THE ROLE OF SPATIAL POSITION ON GAIT SYNCHRONIZATION DURING GROUP MOVEMENT

by

Wendy Lee Baccus
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of
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Committee:

_______________________________________ Director

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_______________________________________ Department Chairperson

_______________________________________ Program Director

_______________________________________ Dean, College of Humanities and Social Sciences

Date: _________________________________ Summer Semester 2019
George Mason University
Fairfax, VA

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Wendy Lee Baccus
Master of Arts
George Mason University, 2013
Bachelor of Arts
George Mason University, 2008

Director: James C. Thompson, Associate Professor
Department of Psychology

Summer Semester 2019
George Mason University
Fairfax, VA

DEDICATION

This is dedicated to my mother, Linda D. Baccus, who taught me that I could do anything I set my mind to, as long as I put in the hard work. I know you would be proud.

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I would like to thank the many people whose unwavering support gave me the strength I needed to accomplish the hardest thing I have ever done. To my dad, Leroy: thank you for keeping my spirits up, reminding me not to take things too seriously and for always being there to give me a hug. To my sister, Sonya: thank you for being my first paper editor, my educational cheerleader, and a shoulder to lean on. To my brother-in-law, Dan: thank you not only for housing, feeding, and assisting me with finances through my graduate career, but for being a steadfast caretaker with a joke or meme for every situation. To my twin sister, Kelly: for never letting me give up or complain for very long, for being my truth cannon and protector, but most of all, for being there every step of the way, whenever I needed you.

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LIST OF ABBREVIATIONS

Straight Line	StrL
Staggered Line	StgL
Inverted Triangle	InvT
Principle Component Analysis	PCA
Position 1	P1
Position 2	P2
Position 3	P3

ABSTRACT

THE ROLE OF SPATIAL POSITION ON GAIT SYNCHRONIZATION DURING GROUP MOVEMENT

Wendy Lee Baccus, Ph.D.

George Mason University, 2019

Dissertation Director: Dr. James C. Thompson

The human predisposition to synchronize bodily movements arises from an ecological need to nonverbally signal social bonds within growing social circles (Dunbar, 2012). Rhythmic coordination is accomplished through motor entrainment and simulation at the intra- and interpersonal levels (Repp & Su, 2013); however, the current field of literature lacks investigation into more than two interacting individuals (Hasson & Frith, 2016). This dissertation included three experiments with the aim of examining 1) spatial configuration as a means to alter the availability of cues to each individual during a synchronized walking paradigm 2) the impact of fluctuating leadership on group movement synchrony 3) how assigned leadership effects group movement synchrony. Participants were recorded using a motion capture system (NaturalPoint, Corvallis, OR) to study synchrony dynamics of gait measured using a marker on the right and left heel of each participant. Overall group synchrony, dyadic synchrony, and dyadic phase lag were

analyzed using linear correlation and a cluster phase quantification methods (Richardson, Garcia, Frank, Gergor, & Marsh, 2012). Overall, it was found that group synchrony changes with spatial configuration and that it is highest when participants are in a straight line and moving along straightaways as opposed to turns. Interestingly, when leadership is allowed to fluctuate and the group's turning behavior is centered on the axis of the individual (rather than the group), group synchrony during turns increased. Assigned leadership decreased overall group synchrony when the "leader" was not in view. Assigned leadership as measured in this dissertation had little impact on group synchrony. Accuracy with respect to leader identification played a minor role in terms of follower ability to synchronize with the leader and the group as a whole. Taken together, these experiments reveal the complex nature of group synchrony dynamics and the interplay between leadership roles and spatial position during movement.

CHAPTER ONE: INTRODUCTION

On average, human social communities consist of 150 individuals, of which approximately 20% of their waking hours are spent socializing (Dunbar, 2012). Even at the earliest stages of life, nonverbal coordination between caregivers and infants foster more secure attachments and healthier social bonds (Cappella, 1997). The need to express social bonds are not only reserved for kin or intimate relationships, but expand to friendships, with both weak and strong ties (Dunbar, 2012). Progressively increasing group size and our evolution to modern hominins requires more complex and sophisticated signals to foster a greater number of relationships. The establishment of social bonds, as described thus far, is only effective during one-on-one interaction and requires a great deal of energy. What needed to emerge were ways to boost social ties to more than one individual at a time that did not require direct contact. Dunbar (2012) proposed laughter as a mechanism to bridge social bonds in such a fashion, while others have emphasized the importance of other nonverbal gestures, like facial expressions (Frith, 2009); however, a particularly strong behavior responsible for uniting humans and other species is synchronized movement (Phillips-Silver, Aktipis, & Bryant, 2010).

Movement synchrony is an element of social behavior that is evident in many human activities ranging from rowing to dancing and singing, marching, or tapping in time together. Perceptual-motor couplings (Repp & Penel, 2004; Schmidt and Richardson, 2008) facilitate these interpersonal behaviors that emerge during social interaction to different degrees, as both magnitude and stability of movement synchrony can depend on a variety of factors, such as availability and reliability of perceptual cues (Chang, Livingstone, Bosnyak, & Trainor, 2017). Importantly, close inspection of temporal coupling can reveal the dynamic properties of synchronization or the "dynamic states which involve continuous mutual adaptation, the development of complementary behavior, and division of labor, such as leader/follower roles". In general, I will explore 1) how group movement synchrony manifests and changes at the level of the group and of the individual based on the availability of visual cues provided by other group members, 2) the impact of leadership stability on group movement synchrony 3) how assigned leadership effects group movement synchrony.

