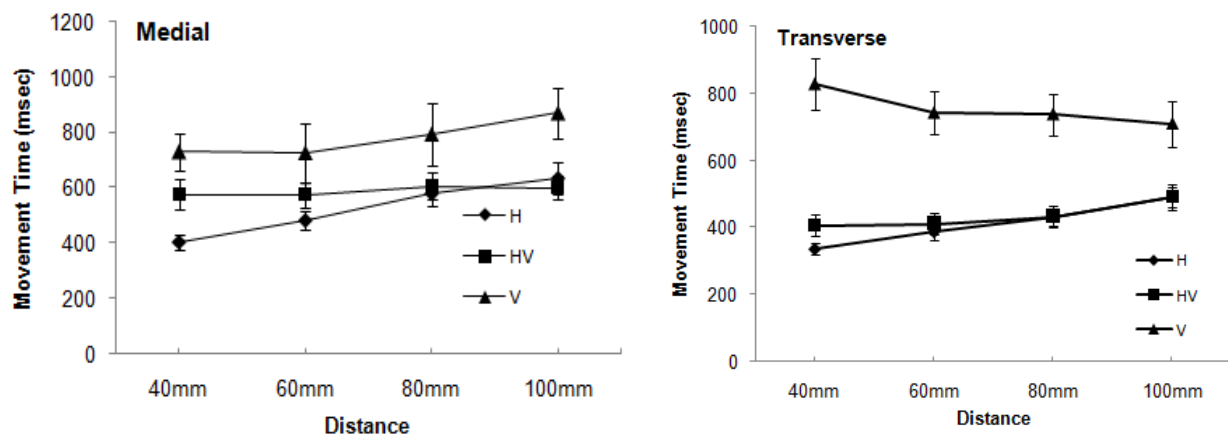


Figure 9 Average dyad movement time as a function of distance and coupling for (left) medial and (right) transverse movement directions.

Error and Endpoint Variability. Average error for each dyad is shown in Table 6. To evaluate if dyads' error is affected by orientation and coupling, the trial averages were submitted to a three-way repeated-measures ANOVA with the within-subject variables: coupling, orientation and distances. There were two main effects: distance and coupling. Contrary to expectation, error

Table 6

Average Error (mm) for Each Dyad as a Function of Movement Direction and Coupling.

Participant	Direction	Haptic	Haptic + Visual	Visual
Pair 1	T	2.29	3.55	3.37
	M	2.83	3.59	3.20
Pair 2	T	5.25	5.79	7.54
	M	5.06	6.96	11.24
Pair 3	T	3.67	3.49	4.25
	M	4.29	3.05	3.93
Pair 4	T	4.57	3.75	6.95
	M	4.34	3.19	6.23
Pair 5	T	3.68	4.77	5.06
	M	4.43	4.40	6.26
Pair 6	T	6.96	4.75	5.08
	M	6.24	5.68	5.78
Pair 7	T	5.85	4.69	7.57
	M	5.87	5.70	7.10

worsened as the distance increased (40 mm $M = 4.85$, 60mm $M = 4.89$, 80 mm $M = 5.04$, and 100 mm $M = 5.39$), $F(3, 39) = 3.80$, $p = .02$, $\eta_p^2 = .23$. Of particular interest, dyads were most accurate ($M = 4.52$, $SD = 1.31$) in the haptic + visual condition, followed by blind haptic ($M = 4.67$, $SD = 1.17$) and visual only condition ($M = 5.97$, $SD = 2.12$), $F(2, 26) = 9.20$, $p = .001$, $\eta_p^2 = 0.41$. Post hoc pairwise tests highlighted the unique contribution of a haptic connection to error: When only visually coupled, dyads were significantly less accurate than any other condition that contains a haptic connection: haptic + visual coupling, $F(1, 13) = 16.66$, $p = .001$, $\eta_p^2 = .56$; and haptic coupling alone, $F(1, 13) = 8.55$, $p = .012$, $\eta_p^2 = .40$); while haptic coupling

did not differ significantly from haptic + visual coupling, $F(1, 13) = 8.55, p = .012, \eta_p^2 < .05$.

Dyads were on average slightly more accurate in the transverse direction ($M = 4.90, SD = 1.45$) than in medial direction ($M = 5.21, SD = 1.91$), though the difference did not reach significance, $F(1, 13) = 3.32, p = .09, \eta_p^2 = .20$. The main effects of distance and coupling are also qualified by a significant two-way interaction: distance \times coupling, $F(6, 78) = 2.79, p = .016, \eta_p^2 = .18$.

Figure 10 illustrates that the error gap between haptic coupling and visual coupling is pronounced at all distances except at 80 mm, $p > .10$. The error gap between haptic + visual and visual coupling alone is pronounced only at shorter distances (40 mm and 60 mm, $ps < .05$) while the error in haptic and haptic + visual conditions are not significantly different from each other across all distances ($ps < .02$).

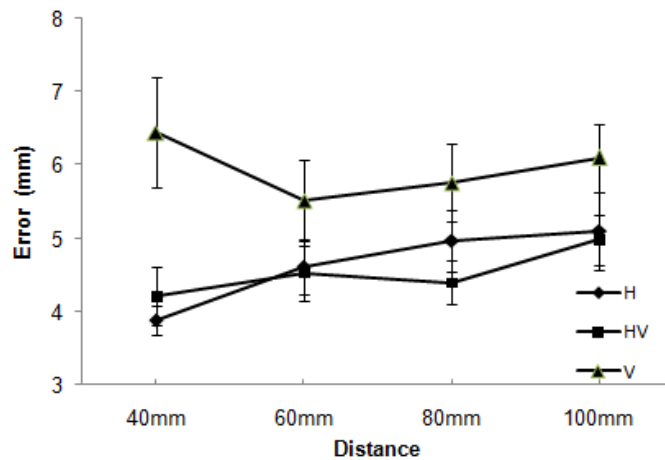


Figure 10. Average dyad error over four distances with the coupling formats.

To evaluate if endpoint variability is affected by orientation and coupling, the trial averages were submitted to a three-way repeated-measures ANOVA with within-subject variables of coupling, orientation, and distances. There were two main effects: distance and orientation. The

endpoint variability significantly increased as distance increased (40 mm $M = 2.37$, 60 mm $M = 2.53$, 80 mm $M = 2.56$, 100 mm $M = 2.88$), $F(3, 39) = 7.07$, $p = .001$, $\eta_p^2 = .35$. Of particular interest, dyad movement in the medial direction ($M = 2.75$, $SD = 1.26$) is significantly more variable than in the transverse direction ($M = 2.42$, $SD = 1.19$), $F(1, 13) = 6.20$, $p = .027$, $\eta_p^2 = .32$. Although numerical differences in variability as a function of coupling were consistent with the results for error—dyads were least variable with haptic + visual coupling ($M = 2.37$, $SD = .93$), followed by haptic coupling ($M = 2.54$, $SD = 1.27$), then visual coupling ($M = 2.84$, $SD = 1.41$)—the main effect of coupling did not reach significance, $F(2, 26) = 2.09$, $p > .10$, $\eta_p^2 = 0.14$. Its influence is apparent, however, in the Distance \times Coupling interaction, $F(4.41, 57.35) = 2.91$, $p = .025$, $\eta_p^2 = .18$ (Figure 11). The variability gap between vision only and the haptic conditions (i.e., both haptic and haptic + visual coupling) is greater at the shortest distance 40 mm than the rest, $ps < .01$, and the gap among all three kinds of coupling shrinks at the greatest distance, $ps > .10$.

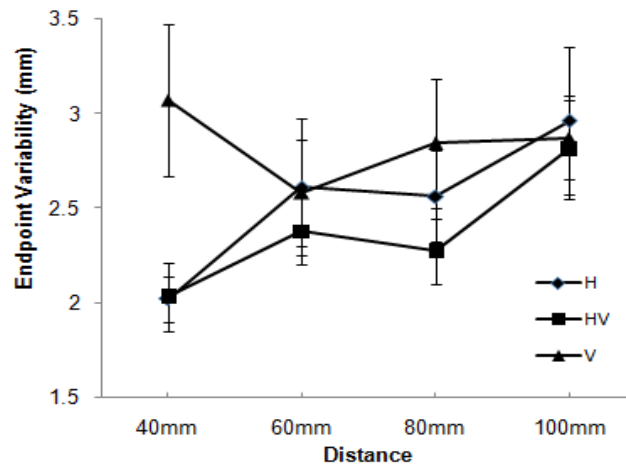


Figure 11. Average dyad endpoint variability (SD of error) over four distances in three coupling formats.

Comparison between solo and dyad performance

Table 7 provides a comparison of solo and dyad performance on several measures of interest. Error was comparable between solo and dyad performers, contrary to the finding in Gentry et al. (2005). Movement direction mattered for dyads speed but not for solo speed. Averaged over trials and individuals (as in nearly every solo Fitts's law experiment), the Movement Time \times Obtained ID fits were much better for solo than for dyads (Table 7). The aggregated dyad data, in contrast, showed very little sign of the signature Fitts line fit (Figure 6) partially due to the large between-dyad variance that arose in the current task. As a result, regression analyses on continuous ID were not obtained for the dyad data as they were on the solo data. A linear least-squares fit between Obtained ID and MT was calculated for each individual and dyad in each orientation and coupling condition to observe (1) skill variances among dyads, (2) skill variance by coupling condition, and (3) solo and dyad comparison.

Table 7

Average Movement Time (msec), Error (mm), and Fitts line fits (r^2) for All Solo and Dyad Trials.

	Transverse	Medial
<i>Solo</i>		
MT	301.13	285.71
Error	4.59	5.14
r^2	0.73	0.78
<i>Dyad</i>		
MT	534.95	633.54
Error	4.93	5.21
r^2	0.33	0.40

Discussion

We examined the effects of different forms of perceptual support on a dyadic Fitts task in two movement orientations. The manipulations in Experiment 2 take direct inspiration from tango. Dyads were connected by either direct haptic information, visual information, or a combination of both to mirror the reality in tango dancing and training. Meanwhile, dyads also moved sideways and forward-backwards to mimic the side steps and forward-backward steps in tango, two fundamental stepping modules in the tango vocabulary (Chapter 2). As noted in the introduction, none of the prior studies shared our focus on coordination by information-L. In Mottet et al. (2001), the collaboration was not physical; the individuals could not feel the motion of the other as they could only watch the shared motion on a display. In both Gentry (2005) and Reed et al.'s (2004) two-person Fitts tasks, because the physical connection is mediated by a shared aiming device, the individuals are constrained to move at a constant velocity. This kind of instrumentation of haptic coupling simplified these dyadic relationships. For example, Reed et al. (2004) reported that participants may have adopted specialized roles to complete the Fitts task, where one person controlled the “launch” phase, let the middle-phase be carried by momentum and the other person controlled the “braking” phase in the end. In so doing, the dyad functioned as “agonist” and “antagonist” muscle bursts at specific phases of the task. Similarly, Gentry (2005) did not rule out the possibility that dyads performed faster on average than solos simply because two persons could apply bigger forces on the lever than one. This kind of setup does not compare with the moment-to-moment coordination required to succeed at our current task where for example, the continuous rate of force application by multiple muscle groups across arm, wrist and finger is crucial to shaping coordination. The dyad performance in Experiment 2, therefore,

stands as a demonstration of complex coordination by informational-L.

When comparing solo (Chapter 3) and dyad performances, it is not surprising that, unlike previous studies (Gentry et al., 2005; Reed et al., 2004), we did not find that dyads moved faster. In fact, the dyads are on average slower than solos considering the time cost of coordination in our current task (Table 7). Dyads also did not produce the higher error rate that characterized Gentry et al., (2005), a finding that might have contaminated their finding of dyad speedup. Table 7 showed that on average, both dyads and solos missed the target center by approximately a factor of 2 or 3 times the size of the target (i.e., 1.5-2.5 mm) in both directions. However, Fitts's law was not obtained as clearly in the dyad case as it was in the solo case. Comparisons of Figure 3 with Figure 6-8 highlight the differences between solo and dyad least-squares fits between ID and MT. In the solo case, the slopes are all positive and, regardless of the movement direction, the fits are stronger than the dyads'. In addition, the correlation analyses showed strong evidence that solos became more accurate when they moved slower and less accurate when they speeded up. These not only validated the line fit but also directly supported the physical interpretation of Fitts's law: the speed-accuracy tradeoff. Similar results showing the slope differences between solos and dyads have been obtained in Gentry et al. (2005). What is novel to the current data set is the large slope differences *between* dyads and that Fitts's law was not observed in every dyad as with prior haptic two-person Fitts studies. The differences in the results are due to the different instrumentations of coupling that may have altered the nature of the tasks. In fact, judging by the model fit (Table 4) the capabilities to do the dyad task were largely defined by the availability of haptic coupling, an important finding for our central thesis.

We also formulated the hypothesis that the coordination challenges inherent in moving in

different directions together with another person would manifest as a stronger effect of movement orientation in dyads than in solos. Our data supported this, as demonstrated differences in the influence of movement direction on movement time. First of all, numerically, the Fitts model fit is better in medial than in transverse direction for dyads, though not significant. More meaningfully, the ANOVA on individual dyads' performance metrics revealed that it took dyads significantly more time moving forward and backwards together (on average, a 100 ms slowdown) than moving sideways together. Dyads are significantly less precise moving forward and backwards than sideways (Table 6). Lastly, the speed gap between dyads with only visual support and with only haptic support is significantly larger in sideways than in forward-backward direction (Figure 9). Together these results contrasted with the lack of a significant effect of movement orientation on the overall Fitts model in the solo data.

A central contribution of the current thesis is the exploration of haptic coupling in interpersonal coordination, with or without the addition of optic coupling. We manipulated the availability of optic coupling by having the follower (the one who taps on the tablet) either open or close their eyes while coordinating at the finger joints with the leader (the one who navigates); in the third condition, we removed the haptic coupling by having the follower visually track the fingertip location of the leader at a fixed distance from each other. Importantly, with the aid of a tablet screen guard, the leader supported the follower without the follower's having optic information about the target locations. This last element again reflects a core aspect of tango dancing where the follower relies primarily on a haptic exchange with the leader to dance across the floor without seeing where to step next. These results are the first to demonstrate the importance of direct haptic coupling in sustaining a two-person Fitts task. Whenever the

coupling conditions contained haptic exchange, the Fitts model fit is better (haptic $M = .42$, haptic + visual $M = .36$) while the visual coupling alone ($M = .28$) yields the worst to no fit at all. This pattern of haptic dominance is seen throughout the results of the ANOVA on individual dyads' performance metrics: Dyads were the fastest (Figure 9), the most accurate (Figure 10), and the most precise (Figure 11) when coupled by touch, followed by the addition of sight which yields still higher speed, accuracy and precision than having only sight. Adding both touch and sight makes no difference in these metrics compared to when the dyads were coupled by touch only (i.e., when the follower's eyes were closed), especially at larger distances (Figure 9). To recapitulate, haptic coupling is dominant in the sense that when removed, dyads' performance changed drastically, while adding optic coupling does not seem to make a difference. This means that haptic coupling is superior to visual coupling when both perceptual systems are given equal expression in the Tango-Fitts task.

We note that in our experiment, only the leader could see the targets at all times. This is similar to the asymmetric joint action scenario investigated by Vesper and Richardson (2014) where the leader and follower have unequal visual access to target locations in a synchronizing taps task. They showed that when attempting to coordinate, the leader amplified the range of motion to emphasize correct targets to the follower. This result may explain why visual coupling yields the slowest and most variable performance in current experiment. Given that dyads were deprived of force application mechanisms when coupled only by sight, the leader may have exaggerated his or her movement intending to coordinate with the follower, resulting in high variability and movement time. On the other hand, when dyads are coupled by touch it allows for force communication without the leader increasing the amplitude and variability of motion. It has

been shown by others that dyads produce more overlapping forces than individuals when performing a joint task moving a pole back and forth between two targets by pulling on two ends of the cords attached to the pole (Van der Wel, Knoblich, & Sebanz, 2011). This finding lends support to the haptic dominance effect in our results. The force amplification mechanism could have reduced variability of the dyad's joint movement and led to better coordination (cf. Vesper, Van der Wel, Knoblich, & Sebanz, 2011).

Without trajectory data to uncover the continuous behavior underlying coordination (e.g., coordination pattern and strength), we are of course unable to provide a full interpretation of the haptic dominance effect. However, combining crude observations of the dyad behaviors and past research on the dynamics of discrete and cyclical Fitts tasks, we are able to provide an initial pass at an explanation. The highlight of our results is that participants restricted to vision are slower and less accurate compared to those restricted to haptics, especially at lower difficulty levels, and overall, dyads with only haptic coupling show the strongest Fitts model fit and performance indices. The work of Guiard (1993, 1997) provides hints that this result may be due to the harmonicity enabled in the blind haptic task but not possible in the vision only task. Guiard (1997) showed that full-cycle harmonic smooth motion provides a movement time advantage over discrete aiming movements performed in two half-cycles, because harmonicity permits storage and reuse of the kinetic energy at each reversal phase (Kugler & Turvey, 1987). Moreover, cyclical aiming also displays a phase shift as the ID increases. Guiard (1997) observed a critical ID (≈ 4) at which discretization of movements in a Fitts task inevitably occurs. Huys, Fernandez, Bootsma, & Jirsa. (2010), using a phase space vector reconstruction technique, further confirmed the existence of limit-cycle dynamics associated with cyclical movement in

low ID regions and fixed point dynamics associated with discrete movement in high ID regions. In the fixed point regime, movement time increased with ID owing to the lengthening of the deceleration phase. This leads to the interesting conclusion that target width is proportionally related to the strength of a fixed point attractor corresponding to the end-point of the movement trajectory (Huys et al., 2010; Strogatz, 1994). At one level, movement organization is the product of dynamic interaction between body and environment. However, at a deeper level of analysis, as Kelso (1995) and Kugler and Turvey's (1987) work has exposed, the self-organization of movement can be constrained by informational coupling just as it is constrained by mechanical coupling. From this dynamical perspective, the linkage between Fitts' Information-S based conceptualization of fine motor control and the apparatus of dynamical systems theory is not paradoxical. Because of the harmonicity and continuity afforded by touch connections but not by sight, the dyads could have had more informational support in the haptic coupling conditions.

CHAPTER 5

EXPERIMENT 3

The experiments so far addressed how the continuums of perceptual support (visual, haptic, visual + haptic) impacts the kinematic markers of Fitts behavior. In particular, they highlighted the importance of haptic connection, the kind that sustain tango, in also sustaining the traditional Fitts task. In addition to haptic collaboration, another defining quality of the tango is that it is improvisational (Chapter 2). While the musical aspect of tango improvisation relies on expert listening and skill training, the spatial constraints for tango improvisation are characteristic of the environmental perturbations found in everyday perception and action. In a crowded social tango dancer floor, tango dancers have to adapt their movement kinematics and movement vocabulary online to the changing stepping space. A good leader can improvise with each step to what is available without relying on rules or pre-set movement phrases. To study how such improvisation changes Fitts task performance, Experiment 3 will manipulate the preview of target distance as it changes online.

There is a history of research that manipulated visual obstruction during locomotion and cyclical manual aiming movements in a Fitts task (Cullen, Helsen, Buekers, Hesketh, Starkes & Elliott, 2001; Elliott, Chua, & Pollock, 1994). For example, removing vision during target contact only did not affect the Fitts performance outcome (speed and errors) while removing vision during flight did (Cullen et al., 2001). Unlike our situation, in these studies the choices of motion segments to be seen or to be hidden were rather arbitrary and are not inspired by natural events; moreover, the inter-target distances were fixed and predictable. Our tango-inspired manipulation brings us closest to Matthis and Fajen's (2014) experimental paradigm studying

natural walking behavior in complex terrains. Manipulating vision of the future path revealed that seeing at least two step lengths ahead in the future path is needed to guide walkers' foot placement so as to avoid randomly distributed obstacles (Matthis & Fajen, 2014). This is attributed to the visual control threshold that allows walkers to exploit passive mechanical forces inherent to bipedal locomotion (Matthis, Barton, & Fajen, 2015). In the current experiment, we will explore the spatial constraints for tango improvisation in a Fitts task by making target distances unpredictable and varying the look-ahead. In so doing, we took the improvisation out of the person and embedded the constraints in the experimental program to solicit the improvisational responses and study their effect on the Fitts task. Of interest is whether the improvisational act implemented in our experiment will rewrite the Fitts phenomenon in the extreme case of Zero Preview and whether solo actors and haptic dyads will differ in their performance.