Presently, most studies investigating movement synchrony limit their comparisons to pairs of individuals, which only partially describe the complexity of interpersonal interactions. Theoretically speaking, Hasson and Frith (2016) emphasize the need for a "multiple-brain" frame of reference, which highlights the fact that humans are not always acting in isolation, but oftentimes in conjunction with others. They argue that interpersonal coordination occurs through the process of "alignment", which involves any interaction where information is exchanged between individuals. That information can be verbal in nature, as in a conversation between individuals, or non-verbal, such as facial expressions that indicate mood or rhythmic tapping of a finger (Konvalinka, Vuust, Roepstorff, & Frith, 2010). When individuals align as a group, they can be said to be in "we-mode". "We-mode" involves the communal representation of the environment, such that people acting together take each other's potential for action, goals, and knowledge into account, usually without awareness to achieve dynamic coordination (Hasson & Frith, 2016). The proposed research will not only inspect paired interactions, but global synchrony at the group level.

Intra- and Inter-Personal Rhythm during Movement Synchronization

But how does intentional movement synchrony occur and what components contribute to variability in group synchrony? A prevalent model of how interpersonal coordination happens is described by the dynamical systems account (Kelso, 1984; R. Schmidt & Turvey, 1994). This biological model of coupled oscillators is based on the premise that rhythmic movements are characterized by two competing states: a "maintenance tendency" and a "magnet effect" (von Holst, 1973). The "maintenance tendency" is described as a biological unit's resistance to entrainment due to its own preferred oscillation frequency (intrapersonal rhythm). The "magnet effect" facilitates entrainment as it is the opposing tendency for biological units to draw to each other's respective oscillation frequency (interpersonal rhythm). It is these measureable, reciprocal processes that characterize movement synchronization during a wide range of tasks including walking (Marmelat, Delignières, Torre, Beek, & Daffertshofer, 2014), swinging pendulums (R. Schmidt & Turvey, 1994), or rocking chairs (Richardson, Garcia, Frank, Gergor, & Marsh, 2012).

Phillips-Silver (2010) describes similar capacities: "self-entrainment" which is the ability to respond to self-generated rhythmic signals and "social entrainment" which is responding to the rhythmic signals of others. Levels of social entrainment characterize how synchrony emerges. Most often studied is the dyadic interaction or "mutual social entrainment" which results in an information processing loop, where output signals generated by one individual act as the feedback and subsequent input for another individual. The mechanism subserving this temporal coordination is motor simulation, which allows one to predict another's movement from running internal models of their own motor systems (Keller, Novembre, & Hove, 2014a). Expanding upon the mutual social entrainment level is the concept of "collective social entrainment" or the network of input and output connections that comprise the interactions of a group (Phillips-Silver et al., 2010). Broadly speaking, behavioral entrainment, whether spontaneous or with intent, is observed when individuals are able to detect, produce, and adjust to rhythmic events and characterizing this process at the level of the collective is a relatively recent endeavor.

Synchrony Strategy and Results Vary with Cue Source

Individuals maintain group synchrony by continuously correcting their movements based on the temporal cues available (Sanders & Donk, 1996). Humans can extract temporal cues from sources that provides a rhythmic beat, such as another individual or the pulse of a metronome (Honisch, Elliott, Jacoby, & Wing, 2016). Previous research suggests that cue modality (Chang et al., 2017a; Zivotofsky & Hausdorff, 2007), leader/follower roles (Elliott, Wing, & Welchman, 2014), and the number of other individuals available to synchronize with (Honisch et al., 2016) affect the strategy individuals adopt when synchronizing their movements.

Cue Modality

Zivotofsky et al. (2007) investigated the effectiveness of feedback modality in a side-by-side walking paradigm. Three conditions were included: walking using side-blinders to decrease the visual field and prevent subjects from seeing their partner, wearing headphones playing white noise, and having subjects walk while holding hands. Of those participants who spontaneously synchronized, tactile feedback resulted in the greatest level of in-phase synchrony. To accomplish group synchrony, individuals must infer what information each person in the group has perceptual access to, which varies between members depending on the situation (R. Schmidt & Richardson, 2008) and evidence suggests that availability of sensory information impacts synchronization variability and stability.

When auditory and tactile feedback is reduced during group performance, visual cues support sensorimotor synchronization. For example, when playing together, pianists achieved a greater degree of synchrony when they were able to see each other than when they were not, lending support to the beneficial properties of visual cues (Kawase, 2014). Also, piano players show greater body movement synchronization when auditory feedback is reduced (Goebl & Palmer, 2009). Chang et al. (2017) also manipulated availability of visual information in a study using a string quartet. Here, body sway was recorded in the four members while they played a musical piece. Each player was secretly given a leader or follower role to assess the magnitude and direction of information flow. Leaders had greater influence on followers regardless of whether or not they could see the others, but the presence of visual information selectively facilitates leader/follower couplings (Chang et al., 2017). Taken together, synchronization is adaptive depending on the availability and modality from which cues originate. When auditory and tactile feedback is unavailable, visual cues become the primary cue for temporal synchrony. Across modalities, tactile or haptic feedback appears to be the most informative during synchronization tasks.

Leader/Follower Roles.