Method

Participants

For the dyad portion of the task, six new dyads were assembled from 12 UCONN undergraduates who volunteered to participate in partial fulfillment of a course requirement. All participants were right-handed, identified by the hand with which he or she preferred to do the tapping. Of the six pairs, three were opposite-sex and three pairs are male-male dyads. Participants were all strangers before the experiment. None had any prior experience with partnering dance. Due to scheduling difficulties, 7 of the 12 UCONN undergraduates participated in the solo portion of the tasks. The UCONN Institutional Review Board approved all recruitment and experimental procedures.

Task Design

The entire apparatus remained the same as in Experiment 1 and 2. The number of distances between targets was reduced from four to three (40, 60, 80 mm distances). They were presented in a random order with either Zero- or One-step Preview (Figure 12a). For Zero Preview, at any given time only one target was visible to the leader; the next target did not regenerate until the leader had tapped the current one (a setup that reportedly resembled the “whack-a-mole” sensation; Figure 12b). For One-step Preview, only two targets were visible on the tablet at any given time; this means only the $n+1$ *th* aim was previewable on the screen but not more than one

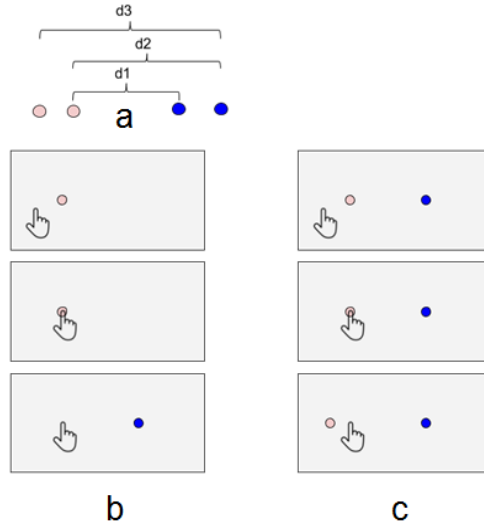


Figure 12. (a) Randomized inter-target distances drawn from $\{d1, d2, d3\}$. (b) The participant moves towards the n *th* target (top), taps the n *th* target (middle) and the $n+1$ *th* target appears (bottom) in the Zero Preview. (c) In the One-step Preview, the participant moves towards the n *th* target while the $n+1$ *th* target is also in view (top), taps the n *th* target and continues to $n+1$ *th* target (middle) while the $n+2$ *th* target appears (bottom).

aim ahead (Figure 12c). The $n+2$ *th* target location was randomly selected from 3 possible inter-target distances.

At the start of each condition, both targets were visible to the leader until one target was tapped by the follower.

Procedure

The general procedure remained the same as in Experiment 1, with the exception that movement was limited to the transverse direction. The critical addition was that the targets' location along that transverse direction changed within a trial. Participants were asked to always alternate tapping (between two colors) despite the changing target distances. Members of a pair took turns completing the solo trials, starting with a 30-aim practice session for each condition. While one participant was in the solo trials, the other waited outside the lab for approximately 10 minutes. After solo trials were completed, the lead and follow roles were assigned by drawing lots. As before, only the leader/navigator could see the targets and know the location of the next aim. A 30-aim joint practice session helped the dyad establish coordination and partnership as with the haptic coupling conditions in Experiment 2. The same instructions for how to connect via touch were applied.

Each individual participant performed 10 trials resulting from a within-subject design with 2 factors and 5 trial repetitions: 2 preview conditions (zero or one target ahead). Each dyad performed 6 trials resulting from a within-subject design with 2 factors and 3 trial repetitions. Each trial consisted of 120 aims where approximately 40 aims per 3 targets (40, 60, 80 mm

inter-target distances) were randomly distributed, lasting approximately 1-2 minutes. The entire experiment lasted 1 hour for each pair of participants. The order of preview conditions was counterbalanced.

Apparatus and Data Processing

The apparatus was the same as in Experiment 1 and 2. Using a customized Javascript tool, each trial's tap events were split by the distances so three sets of summary statistics were extracted for every trial, i.e. separated by the three distance conditions (40, 60 and 80 mm). As explained before, the top 5% (2-3 taps) of error and MT outliers were deleted from data analysis.

Statistical Consideration

See Experiment 2.

Results

Obtained ID. As in Experiments 1 and 2, the IDs were calculated using the distribution of absolute errors instead of displacement-specific errors. Table 8 summarizes the average ID values that each solo and dyad pair produced, separated by the preview condition.

Solo Trials. We began by investigating the validity of Fitts's law with respect to the solo data aggregated over the preview conditions. As before, a linear least-squares fit between Obtained ID and MT and their associated r^2 value was calculated for each solo participant. A summary of these results appear in Table 9. Overall, the numerical fit is not as strong as the solos' in Experiment 1 who operated in normal conditions, with the exceptions of P4, 5, and 6 with one preview. A reasonably strong linear relation between MT and ID was obtained for both preview conditions with the numerical fit better in one preview than zero preview condition (Figure 13); the correlation $r(104) = .62$ ($p < .001$) for zero preview and $r(104) = .72$ ($p < .001$) for one

Table 8

Average ID Produced By Every Solo (top) and Dyad (bottom) separated by Preview Condition.

	Zero Preview		One Preview	
	Min	Max	Min	Max
<i>Solo</i>				
P1	2.53	5.1	2.48	4.13
P2	3.51	5.00	3.58	5.21
P3	2.84	4.74	2.60	4.45
P4	3.42	5.15	3.48	5.26
P5	4.00	5.26	3.66	5.74
P6	4.15	5.51	3.91	5.32
P7	3.63	5.15	4.10	5.26
<i>Dyad</i>				
Pair 1	3.74	5.58	3.55	5.10
Pair 2	2.72	4.03	2.84	4.07
Pair 3	3.82	4.74	3.38	4.55
Pair 4	3.7	5.38	3.51	4.86
Pair 5	3.13	4.86	3.02	4.38
Pair 6	3.85	4.86	3.35	4.70

preview. There is also a reasonably strong, negative linear relation between error and movement time, with the overall correlation $r(104) = -.62$ ($p < .001$) for zero and $r(104) = -.58$ ($p < .001$) for one preview. Fitts's law and the speed-accuracy trade-off is observed in both preview conditions.

Table 9

Average Fitts line fits (r^2) as a Function of Preview Condition for Solos.

Participant	P1	P2	P3	P4	P5	P6	P7
Zero Preview	0.48	0.08	0.19	0.12	0.57	0.33	0.24
One Preview	0.33	0.09	0.30	0.70	0.73	0.71	0.42

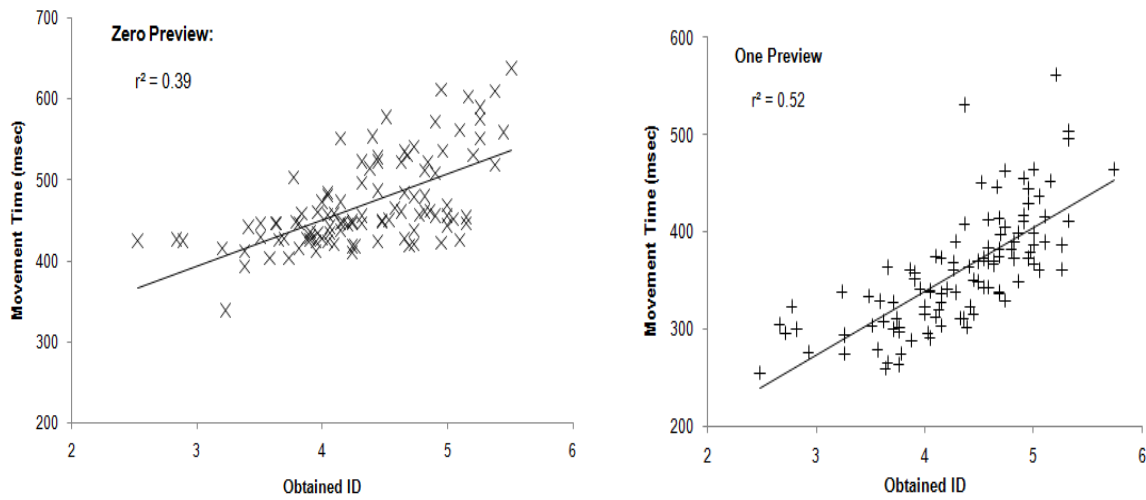


Figure 13. Data for the seven individuals (not averaged). (left) The relation between MT and obtained ID in zero preview. (right) The relation between MT and obtained ID in one preview.

The performance measures of interest for each participant were calculated to systematically examine the effect of preview condition and distances. Respectively, trial average movement time, error and endpoint variability are submitted to a two-way repeated measures ANOVA with within-subject variables: preview (Zero vs. One) and distances (40, 60, and 80 mm).

The analysis on movement time revealed two main effects: As expected, solo participants slowed down as the distances increased (40 mm: 387.83, 60 mm: 416.81, 80 mm: 439.50), $F(1.28, 43.75) = 121.35, p < .001, \eta_p^2 = .78$. Importantly, participants were about 100 ms faster in the One Preview condition ($M = 469.75, SD = 54.62$) than in the Zero Preview condition ($M = 359.67, SD = 60.10$), $F(1, 34) = 228.01, p < .001, \eta_p^2 = .87$. In addition, there is a significant interaction: Preview \times Distance, $F(2, 68) = 6.32, p = .007, \eta_p^2 = .16$. Figure 14 showed further that at longer distances (i.e., 60 mm and 80 mm), the speed differences are significant for one preview ($p < .01, \eta_p^2 = .17$) but not for zero preview ($p > .10, \eta_p^2 < .10$).

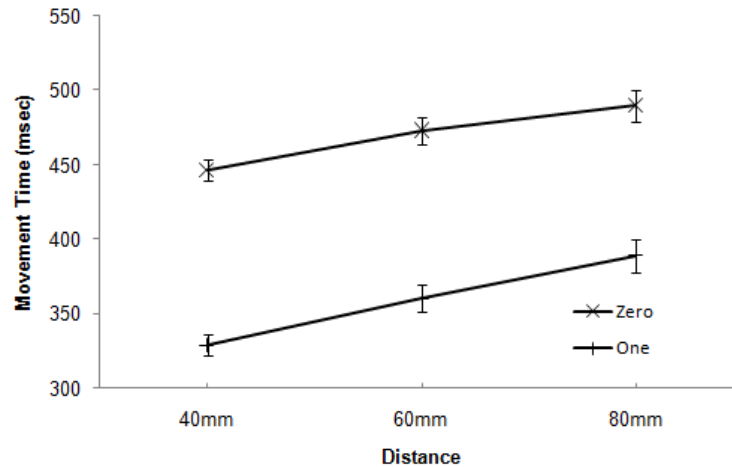


Figure 14. Average movement time as a function of distance and preview condition in solos.

The analysis on error revealed a main effect of preview condition and an insignificant Preview \times Distance interaction. Importantly, solo participants were less accurate in One Preview condition ($M = 3.10$, $SD = .59$) than Zero Preview ($M = 2.78$, $SD = 1.03$), $F(1, 34) = 6.69$, $p = .014$, $\eta_p^2 = .16$. The distance variable however, did not discriminate the errors significantly (40 mm: 2.95, 60 mm: 2.94, 80 mm: 2.92), $p > .5$, $\eta_p^2 < .01$.

No significant main effect or interaction was found in the analysis of endpoint variability. The level of precision was comparable across distances (40 mm: 1.41, 60 mm: 1.42, and 80 mm: 1.42) and between the Zero ($M = 1.37$, $SD = .46$) and One ($M = 1.46$, $SD = .61$) preview conditions, all $ps > .10$, $\eta_p^2 < .01$.

Dyad Trials Dyads were all haptically-coupled in Experiment 3. The scatterplot characterization of aggregated dyad data suggests that the overall behavior obeys Fitts's law with the numerical fit better in the Zero preview condition (Figure 15). Moreover, in the aggregate data the correlation between MT and ID is reasonably strong in both the Zero preview, $r(57) =$

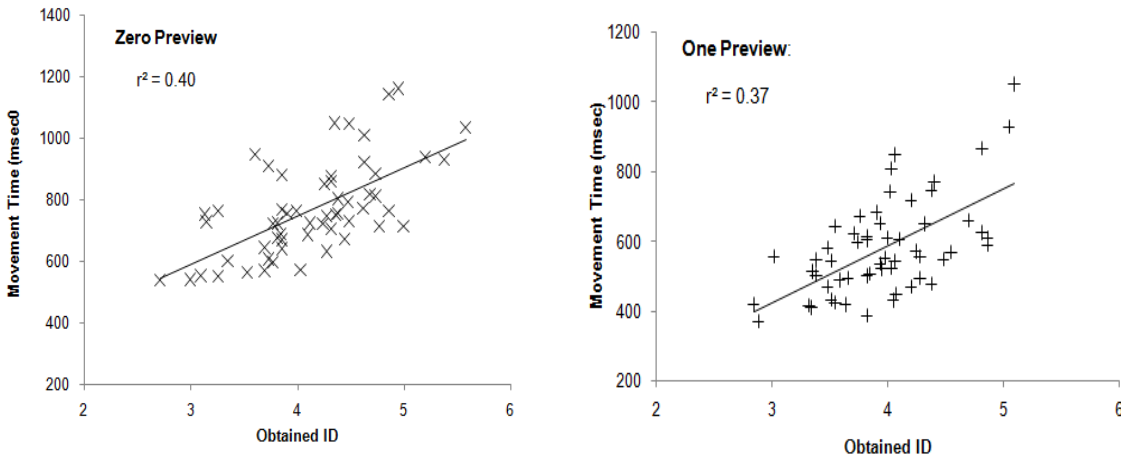


Figure 15. Data for the six dyads (not averaged). The relation between MT and obtained ID in (left) Zero preview, and (right) One preview.

.63, $p < .001$, and One preview condition, $r(57) = .61$, $p < .001$. To reiterate, Fitts's law was observed in the dyad data in Experiment 3. A linear least-squares fit between Obtained ID and MT and their associated r^2 value was calculated for each dyad pair. A summary of these results appear in Table 10. The numerical fit is reasonable for the majority of dyads especially considering that the average line fit in the comparable condition in Experiment 2, that is the transverse and haptic coupling condition, is 0.32.

Table 10

Average Fitts line fits (r^2) as a Function of Preview Condition for Dyads.

Dyad	P1	P2	P3	P4	P5	P6
Zero Preview	0.42	0.34	0.63	0.76	0.53	0.24
One Preview	0.54	0.79	0.00	0.21	0.65	0.55

As with the solo trials, the performance indices for each dyad pair were calculated to systematically examine the effect of preview condition and distances. Respectively, these indices are submitted to a two-way repeated measures ANOVA with within-subject variables preview (Zero vs. One) and distances (40, 60, and 80 mm).

The analysis on movement time revealed two significant main effects. As expected, dyads slowed down as the distances increased, $F(2, 22.33) = 56.63, p < .001, \eta_p^2 = .76$ (40 mm: 601.18, 60 mm: 673.03, 80 mm: 745.39). Importantly, dyads were about 200 msec faster in the One Preview condition ($M = 580.28, SD = 138.36$) than in the Zero Preview condition ($M = 766.12, SD = 151.06$), $F(1, 18) = 87.57, p < .001, \eta_p^2 = .89$.

The analysis on error revealed a main effect of distance. As distances increased, the dyads became less accurate, $F(2, 25.32) = 5.34, p = .02, \eta_p^2 = .23$ (40 mm: 3.46, 60 mm: 3.63, 80 mm: 3.93). The dyads were on average equally accurate in the Zero preview ($M = 3.55, SD = 1.11$) and the One preview condition ($M = 3.78, SD = .92$), $p > .10, \eta_p^2 < .10$.

The analysis on endpoint variability also revealed only a main effect of distance. As distance increased, the dyads became less precise, $F(2, 34) = 5.76, p = .007, \eta_p^2 = .25$ (40 mm: 1.52; 60 mm: 1.76; 80 mm: 1.84). The level of precision is comparable in the Zero preview ($M = 1.64, SD = .66$) and the One preview condition ($M = 1.77, SD = .60$), $p > .10, \eta_p^2 < .10$.

Comparison between solo and dyad performance Unlike in Experiment 2, Fitts's law was present in the aggregated dyad data as well as the solo data (Figure 13 and 15). Preview condition affected solo speed and dyad speed in the same way: Both solo and dyads were, on average, faster in one preview than in zero preview; dyads' speedup was two times solos' speedup. Preview condition affected solo error but not dyad error. However, the means showed

that both solos and dyads were less accurate and less precise in the one preview condition than in the zero preview condition. These measures of interests for the solo and dyad performance were averaged and summarized in Table 11.

Table 11

Average Movement Time (MT in msec), Error (mm), Endpoint Variability (mm), and Fitts Line Fits (r^2) for All Solo and Dyad Trials.

	Zero Preview	One Preview
	<i>Solo</i>	
MT	469.75	359.68
Error	2.78	3.10
Endpoint Variability	1.38	1.46
r^2	0.29	0.47
	<i>Dyad</i>	
MT	766.12	580.88
Error	3.56	3.78
Endpoint Variability	1.61	1.75
r^2	0.49	0.46

To evaluate if the goodness of model fit differs in solo and dyad pairs over the two preview conditions, the individual r^2 values were submitted to a two-way mixed repeated-measures ANOVA with a within-subject variable (Zero vs. One preview) and a between-subject variable (solo vs. dyad). Numerical differences did not reach significance for either main effect or their interaction (all $ps > .10$, $\eta_p^2 > .15$).

Discussion

One main finding that the previous experiment (Chapter 4) uncovered is the haptic dominance effect: Amongst the three means of perceptual support, a haptic connection in dyads not only was the key to establish the linear relationship between obtained ID and movement time—that is, Fitts’s law—it also granted the dyads a movement time and precision advantage compared to visual coupling alone. In light of these findings, we eliminated the visual coupling *only* condition in which the haptic connection was absent. In this last experiment, dyads were assembled haptically with the addition of sight. Targets changed locations with each aim along the transverse direction. As before, only the leader could see them. The primary purpose of the experiment was to assess what impact the preview of targets would have on the Fitts task. The manipulation of being able to see the target locations either zero or one aim ahead of the current aim captures one important way that improvisation manifests in tango: The tango couple’s skills scale with their capability to improvise with each step, meaning to move through the changing floorspace without pre-planning of a set of movement vocabulary ahead of time.