Leader/follower roles also affect the exchange of sensory information between interacting individuals, and different strategies can lead to globally synchronous behavior. When considering a pair, A and B, movement synchrony could arise from a leader/follower coupling, such that person A is moving to their internal beat, and B follows A. Yet, this would be a one-way interaction because cues are passed along a chain from the leader (signal sender) to the follower (signal receiver) (Honisch et al., 2016). This relationship was evident in a quartet of string musicians, where the first violin acted as the leader with whom all the other musicians followed as they adapted more to her than she did to them, yet the group was synchronized together (Elliott et al., 2014).

Another possible scenario is a two-way interaction, as demonstrated in Kovalinka (2010). In a finger tapping paradigm, participant dyads were instructed to tap to a certain frequency while also tapping in time with their partner. Both parties could hear each other tapping. In this case, overall synchrony was defined as matching intervals between successive taps, which pairs were able to do; however, moment to moment interactions conveyed a greater picture of mutual adaptation. From tap to tap, if A was faster than B on one trial, A would slow down on the next trial to adapt. B also exhibited a similar pattern, and the extent to which each person adapted to their counterpart varied. Two-way interactions are evident at the trial level and reveal the importance of investigating the smaller windows of time that may better reflect the dynamics of movement synchrony. The strategy individuals adopt likely depends on whether or not participants have mutual access to temporal cues.

Multiple Cue Sources.

While the previously described interactions make sense when considering a pair of actors, less research exists describing the strategies for synchronizing when there is more than one person available to synchronize with. Honisch et al. (2015) explored how synchronicity varied as a function of cue source in a chain of individuals. Groups of six participants were positioned in a circle, facing outwards. The "leader" was presented with a metronome cue, with which they were to synchronize with, by vertically oscillating their right and left arm movements. The four individuals seated on either side of the circle were dubbed "followers", which meant they were to synchronize their bimanual arm movements with the person adjacent to them, towards the leader. The remaining individual seated at the end of the two tapping chains was called the "integrator", as their role involved combining signals received from the right and left tapping chains.

Two possible integrator strategies were hypothesized. Integrators could combine the sensory information to estimate the rhythmic structure, leading to reduced variability of asynchronies (Elliott et al., 2014). Alternatively, integrators could minimize the variability of their own movements, at the cost of increasing asynchrony variance, thereby increasing the predictability of their own movements (Vesper, van der Wel, Knoblich, & Sebanz, 2013). Results showed that timekeeping strategies differed depending on position in the chain; followers chose to focus on reducing their asynchrony variance with the sequential cue while those in the integrator position opted to reduce their own movement variability in the face of the two highly variable source cues provided by the followers at the end of each chain. Due to the propagation of error along the sequential chains, this study illustrates what an integrator is likely to do with two, highly variable signals and how synchronization strategy changes as a result.

While spatial configuration played a role in the experiments described above, it was never directly manipulated as a variable to alter the availability of cues to each individual during a synchronized task. Spatial position conveys cues for leader/follower roles, affects the exchange of visual synchrony cues, and offers the opportunity to provide multiple sources depending on the group configuration. I used spatial configuration as a variable across three experiments as it provides a unique way to explore several factors involved in group movement synchrony.

Leadership Stability and Turns

An aspect of ecologically realistic group coordination that is not well understood is the effect of fluctuating leadership as a function of turning during movement. For example, if making a 90 degree turn while walking parallel to another person, the inner individual will have to take a smaller step while the outer individual will need to take a large one, in order to remain parallel. This situation likely increases prediction demands and movement variability within the group that would not otherwise be captured when walking a straight line. Previous studies of walking behavior have been carried out along a straight path (Zivotofsky & Hausdorff, 2007) or on side-by-side treadmills (Nessler & Gilliland, 2009) which fails to address synchronization changes related to turning as group. This feature of movement behavior introduces room for variability associated with predicting interpersonal behavior in space and time.

While leadership dynamics have been an important factor in group synchrony as described previously, less research has allowed leadership roles to change *within a trial of study*. Another realistic scenario when walking within a group is that the leader of the group could change, depending on the direction of travel. This sort of behavior would reduce each individual's turning radius and each individual would be making taking the same approximate step to maintain the group configuration. This could increase signal reliability and minimize the interpersonal predictions one would have to make about how the rest of the group will take the turn (Vesper et al., 2013); however, less leadership stability could have the opposite effect. Alternating leaders could result in an increase in movement variability due to evolving strategies based on position and cue availability.

Leadership stability during turns could change group synchronization and experiment two of my work extends previous literature by investigating leadership stability while moving and the subsequent effects on group synchronization.

Assigned Leadership

When acting jointly, leader/follower roles can be assumed or assigned. For example, two people moving furniture must coordinate their movements, but who assumes the role of the leader and follower emerges during coordination. In contrast, leadership roles can be assigned, like first violinists playing classical period music in a quartet or the male counterpart of a couple performing the tango. A question that remains is how assigned leadership affects nonverbal group movement coordination.

Chang and colleagues (2017) experimentally manipulated the role of leadership in a string quartet and found that body sway is not simply a characteristic of music performance, but actually represents nonverbal communication amongst the group. More specifically, assigned leaders influence followers more than followers influence leaders or followers influence other followers. The followers use visual information provided by leaders to anticipate and coordinate their own actions with the leader. When no performers were secretly granted the role of leader while performing, synchronized movements increased from beginning to end of the musical piece, suggesting that the exchange of visual cues over time enhanced performance. Interestingly, the researchers exposed some differences in performance related to the intrinsic strength of leadership roles inherent in the musical period when comparing baroque and classical groups. Classical music is characterized by one instrument playing the melody while the others follow as accompaniment, whereas Baroque music lacks these distinguishing roles and as a result, the groups established different coordinative strategies. Classical music led to greater differences in default leadership than when compared to Baroque music, which shows that the strength of the structural elements of a situation can influence group movement synchrony.