Thus, the main hypothesis we explored was the mediation of the classic Fitts effect (i.e., the relationship between ID and speed) by the preview condition. The current results showed that Fitts’s law was present in the aggregated dyad data as well as solo data in both preview conditions (Figure 13 and 15, Table 9 and 10). This immediately implies two things. First, it demonstrates that the validity of Fitts’s law in the cyclical aiming Fitts task is independent of knowing where the target is next. This finding agrees with studies on the effect of visual occlusion on locomotion as well as cyclical aiming (Cullen et al., 2001; Elliott et al., 1994). Most impressive in cyclical aiming is the finding that participants could perform the Fitts task with

very little visual contact with the effector and the target (e.g., vision available only 20% of the time). Specifically, Elliott et al. (1994) manipulated the intermittency of the sight of the targets by having participants don liquid crystal spectacles that interfaced with interval timers. As the occlusion times increased stepwise from 80 ms up to 200 ms, the linear relationship between ID and MT was preserved while the slopes were rescaled by the degradation of visual continuity, with the higher loss of information corresponding to higher intercepts. This is consistent with our finding that both solos and dyads were faster when visual support was more continuous in the one look-ahead than the zero look-ahead condition (Table 11). However, unlike these kinds of studies, we would not attribute the Fitts performance with inadequate visual guidance to participants' having any kind of internal spatial representation of the task space. Such a representational account of the findings is often conveniently derived from the experimental apparatus (e.g., in Elliott et al., 1994, where inter-target distances stayed constant throughout the course of the intermittent visual sampling). In our case, the target location (distance) is not only randomly drawn from tap to tap, but also varies at random from trial to trial. By approximating a changing task environment, our experimental setup finds no utility in talk of an internal representation or spatial memory of "a static world." Such an account is part of a history of the internal model-based approach to the visual control of action that contrasts with the natural, on-line approach promoted by the current experiment (see Zhao & Warren, 2015, for a critical review of the two approaches). In the tradition of Gibson's (1958, 1979) emphasis on studying everyday action guided by information-L, the online control of action emphasizes the actor's coupling to the environment by means of visual information specific to a natural task (see Warren, 1998, 2009). The online approach thus contributes by identifying informational

variables, formulating control laws that relate information to movement, as well as characterizing the emergent dynamics of the movement at the organism-environment level (e.g., Bruggeman, Zosh, & Warren, 2007; Harrison & Richardson, 2009; Michaels & Oudejans, 1992). That said, how does the current experiment fit in? We crafted an experimental task that falls into the proper domain of online control, where the visual preview information is what naturally constrains the dancer(s) to complete the stepping task that is Fitts-like on a dance floor. Our task summoned the natural perception and action resources (e.g., preview of a future environment) that would constrain the activity of interest. But we have not contributed by identifying how the control comes about or *how* the coordination tasks are informationally-guided. There has been exemplar work at such a level of analysis. For example, Meerhoff, De Poel, and Button (2014) manipulated the segmental versus global presentation of information by studying how following a forward-backward moving avatar differed from following a sphere. It was demonstrated that the rate of global optical expansion can directly specify keeping distance in such cyclical whole-body coordination tasks, as discrete interceptive tasks have shown before (Menuch & Gobbi, 2012; Rio, Rhea, & Warren, 2014; Warren, Kay, Zosh, Duchon, & Sahuc, 2001). With granular measurements, Meerhoff et al. (2014) were also able to show that segmental information provides a temporal synchrony advantage by enabling earlier anticipation, for instance, preparing foot placement or tilting the body before direction changes. These findings not only are about informationally-guided coordination but also strive to show task-specific differences. As to the current experiment, future work may provide a fine-grained analysis of how the movement is organized online *differently* over different preview conditions to achieve the same Fitts pattern.

In comparison to data in Experiment 2, obstruction of the future view slowed all participants down, including both solos and dyads. The dyads in the zero preview condition not only are the slowest in all current comparisons (Table 11), but are also slower than dyads moving with no obstruction of the future view in the same direction and coupling, namely haptic and visual coupling (mean = 435.89 ms). Another finding from the current experiment's ANOVA results is that solos are significantly less accurate in the one preview than the zero preview condition, which is expected by Fitts's law while, in contrast, how far one sees into future did not seem to distinguish dyads' accuracy. It is difficult to rule out that this difference between solo and dyad performance is due to dyads being altogether slower than solos doing the task, that is, it takes longer to move together with another person, thereby enhancing spatial accuracy by virtue of the conditions of Fitts's law. Regarding the finding that preview condition did not yield differences in dyad accuracy, it is possible that dyads moved so slowly in the zero preview condition that spatial constraints on the task were obliterated. One caveat of the current experiment lies in not having a record of time spent in contact with the target, namely, dwell time. Previous research (Elliott, Pollock, Lyons, & Chua, 1995) that derived dwell time from the time spent transporting the limb from target to target showed that an Occlusion \times ID interaction is still present in limb transport time alone. Nonetheless, future attempts should still register dwell time in order to reveal whether solos and dyads adopt different strategies (e.g., "waiting on" a target for different amounts of time until the future is visible).

Moreover, by comparing our error and MT results to those of Experiment 2 in the same coupling condition, there is equivocal evidence suggesting that the unpredictability of the future seems to function as a constraint on spatial accuracy: Both solos and dyads are on average 1 - 2

mm more accurate in the current experiment than in Experiment 2 (Table 7 and 11). However, this global accuracy advantage might be confounded by the collective slowdown in the current experiment, as predicted by the speed-accuracy tradeoff. A more thorough comparison might be provided by adopting a time-minimization instruction (R. A. Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979), a close variant of the time-precision dual instruction of the Fitts task (cf. Carlton, 1994), namely, to have participants tap reciprocally between targets with full view of the future at a fixed speed defined by the speed exhibited in the current experiment.

CHAPTER 6

GENERAL DISCUSSION

The experiments reported here were intended to examine a kind of *coordination via informational coupling* found in everyday perception-action tasks involving joint action. Such actions are enabled by the flow of entangled Information-L via touch, sight and sound as individuals adjust to themselves, their action partners, and to the environment. Using the social dance of Argentine tango as a source of inspiration, we examined new behavioral comparisons that are particular to interpersonal coordination via touch beyond what has been considered in the HCI paradigms that dominate this domain. Thus, the present series of experiments provide the first exploration of the impact of haptic and optic coupling on the ability to perform movement tasks with another person using constraints found in dance. We did so by exploiting one of the most robust relations in all of human movement, that is, Fitts's law. We are the first to challenge the long-standing Fitts fit by using continuous error performance data to calculate actual target width (Experiment 1). We suspected that the influence of categorical, *a priori* target width manipulations on movement time is a red herring, that it is more a visual artifact, and is carried out throughout the decades by Fitts researchers for its convenience. The advantage of using the traditional binary outcome of error (either hit inside or outside of the circle) is that it is easy to track for both the experimenter and the participant and the outcome is scalar which is also easy to deal with. We showed that Fitts's law can be observed just as a direct consequence of inter-target distances and continuous measurement of accuracy. The correlation between $\text{Log}_2(2D/W)$ and MT, $r = .85$, is not much less than the traditional correlation values that typically exceed .90. Having successfully proved the optimized method, we took the same

apparatus to Experiment 2 and 3 to test our central theses. We showed that haptic information not only enables dyadic coordination (Experiment 2 and 3), but is also superior to visual information (Experiment 2) to enable dyadic coordination with unpredictable targets (Experiment 3) in the two-person cyclical aiming task.

As promised, our findings challenged the information-S grounding of traditional Fitts's law by showing that the putative information processing capacity is constantly rewritten by meaningful constraints such as the biomechanical limits of the body (i.e., the direction results obtained in Experiments 1 and 2), multiple informational sources (i.e., the coupling results in Experiment 2), and environmental unpredictability (i.e., the preview results in Experiment 3). As formulated in Chapter 1, Fitts's law is grounded in a direct analogy to Claude Shannon's theorem (Shannon & Weaver, 1949). We dubbed this grounding the Information-S grounding. To reiterate the earlier assertion, Shannon's theorem is motivated by a theory of information that excluded all references to meaning. Yet for more than six decades, Fitts's law derived from Shannon's theorem has been applied extensively to study human movement that demands a theory of meaning, a theory that deals with semantic information in the sense of information-L. Any natural form of human action, joint or solo, concerns the utilization of information-L, not mathematical and syntactical information, to adapt action to other actors and the environment (Michaels & Carello, 1981); optic, haptic and acoustic information in the sense of information-L is always needed to guide that action. As one principle of ecological psychology goes, meanings "write perception in the language of action" (p. 47, Michaels & Carello, 1981). Fitts's law sits somewhere between a model that has "loose verbal analogy and metaphor on one end and closed-form mathematical equations on the other" (p. 98, Mackenzie, 1992). The Shannon

information theory that Fitts's law drew its direct analogy from is inadequate to predict our current results. Indeed, others have raised the question too: What is the meaning of the human motor system's purported information-processing rate of 11 bits/second (Zelaznik & Forney, 2016)? In information theory, the capacity of the system is construed as a matter of signal to noise ratio. The theory considers any information-S as processing load that the given system needs to filter through. Considering information-S as *load* and information-L as *coupling*, dynamical systems makes contrary predictions about the effect of perceptual coupling. From the load perspective, multiple sources of feedback (e.g., haptic and visual), should decrease performance, inasmuch as this necessarily adds processing delay and noise, since the perspective assumes that each sensory "channel"³ is necessarily noisy. This is clearly not the case in our data especially when we revisit the results in Experiment 2. Given that the information is redundant in the haptic + visual condition, it should predict the weakest performance by the information processing perspective. Our results showed that adding visual information does not significantly change the dyads' Fitts performance while haptic information is crucial to the success of the task. This is unsurprising from an ecological-dynamical system theory (DST) perspective, where the differences in informational sources during interaction are meaningful (e.g., Harrison & Richardson, 2009; Richardson et al., 2005). Our results tally with the most recent evidence from the ecological-DST perspective suggesting a kind of multisensory benefit (Roy, Lagarde, Dotov, & Dalla Bella, 2017). When auditory and tactile unimodal and bimodal coupling with the

³ In the information-S model of communication, the concern is how to transmit information flow through the physical characteristics of the channel (e.g., copper wires) in such a way that maximizes the signal to noise ratio. The notion of channel in such a construal applies to the deterministic science of the inanimate and does not apply to animate bodies where sensory "channels" are replaced by complex "networks" (for a rigorous treatment, see West, Geneston, & Grigolini, 2008).

environment structure are compared, the entrainment performance on certain tasks is improved when the coupling is stronger, that is, when the ambient array is sampled across multiple sensory modalities.

Perhaps embodied cognition can provide another theoretical pathway that clarifies the distinction between Fitts's information-S grounding and current information-L grounding. The ideas in embodied cognition were developed to rescue the dead-end of a dis-embodied, representational account of cognition (and by proxy, movement) that seeded Shannon's information-processing theory. With the spirit of the time being all about telecommunication and data processing, the central nervous system (brain, for short) was conceptualized as the "central processing unit" and the person was conceptualized as engaging in the same symbol-manipulation process as a computer that takes in "bits" information and then outputs the results (e.g., on a teletype). Much work has already been done explicating how the representational theory of mind is bankrupt; we need not revisit it here (e.g., Chemero, 2011). It suffices to say that the major problem with the representational account is that the symbol-manipulating, data-crunching agent falls short of the real challenges in dealing with the world. But not all embodied cognition accounts would object to the abstract mathematical form of information processing. Some more conciliatory forms of embodied cognition (Beer, 1995; Brooks, 1991; Clark, 1997; Lakoff & Nunez, 2000) would not object that Shannon's equation is relevant to describing the effect of constraints on performance in a Fitts task. They would only object to the restrictive thesis that information processing is only formal symbol manipulation happening within the bounds of the brain. So, it is not impossible that, inasmuch as Fitts's law is empirically supported, it is so not only because of the rate of information *processing in the brain*

but also because of the way muscles and bones move, the way muscles and bones interact with surfaces, and the way the laws of mechanics constrain the interaction between limbs and surfaces. So Fitts's law is not about the brain but about the brain-body-environment system of dynamic exchanges. Obviously, given the current form of our experiments, this statement is weak because it promises but does not yet provide a specific proposal as to how the dynamics of hand movement leads to Fitts's law. As discussed in Experiment 2 and 3, the current work is admittedly lacking in its capacity to describe the dynamics of the individuals and dyads as complex systems comprising the coordination tasks. The current work contributes by developing a scalable method and identified novel coordination patterns that can inform future investigation at a much finer scope. Future work should take what was learned in West et al.'s (2008) rigorous study of "information" for sociobiological systems. For instance, West (1999, 2006) has derived an explanation of the special role of $1/f$ noise in complex systems on the basis of statistical mechanics and Shannon's equation. $1/f$ is a kind of multiscale Shannon-esque metric for sociobiological systems that are complex, have many layers of dynamics, and interact with each other through all these layers simultaneously.

Epilogue: Implications for the study of dance

The current study is an unprecedented, unique attempt to advance the current status of collaboration between psychological science and dance, in particular, dance improvisation. There has been a small but growing interest in dance within the bounds of cognitive science (Brick & Boker, 2011; Grove, 2005; Steven & McKechnie, 2005). However, the trend is to study what has been labeled neuroaesthetics (see review in Carroll & Seeley, 2013). Such studies investigate the neural concomitants of a person's observing a stereotypic dance movement or dancers' learning a

dance phrase. By doing so, dance is used primarily as a means but not the ends, to uncover different relevant neural “seats” in the brain. Strong and extensive concerns have been voiced against the fixation with relating dance events to happenings in the brain (Hagendoorn, 2012; Sheets-Johnstone, 2012). We will not repeat them here. Not only are current empirical approaches to dance limited in their tethering to neuroscience. Additionally, little attention has been paid to improvisation dance, with two exceptions. Cognitive psychologist Jeff Pressing (1984, 1988), with a background in jazz improvisation, has written extensively on the methods and theories of musical improvisation. His focus, however, was an individual performer’s skill requirements for improvisation. This leaves unexplored the question of what underlies improvisation at an interactive, interpersonal level. By directly bringing research on motor control from physical sciences and control theory, Pressing (1988) tried to codify problems of improvisation skills in terms of traditional motor control problems such as feedback (auditory, visual, tactile, and proprioceptive) and error correction. Although dance improvisation shares many qualities with music improvisation, taking the phenomena of dance improvisation seriously means to confront such joint action problems on their home turf, that is, the dancer interacting with the real world, made up by other dancers and the physical surround. The current experiments embodied the latter approach. Another exception is the proposal to study improvisation as self-organizing complex systems (Sgorbati & Weber, 2010). It bears promise, but the current stage of the proposal remains largely unspecific. Besides matching concepts from complex systems science with elements of improvisation dance, it does not generate further hypotheses and experimentation. The current thesis attempted to lead by a modest example, taking direct inspirations from tango and implementing them experimentally.

A promising future avenue for the study of dance from a natural, ecological perspective could come from studying improvisation as communication. One may forcibly represent the ever-changing and evolving communication processes in improvisation as information processing. A dancer encodes certain kinds of information into a movement signal which then passes to another dancer who decodes the signal and responds suitably. The continuous, mutually regulated nature of improvisation, as seen in the example of haptically-coupled tango dance, however, readily refuses being characterized as such. By definition, improvisation dance (in dyads or groups) is an exemplary communicative activity viewed from the dynamical system perspective. As a model of application, it has much to offer for scientists who study dynamics of communication and language development from the dynamical system perspective. As one example, it can build on current interpersonal coordination research programs studying movements seen in conversation as implementing an interpersonal synergy (Fowler et al., 2008; Fusaroli & Tuyen, 2012; Fusaroli, Raczaskzek-Leonardi, & Tuyen, 2013). The interpersonal synergy idea borrows insights from the ecological approach to movement (Bernstein, 1967; Turvey, 1977) to show how interlocutors flexibly form dialog, similar to how muscles form functionally-specific but not anatomically-specific, highly context-specific assemblies to create coherent movement—all the time, just as happens in ensemble (i.e., more than one person) improvisation dance. Improvisation is a signature of tango dance, and of many other forms of contemporary dance practice (see Buckwalter, 2010). By scratching the surface of improvisation, moreover, the methodology lends itself to accommodating fluid, functionally-appropriate and context-sensitive actions that are the hallmark of human movement and cognitive abilities. The non-engineered environments of everyday life are an open-ended source of constraints and

possibilities for action. The ability to discover and exploit these possibilities is comparable to the improvisation inherent to tango. One might argue that the ability for improvisation is what differentiates humans from machines that can be made or trained to perform a given task reliably but fail in the vagaries of coordination challenges.

References

- Accot, J., & Zhai, S. (1997). Beyond Fitts' law: models for trajectory-based HCI tasks. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems* (pp. 295-302). ACM.
- Beer, R. D. (1995). A dynamical systems perspective on agent-environment interaction. *Artificial Intelligence*, 72(1), 173-215.
- Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Elmsford, NY: Pergammon Press.
- Bootsma, R. J., Boulard, M., Fernandez, L., & Mottet, D. (2002). Informational constraints in human precision aiming. *Neuroscience Letters*, 333(2), 141-145.
- Brick, T. R., & Boker, S. M. (2011). Correlational methods for analysis of dance movements. *Dance Research*, 29, 283-304.
- Brooks, R. A. (1991). Intelligence without representation. *Artificial Intelligence*, 47(1-3), 139-159.
- Bruggeman, H., Zosh, W., & Warren, W. H. (2007). Optic flow drives human visuo-locomotor adaptation. *Current Biology*, 17(23), 2035-2040.
- Buckwalter, M. (2010). *Composing while dancing: An improviser's companion*. Madison, WI: University of Wisconsin Press.
- Carroll, N., & Seeley, W. P. (2013). Kinesthetic understanding and appreciation in dance. *The Journal of Aesthetics and Art Criticism*, 71(2), 177-186.

- Carlton, L. G. (1994). The effects of temporal-precision and time-minimization constraints on the spatial and temporal accuracy of aimed hand movements. *Journal of Motor Behavior*, 26(1), 43-50.
- Castro, M. (2005). *Tango: The structure of the dance, Vol. I*. www.Tango-discovery.com.
- Chemero, A. (2011). *Radical embodied cognitive science*. Cambridge, MA: MIT press.
- Clark, A. (1997). *Being there: Putting brain, body, and world together again*. Cambridge, MA: MIT press.
- Cos, I., Bélanger, N., & Cisek, P. (2011). The influence of predicted arm biomechanics on decision making. *Journal of neurophysiology*, 105(6), 3022-3033.
- Cos, I., Medleg, F., & Cisek, P. (2012). The modulatory influence of end-point controllability on decisions between actions. *Journal of Neurophysiology*, 108(6), 1764-1780.
- Crossman, E. R. F. W., & Goodeve, P. J. (1983). Feedback control of hand-movement and Fitts' law. *The Quarterly Journal of Experimental Psychology*, 35(2), 251-278.
- Cullen, J. D., Helsen, W. F., Buekers, M. J., Hesketh, K. L., Starkes, J. L., & Elliott, D. (2001). The utilization of visual information in the control of reciprocal aiming movements. *Human Movement Science*, 20(6), 807-828.
- Demos, A. P., Chaffin, R., Begosh, K. T., Daniels, J. R., & Marsh, K. L. (2012). Rocking to the beat: Effects of music and partner's movements on spontaneous interpersonal coordination. *Journal of Experimental Psychology: General*, 141(1), 49.
- Elliott, D., Chua, R., & Pollock, B. J. (1994). The influence of intermittent vision on manual aiming. *Acta Psychologica*, 85(1), 1-13.

- Elliott, D., Pollock, B. J., Lyons, J., & Chua, R. (1995). Intermittent vision and discrete manual aiming. *Perceptual and motor skills*, 80(3_suppl), 1203-1213.
- Fine, J. M., & Amazeen, E. L. (2011). Interpersonal Fitts' law: when two perform as one. *Experimental Brain Research*, 211(3-4), 459.
- Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47(6), 381-391.
- Fitts, P. M. (1992). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology: General*, 121(3), 262-269.
- Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology*, 67(2), 103-112.
- Fowler, C. A., Richardson, M. J., Marsh, K. L., & Shockley, K. D. (2008). Language use, coordination, and the emergence of cooperative action. In *Coordination: Neural, behavioral and social dynamics* (pp. 261-279). Springer Berlin Heidelberg.
- Fultot, M. F., Nie, L., & Carello, C. (2016). Perception-Action Mutuality Obviates Mental Construction. *Constructivist Foundations*, 1, 103-110.
- Fusaroli, R., Rączaszek-Leonardi, J., & Tylén, K. (2014). Dialog as interpersonal synergy. *New Ideas in Psychology*, 32, 147-157.
- Fusaroli, R., & Tylén, K. (2012). Carving language for social coordination: a dynamical approach. *Interaction studies*, 13(1), 103-124.
- Gentry, S. (2005). *Dancing cheek to cheek: Haptic communication between partner dancers and swing as a finite state machine*. (Unpublished doctoral dissertation). Massachusetts Institute of Technology, Cambridge, MA.