While leadership may be inferred in my proposed experiments based on spatial position, as it was based on music period convention in Chang et al. (2017), experiment three will explicitly assign leadership roles by providing one of the three walking individuals with a metronome signal with which they are to synchronize, making them the leader, regardless of their present spatial position. This experiment will investigate how group synchrony is affected by the assignment of leadership.

Presently, research investigating interpersonal synchronization has focused on the interactions of dyads (Richardson et al., 2012), but a large gap exists exploring how three or more individuals behave when actively coordinating their movements. Bluedorn (2002) eloquently described the complexity of entrainment as “rhythms often being more powerful or dominant and capturing the rhythm of the other”, but not necessarily requiring that patterns exactly overlap; they may “maintain a consistent relationship with each other” (Bluedorn, 2002). My research harnesses the bodily coordination of participants in triads to explore gait synchronization and the complex relationships that underlie mutual adaptation, like those Bluedorn describes.

Rationale

The purpose of the current study is to characterize the dynamics of group synchronization while walking in groups of three individuals. To broadly examine factors that affect interpersonal coordination, this study included three experiments. The first experiment investigated how patterns of spatial configuration affect group synchrony. Specifically, does overall synchrony differ across walking configurations, and is this related to the number of sources (other people) visible to synchronize with? How do followers with more than one synchronization source integrate multiple cues?

The second experiment explored leadership stability by introducing fluctuating leadership roles while engaged in movement and sought to measure the subsequent changes in synchrony. Does synchrony improve or degrade with fluctuating leadership?

Lastly, the third experiment built upon the methods of the first, but also explored how a hidden (only provided to one individual of the three) auditory synchrony signal could alter group synchrony by assigning leadership. Can participants identify who possesses the signal? Does effective relay of the signal depend on position within a configuration? How well do followers synchronize with the signal holder in each position?

CHAPTER TWO: EXPERIMENT 1

The purpose of experiment 1 was to determine the effect of spatial configuration on group synchrony. More specifically, would synchrony improve with access to more visual cues from other individuals with which to coordinate? The experiment tested this question by manipulating the spatial configuration of the participants, thus influencing the availability of visual cues with which a follower can synchronize with. Overall, it was expected that synchrony would differ across walking configurations, and that synchrony would be best when the greatest number of synchrony cues were available to the follower.

The second question explored how synchrony could change as a function of the number of synchrony sources within each configuration. When walking in the straight line configuration, I predicted a decrease in synchrony along the chain; position one and position two would be more synchronized than position one and position three due to limited visual synchrony sources and the injection of noise along the chain of walkers (Honisch et al., 2016). The staggered line configuration would provide position three the ability to see both position one and position two, which could result in a number of interpersonal patterns. Position three could be more in synch with position two than position one, because position two is closer to them, providing a more salient cue. Position three could alternate stepping in time with position one and position two, demonstrating moments where they are more in synch with one or the other. Lastly, position three could attempt to integrate cues from position one and position two, resulting in a decrease in synchrony with position one and two, but an increase in the stability of their own intrapersonal stepping (Honisch et al., 2016). The inverted triangle configuration allowed position one and two peripheral visual cues while position three had equal access to position one and two. In this scenario, position three could attempt to integrate signals from position one and two as in the staggered line configuration. Position three could also direct their attention solely to position one or two, or alternate stepping in time with position one or two. The strategy used by position three may depend on the reliability of position one and two synchrony. If position one or two assumes a leadership role or position one and two are unable to use peripheral visual synchrony cues, reliability of their signals would change.

Methods

Participants

Participants included 24 right-handed female undergraduate students with normal or corrected vision from George Mason University and the surrounding community, for a total of eight groups made up of three participants (age range 18-30; average age 21; ethnicity: 38% White/Caucasian, 25% Asian, 25% Black/African American, 8% Other, 4% Hispanic/Latino). They were recruited from the George Mason University campus and community using flyer, emails, and social media posts. Participants signed a consent form in accordance with the Declaration of Helsinki and the Human Subjects Review

Board at George Mason University and were compensated for their time either through course credit or cash.

Task Design

First, participants were grouped into triads, matched for approximately for height with no pre-existing relationship to their other group members. Upon arrival to each experimental session, participants were outfitted with full body motion capture suits, and tracked using 41 retro-reflective markers placed onto the participant's body (see Figure 1). Markers of particular interest for analysis in this experiment included the right and left heel, as well as the four hip markers which defined the participant's center of mass, although all markers were placed to recreate the human skeleton accurately within the Motiv software (Motive, Version 2.0, 2017). Each session took place in a dance studio in George Mason University's School of dance, which houses the 20-camera Optitrack Motion Capture System (Motive, Version 2.0, 2017) that recorded participant movements at a rate of 120 frames per second.

Figure 1: Retro-Reflective Marker Configuration - only representative of the number and locations of the markers for all experiments.

Triad Configurations

The triad executed a continuous trial lasting 3 minutes in every position of the respective configuration. Participants completed as many laps as necessary to fill the 3 minute period. Positions were pseudo-randomized on each trial, so as to ensure that each participant walked in each role (i.e. P1, P2, and P3), two times for each configuration. Experiment 1 had trials of all three configurations.

Table 1: Position Allocation - The table shows an example of position allocation (role) for each participant for each trial. The numbers in the table refer to a specific participant. For example, '1' stands for participant 1 who in trial one was allocated the role of the Leader and in trial three the role of the follower one, and so forth. Participant's positions were counterbalanced and trial order was randomized, so that each participant performed two trials in each position.

Position	P1	P2	P3
Trial 1	1	2	3
Trial 2	1	3	2
Trial 3	2	1	3
Trial 4	2	3	1
Trial 5	3	1	2
Trial 6	3	2	1

Straight Line (StrL)

Participants were arranged in a single-file line, where the position was named in linear order, such that the first person in line (P1), is followed by the next person in line (P2), and is in turn followed by last person in line (P3). Order of the straight line was maintained regardless of the direction of movement (see Figure 2). For the sake of brevity, the Straight Line configuration will be referred to as "StrL" for the remainder of the paper.

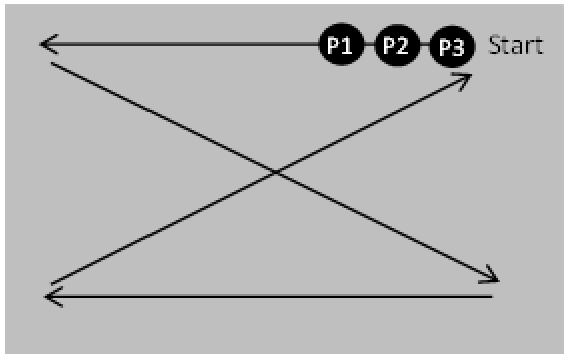


Figure 2: Straight Line (StrL) Configuration and Designated Walking Path (seen from above).

Staggered Line (StgL)

Participants were again, arranged in a single file line, but the position of P2 was offset towards the center of the space (approximately 1 arm-length away from the leader (P1) and the last person in line (P3), who was then able to see both P1 and P2, because P2 was no longer directly behind P1 and in front of P3). Order of the Staggered Line was maintained regardless of the direction of movement (See Figure 3). For the sake of brevity, the Staggered Line configuration will be referred to as "StgL" for the remainder of the paper.

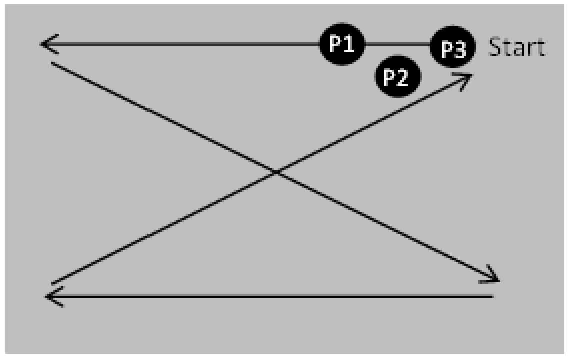


Figure 3: Staggered Line (StgL) Configuration and Designated Walking Path (seen from above).

Inverted Triangle (InvT)

Participants were arranged in the shape of an inverted triangle, where two participants acted as joint leaders, side by side (P1 and P2), with one follower (P3) who created the lower point of the triangle, walking behind P1 and P2. Order of the Inverted Triangle was maintained regardless of the direction of movement (see Figure 4). For the sake of brevity, the Inverted Triangle configuration will be referred to as “InvT” for the remainder of the paper.

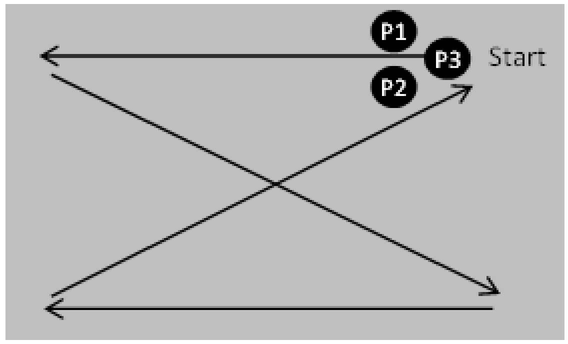


Figure 4: Inverted Triangle (InvT) Configuration and Designated Walking Path (seen from above).

Procedure

Following marker setup, the participants were shown the path they were to walk within the motion capture volume by the experimenter (see Figure 1,2, or 3) and practiced initiating their walk using a metronome signal. The metronome signal consisted of a 60ms tone played at a rate of 120 beats per minute, which is comparable to walking pace (Franek, van Noorden, & Rezny, 2014). Participants heard 12 beats at a lower frequency (meant to set their walking pace) and were signaled to start at the onset of 4 higher frequency tones, at which point they would take their first step upon presentation of the last beat. Participants followed the same path, regardless of the triad configuration. Each trial lasted three minutes and participants completed one trial per order permutation in each configuration. Participants were instructed to walk as normally and comfortably as possible, to maintain their spatial configuration for all trials, while striving to meet their primary goal, which was to synchronize their steps with one another, as a group. Participants were not given explicit instructions as to where to focus their gaze, thereby simulating the natural lack of restriction to vision during normal side by side walking where both individuals would likely vary the focus of their gaze; however, auditory cues were mitigated using wireless headphones and a white noise mask. Participants were also instructed not to converse with one another throughout the duration of the experimental session, since speaking and breathing patterns may influence synchronization and thereby provide a confounding variable to the analysis as illustrated by Shockley et al. (Shockley, Santana, & Fowler, 2003).