- Gentry, S., Feron, E., & Murray-Smith, R. (2005, August). Human-human haptic collaboration in cyclical Fitts' tasks. In *Intelligent Robots and Systems, 2005.(IROS 2005). 2005 IEEE/RSJ International Conference on* (pp. 3402-3407). IEEE.
- Gibson, J. J. (1958). Visually controlled locomotion and visual orientation in animals. *British Journal of Psychology*, 49, 182-194.
- Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton Mifflin.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.
- Grove, R. (2005). Show me what you just did. In R. Grove, C. Stevens, & S. McKechnie (Eds.), *Thinking in four dimensions: Creativity and cognition in contemporary dance* (pp. 37-49). Carlton, Victoria: Melbourne University Publishing.
- Guiard, Y. (1993). On Fitts's and Hooke's laws: Simple harmonic movement in upper-limb cyclical aiming. *Acta Psychologica*, 82(1), 139-159.
- Guiard, Y. (1997). Fitts' law in the discrete vs. cyclical paradigm. *Human Movement Science*, 16(1), 97-131.
- Guiard, Y. (2001, March). Disentangling relative from absolute amplitude in Fitts' law experiments. In *CHI'01 Extended Abstracts on Human Factors in Computing Systems* (pp. 315-316). ACM.
- Guiard, Y., Beaudouin-Lafon, M., & Mottet, D. (1999, May). Navigation as multiscale pointing: extending Fitts' model to very high precision tasks. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (pp. 450-457). ACM.
- Hagendoorn, I. (2012). Inscribing the body, exscribing space. *Phenomenology and the Cognitive Sciences*, 11(1), 69-78.

- Harrison, S. J., & Richardson, M. J. (2009). Horsing around: spontaneous four-legged coordination. *Journal of Motor Behavior*, 41(6), 519-524.
- Hoffmann, R. J. (1981). Evolutionary genetics of *Metridium senile*. II. Geographic patterns of allozyme variation. *Biochemical Genetics*, 19(1-2), 145-154.
- Hoffmann, E. R., Drury, C. G., & Romanowski, C. J. (2011). Performance in one-, two- and three-dimensional terminal aiming tasks. *Ergonomics*, 54(12), 1175-1185.
- Huys, R., Fernandez, L., Bootsma, R. J., & Jirsa, V. K. (2010). Fitts' law is not continuous in reciprocal aiming. *Proceedings of the Royal Society of London B: Biological Sciences*, 277(1685), 1179-1184.
- Kelso, J. A. S. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, 246(6), R1000-R1004.
- Kelso, J. A. S. (1995). *Dynamic patterns: The self-organization of brain and behavior*.
- Kovacs, A. J., Buchanan, J. J., & Shea, C. H. (2008). Perceptual influences on Fitts' law. *Experimental Brain Research*, 190(1), 99-103.
- Kugler, P. N., & Turvey, M. T. (1987). *Information, natural law, and the self-assembly of rhythmic movement*. Hillsdale, NJ: Erlbaum.
- Lakoff, G., & Núñez, R. E. (2000). *Where mathematics comes from: How the embodied mind brings mathematics into being*. NY: Basic books.
- Langolf, G. D., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, 8(2), 113-128.
- Latash, M. L. (1993). *Control of human movement*. Champaign, IL: Human Kinetics.

- Luce, R. D. (2003). Whatever happened to information theory in psychology? *Review of General Psychology*, 7, 183–188.
- MacKenzie, I. S. (1989). A note on the information-theoretic basis for Fitts' law. *Journal of Motor Behavior*, 21(3), 323-330.
- MacKenzie, I. S. (1992). Fitts' law as a research and design tool in human-computer interaction. *Human-Computer Interaction*, 7(1), 91-139.
- MacKenzie, I. S., & Buxton, W. (1992, June). Extending Fitts' law to two-dimensional tasks. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 219-226). ACM.
- MacKenzie, C. L., Marteniuk, R. G., Dugas, C., Liske, D., & Eickmeier, B. (1987). Three-dimensional movement trajectories in Fitts' task: Implications for control. *The Quarterly Journal of Experimental Psychology*, 39(4), 629-647.
- Marsh, K. L., Richardson, M. J., & Schmidt, R. C. (2009). Social connection through joint action and interpersonal coordination. *Topics in Cognitive Science*, 1(2), 320-339.
- Matthis, J. S., Barton, S. L., & Fajen, B. R. (2015). The biomechanics of walking shape the use of visual information during locomotion over complex terrain. *Journal of Vision*, 15(3), 10-10.
- Matthis, J. S., & Fajen, B. R. (2014). Visual control of foot placement when walking over complex terrain. *Journal of Experimental Psychology: Human Perception and Performance*, 40(1), 106.
- Meerhoff, L. A., De Poel, H. J., & Button, C. (2014). How visual information influences coordination dynamics when following the leader. *Neuroscience Letters*, 582, 12-15.

- Menuchi, M. R. T. P., & Gobbi, L. T. B. (2012). Optic flow contribution to locomotion adjustments in obstacle avoidance. *Motor Control*, 16(4), 506-520.
- Michaels, C. F., & Carello, C. (1981). *Direct perception*. New York: Prentice Hall.
- Michaels, C. F., & Oudejans, R. R. D. (1992). The optics and actions of catching fly balls: Zeroing out optical acceleration. *Ecological Psychology*, 4, 199-222.
- Mottet, D., & Bootsma, R. J. (1999). The dynamics of goal-directed rhythmical aiming. *Biological Cybernetics*, 80(4), 235-245.
- Mottet, D., & Bootsma, R. J. (2001). The dynamics of rhythmical aiming in 2D task space: Relation between geometry and kinematics under examination. *Human Movement Science*, 20(3), 213-241.
- Mottet, D., Bootsma, R. J., Guiard, Y., & Laurent, M. (1994). Fitts' law in two-dimensional task space. *Experimental Brain Research*, 100(1), 144-148.
- Mottet, D., Guiard, Y., Ferrand, T., & Bootsma, R. J. (2001). Two-handed performance of a rhythmical Fitts task by individuals and dyads. *Journal of Experimental Psychology: Human Perception and Performance*, 27(6), 1275.
- Nie, Caban, & Marsh, (2015). Comparing solo and joint syncopation shows dyadic facilitation. In *Studies in Perception and Action XIII: Eighteenth International Conference on Perception and Action* (p. 69). New York, NY: Psychology Press.
- Pellegrini, R., & Ciceri, M. R. (2012). Listening to and mimicking respiration: Understanding and synchronizing joint actions. *Review of Psychology*, 19(1), 17-27.
- Pressing, J. (1984). Cognitive processes in improvisation. *Advances in Psychology*, 19, 345-363.

- Pressing, J. (1988). Improvisation: methods and models. In John A. Sloboda (Ed.) *Generative processes in music* (pp. 129-178). Oxford, UK: Oxford University Press.
- Reed, K. B., & Peshkin, M. A. (2008). Physical collaboration of human-human and human-robot teams. *IEEE Transactions on Haptics*, 1(2), 108-120.
- Reed, K., Peshkin, M., Colgate, J. E., & Patton, J. (2004, April). Initial studies in human-robot-human interaction: Fitts' law for two people. In *Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE International Conference on* (Vol. 3, pp. 2333-2338). IEEE.
- Richardson, M. J., Marsh, K. L., Isenhower, R. W., Goodman, J. R., & Schmidt, R. C. (2007). Rocking together: Dynamics of intentional and unintentional interpersonal coordination. *Human Movement Science*, 26(6), 867-891.
- Richardson, M. J., Marsh, K. L., & Schmidt, R. C. (2005). Effects of visual and verbal interaction on unintentional interpersonal coordination. *Journal of Experimental Psychology: Human Perception and Performance*, 31(1), 62.
- Rio, K. W., Rhea, C. K., & Warren, W. H. (2014). Follow the leader: Visual control of speed in pedestrian following. *Journal of Vision*, 14(2), 4-4.
- Roy, C., Lagarde, J., Dotov, D., & Dalla Bella, S. (2017). Walking to a multisensory beat. *Brain and Cognition*, 113, 172-183.
- Schmidt, R. A., Zelaznik, H., Hawkins, B., Frank, J. S., & Quinn Jr, J. T. (1979). Motor-output variability: A theory for the accuracy of rapid motor acts. *Psychological Review*, 86(5), 415.
- Schmidt, R. C. (2007). Scaffolds for social meaning. *Ecological Psychology*, 19(2), 137-151.

- Schmidt, R. C., Carello, C., & Turvey, M. T. (1990). Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 227-247.
- Schmidt, R. C., Nie, L., Franco, A., & Richardson, M. J. (2014). Bodily synchronization underlying joke telling. *Frontiers in Human Neuroscience*, 8, 633.
- Schmidt, R. C., & Richardson, M. J. (2008). Dynamics of interpersonal coordination. In A., Fuchs, V. K. Jirsa, (Eds.) *Coordination: Neural, behavioral and social dynamics* (pp. 281-308). Berlin, Germany: Springer Berlin Heidelberg.
- Sgorbati, S., & Weber, B. (2010). Deep and Broad are the Laws of Emergence? In Minai A., Braha D., Bar-Yam Y. (Eds.) *Unifying themes in complex systems* (pp. 11-18). Berlin, Germany: Springer Berlin Heidelberg.
- Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of information*. Urbana, IL: University of Illinois Press.
- Sheets-Johnstone, M. (2012). From movement to dance. *Phenomenology and the Cognitive Sciences*, 11(1), 39-57.
- Smyrnis, N., Evdokimidis, I., Constantinidis, T. S., & Kastrinakis, G. (2000). Speed-accuracy trade-off in the performance of pointing movements in different directions in two-dimensional space. *Experimental Brain Research*, 134(1), 21-31.
- Stevens, C., & McKechnie, S. (2005). Thinking in action: thought made visible in contemporary dance. *Cognitive Processing*, 6(4), 243-252.
- Strogatz, S. H. (1994). Nonlinear systems and chaos. Reading, MA: Perseus Publishing.