After each participant received their instructions and practiced the walking path with the experimenter, the triad was positioned at the start of the path in one of the three proposed configurations (order configuration was also randomized). Participants were prompted to start walking simultaneously while the motion capture system recorded their walking behavior. Participants executed all order permutations (n = 6) in each configuration (n = 3), resulting in a grand total of 18 trials which took approximately one hour. The experiment was repeated with eight triad groups total.

Data Acquisition and Analysis

Signal Pre-processing and Data Reduction

Motion trajectories were recorded using a three-dimensional motion analysis system (Motive:Tracker; OptiTrack, Corvallis, OR, USA) with 20 infrared cameras at a sampling rate of 120 Hz. To recreate the human form within the Motive software, I placed 41 reflective markers (7.9 mm) on the participants' head (3), torso (4), waist (4), shoulders (4), arms (4), hands (6), legs (6), and feet (10). Any missing data due to marker occlusion during recording was interpolated within the Motive software using a model-based approach, where the gaps were filled using corresponding expected marker positions for estimating the trajectory using the other skeleton markers and related skeletal segments to determine a reliable location of the marker during the occluded gap.

All data analyses were performed in MATLAB (Math Works, Natick, MA; https://www.mathworks.com/). A separate time series was calculated for each participant for each trial. Stride time series for each participant was defined by the heel marker on the right and left foot. The center of mass was calculated by averaging the four hip markers (right front, left front, right back, and left back). To remove translational information from the time series, the center of mass was subtracted from the stride data. This allowed for the study of the stride to stride dynamics, including those related to turning).

Principle Components Analysis

Previous studies investigating the kinematics of gait call for the a-priori selection of features, such as excursion, peak angle, and range of motion, all of which are extracted from the full gait waveform; however, this approach discards a large amount of potentially meaningful information (Phinyomark, Petri, Ibáñez-Marcelo, Osis, & Ferber, 2018). More recently, researchers have adopted principle components analysis as a means to compute a set of representative variables composed of motion across different markers and coordinate planes to describe the essential features of normal gait. Walking can be described by a relatively small set of features, given the predictable coordinated pendulum-like oscillations of the feet that alternate at a fixed rate (Daffertshofer, Lamoth, Meijer, & Beek, 2004).

Principle component analysis (PCA) is a dimension reduction technique that transforms a vector of size n to a unit vector of size k, where k is always smaller than n (see Figure 5). This analysis results in a new set of uncorrelated variables, principle components or (PCs) which are linear combinations of the original possibly correlated variables. Typically, the first few PCs capture the majority of the variance and the most dominant movement patterns (Phinyomark, Hettinga, Osis, & Ferber, 2015).

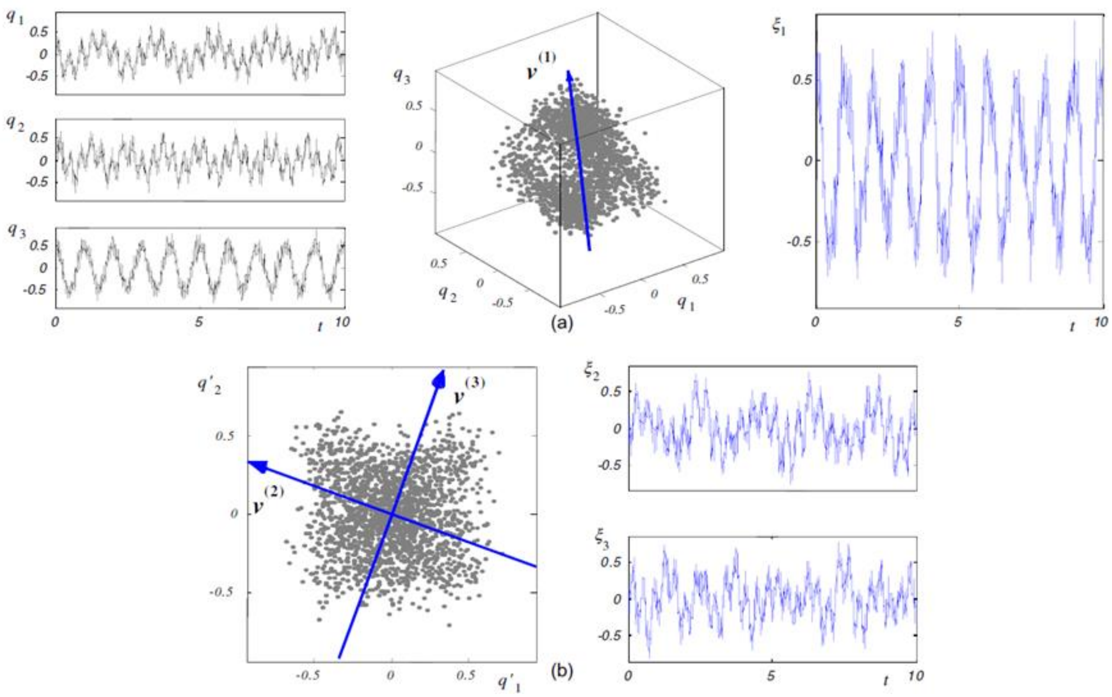


Figure 5: Example PCA data. (a) Geometrical determination of the first principal mode of a three-dimensional data set: (left panel) time series q1 ... q3; (middle panel) q1; ... ; q3 as point distribution in the corresponding vector space and (right panel) projection of the data on the first mode resulting in the corresponding time series n1—see text for further details. (b) Geometrical determination of the second and third modes corresponding to the three time series in (a): (left panel) point distribution in the vector space [q0 1; q0 2] that is orthogonal to the one shown in Fig. 5a and (right panel) projection of the data on the second and third mode resulting in time series n2 and n3—cf. Reprinted from "PCA in studying coordination and variability: a tutorial" by A. Daffertshoder, C. Lamoth, O. Meijer, and P. Beek, 2004, *Clinical Biomechanics, 19,* p.418.

To reduce the three dimensional Cartesian coordinate data into a comprehensive single dimension for analysis, I submitted the right and left heel stride time series of each participant for every trial into a principle components analysis. The final variable for each participant submitted for further analysis was defined by the first component of the PCA for each participant in each trial (see Figure 6).

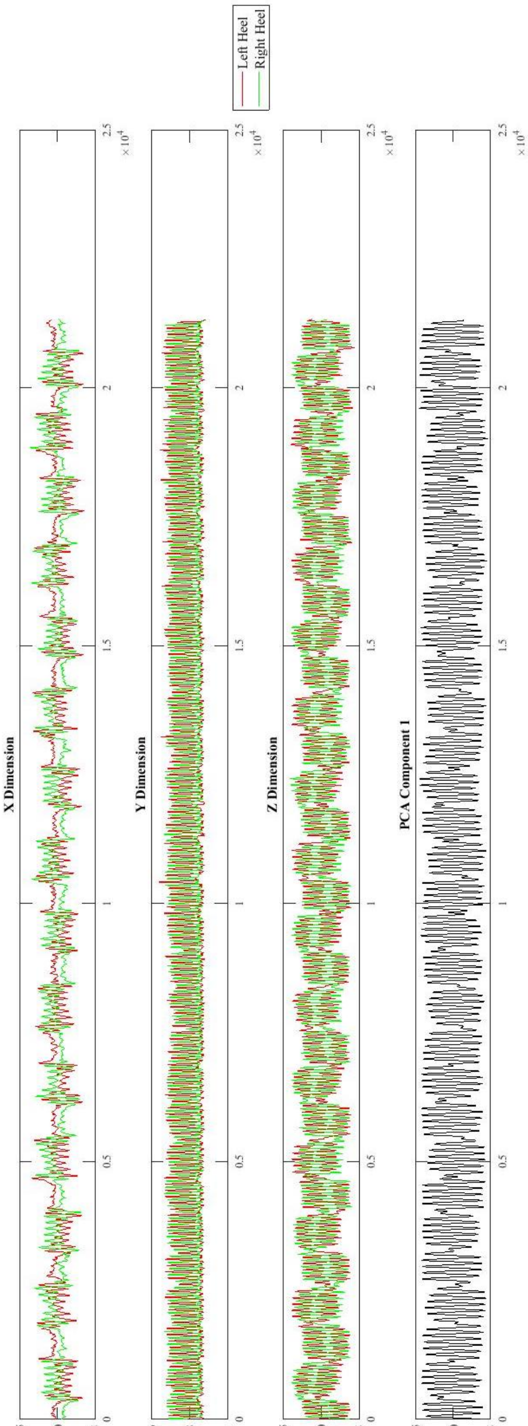


Figure 6: Raw Traces for the Left and Right Heel for one participant and the resulting first component of the PCA.

Movement Type - Turns and Straightaways

Because synchrony was expected to vary depending on whether or not the group was moving along a turn or a straightaway, each participant's data was categorized into turn and straightaway time points (see Figure 7). Over the course of a trial, these time points were identified by selecting the midpoint along each of the four turns and the four straight legs of a trial in addition to the 120 time points (one second) preceding and following the midpoint of each movement. All groups completed a minimum of five laps over the course of a trial throughout the experiment; resulting in 4,820 total turn time points and 4,820 total straightaway time points for each participant from each trial (40 seconds).