- Trenner, D. (2017a). The Argentine Social Dance. Retrieved from URL
<http://danieltrenner.com/the-argentine-social-dance/>
- Trenner, D. (2017b). The Argentine Social Dance. Retrieved from URL
<http://danieltrenner.com/the-basic-step/>
- Turvey, M. T. (1977). Preliminaries to a theory of action with reference to vision. In R. Shaw & J. Bransford (Eds.), *Perceiving, acting and knowing: Toward an ecological psychology* (pp. 211-265). Hillsdale, NJ: Erlbaum.
- Turvey, M. T., & Carello, C. (2011). Obtaining information by dynamic (effortful) touching. *Philosophical Transactions of the Royal Society B*, 366(1581), 3123-3132.
- Turvey, M. T., & Carello, C. (2012). On intelligence from first principles: guidelines for inquiry into the hypothesis of physical intelligence (PI), *Ecological Psychology*, 24, 3-32.
- van der Wel, R. P., Knoblich, G., & Sebanz, N. (2011). Let the force be with us: dyads exploit haptic coupling for coordination. *Journal of Experimental Psychology: Human Perception and Performance*, 37(5), 1420.
- Vesper, C., & Richardson, M. J. (2014). Strategic communication and behavioral coupling in asymmetric joint action. *Experimental Brain Research*, 232(9), 2945-2956.
- Vesper, C., van der Wel, R. P., Knoblich, G., & Sebanz, N. (2011). Making oneself predictable: Reduced temporal variability facilitates joint action coordination. *Experimental Brain Research*, 211(3-4), 517-530.
- Wall, S., & Harwin, W. (2000, July). Quantification of the effects of haptic feedback during a motor skills task in a simulated environment. In *Proc. Second PHANToM users research symposium*.

- Wang, J., Chellali, A., & Cao, C. G. (2015). Haptic Communication in Collaborative Virtual Environments. *Human Factors: The Journal of the Human Factors and Ergonomics Society*.
- Warren Jr, W. H. (1998). Visually controlled locomotion: 40 years later. *Ecological Psychology*, 10(3-4), 177-219.
- Warren, W. H. (2009). How do animals get about by vision? Visually controlled locomotion and orientation after 50 years. *British Journal of Psychology*, 100(S1), 277-281.
- Warren, W. H., Kay, B. A., Zosh, W. D., Duchon, A. P., & Sahuc, S. (2001). Optic flow is used to control human walking. *Nature Neuroscience*, 4(2), 213-216.
- West, B. J. (1999). *Physiology, promiscuity and prophecy at the millennium: a tale of tails* (Vol. 7). River Edge, NJ: World Scientific.
- West, B. J. (2006). Complexity, Scaling, and Fractals in Biological Signals. *Wiley Encyclopedia of Biomedical Engineering*, New York: NY, Wiley & Sons.
- West, B. J., Geneston, E. L., & Grigolini, P. (2008). Maximizing information exchange between complex networks. *Physics Reports*, 468(1), 1-99.
- Zelaznik, H. N., & Forney, L. A. (2016). Action-specific judgment, not perception: Fitts' law performance is related to estimates of target width only when participants are given a performance score. *Attention, Perception, & Psychophysics*, 78(6), 1744-1754.
- Zhao, H., & Warren, W. H. (2015). On-line and model-based approaches to the visual control of action. *Vision Research*, 110, 190-202.

Appendix A

A customized Web-Application written in Javascript, HMTL and CSS was used to draw and animate the targets [cite: <https://github.com/lin10001/fitts-experimenter>], running in a Chrome browser on a tablet. The experiments used a Pixel-C that has an LTPS IPS LCD capacitive touchscreen with a 10 inch display of 2560×1800 pixels with ~ 308 PPI pixel density. When touched by a finger the program records position in two dimensions at 120 Hz, with a pixel-level mean spatial accuracy of 5 pixels (0.4 mm) with standard deviation of 2 pixels. This provides a reliable measurement of the positional and timing accuracy in participants' fingertip contact with the tablet.

The program records an event each time the tablet is touched. This includes the location of the touch event in terms of X and Y coordinates, as well as the time in milliseconds of the touch event. The same X and Y coordinates are used to specify where the circles are displayed (see Figure A.1).

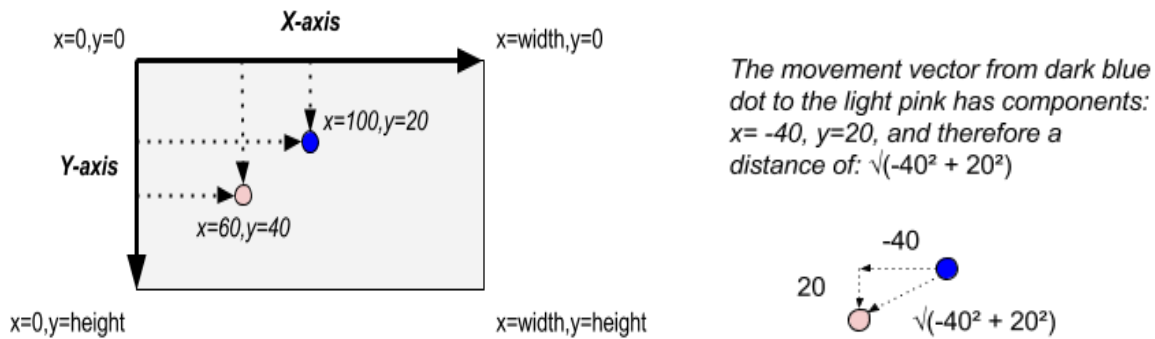


Figure A.1. The coordinate system used by the Fitts-Tango program.

Appendix B

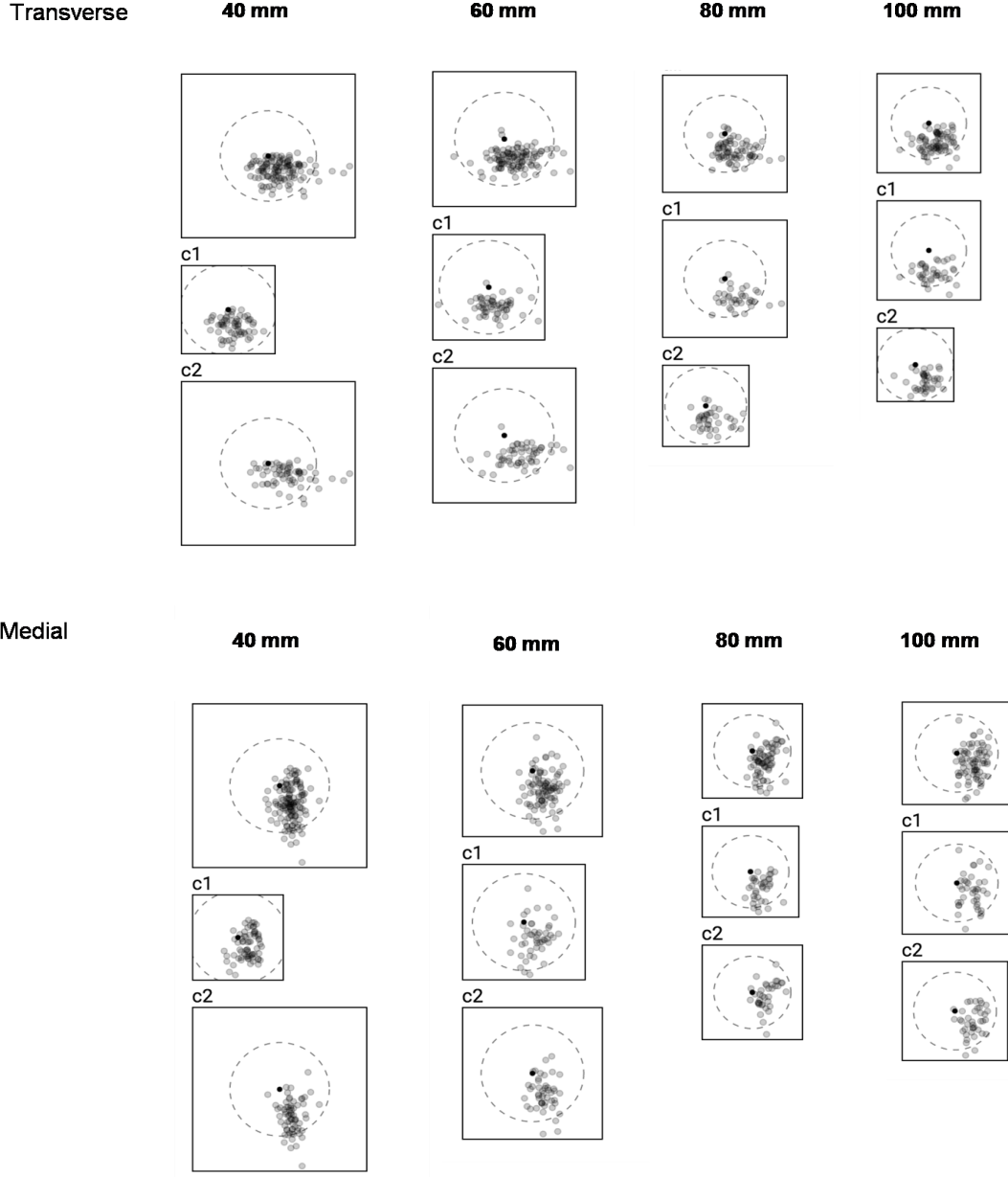


Figure B.1. The visualization plots.

Figure B.1 provides visualization plots for every single tap of a representative solo participant in the task space for two example trials in two directions. Within each direction, the top panel shows the aggregation of taps on the left target circle (=c1) and right target circle (=c2) altogether; the middle panel shows taps on the left target circle and the bottom panel shows taps on the right target circle. The dashed line indicates the cut-off value of the actual width W_A .