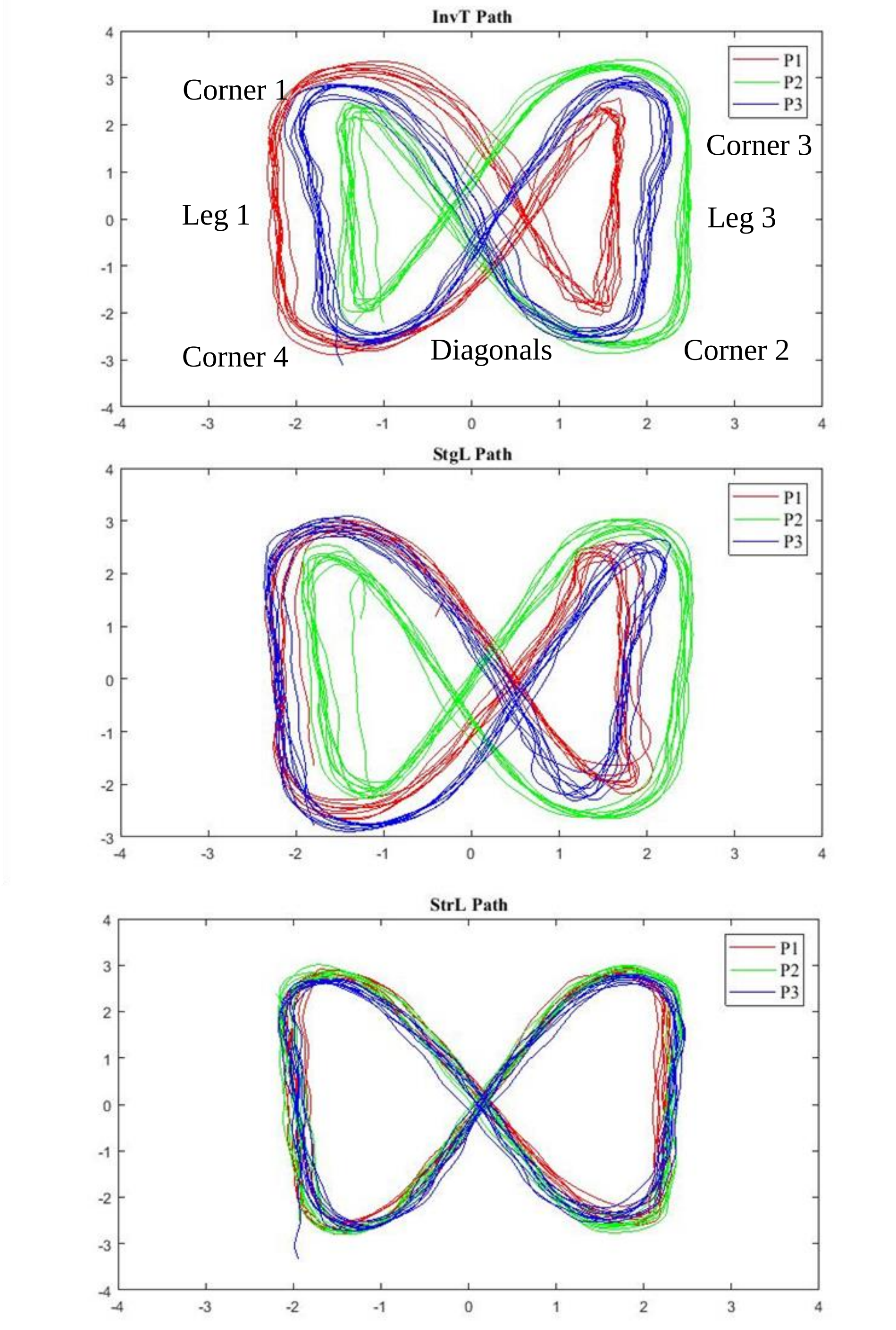


Figure 7: Experiment 1 Example Configuration Paths. Plotted is the center of mass for each member of one triad over the full course of one trial in each configuration.

Group and Dyadic Synchrony

The primary measures of interest included two forms of synchrony: group synchrony and dyadic synchrony. The distinction between the two measures is that group synchronization reveals the extent to all group members establish a “central” or collective group behavior, whereas dyadic synchronization measures the degree to which two individual group members synchronize their behavior when isolated from the rest of the group. Mean group synchrony reflects a mutuality and interdependence of influence between group members. Thus, measures of group level synchrony would be expected to relate to factors that lead to a strong sense of cohesiveness (Frank & Richardson, 2010). The benefit of investigating the dyadic level of synchrony is that it allowed me to empirically test the extent that synchrony emerges as a result of relatively unidirectional influences (Repp & Su, 2013).

To assess group synchrony, a cluster phase quantification method was applied as proposed by Frank and Richardson (2010). The Kuramoto based cluster phase method, originally used to describe the phase synchronization of a large set of oscillators, has been successfully applied to animal behavior like firefly flashing and collective chirping of crickets (Strogatz, 2000) as well as human applause (Néda, Ravasz, Brechet, Vicsek, & Barabási, 2000). This five step method is equipped to handle noisy, multivariate time-series analysis (Richardson et al., 2012).

Richardson et al. (2012) describes the analysis:

> First, the phase time-series for each participant movement time-series is calculated in radians. Second, the group phase time-series, or cluster phase

is calculated. Third, the relative phase for each individual's movements with respect to the cluster phase is calculated. Fourth, the mean relative phase and the degree of synchrony for every movement with the respect to the group behavior is established, and lastly, the degree of synchronization of the group as a whole at each time point is computed, where the closer the value is to one, the larger the degree of group synchronization. This results in a single measure of group synchrony for each trial and a continuous measure of group synchrony.

For each configuration, mean group synchrony was calculated by averaging the degree of synchrony as calculated by Richardson and colleagues (2012) for each positional permutation across the six trials (see Figure 8), resulting in three overall degrees of synchrony, one for each configuration (InvT, StgL, and StrL). This process was repeated for each triad group, where groups were treated as replications, as determined by a variance component analysis which revealed that less than ten percent of the variance in overall synchrony was due to the "Group" factor (Nan, Jenkins, McCarty, & Wu, 2016).

Stride time series were then submitted to a linear correlation analysis to assess dyadic synchrony between all position pairs of the experimental configurations (i.e. the first participant compared to the last participant in the straight line configuration, etc). The correlation between each position pair (P1 and P2, P1 and P3, and P2 and P3) was averaged across all triad groups to determine the level of synchronization between all positions across configurations.

Relative phase lag between dyads was also calculated to further describe the manner in which pairs were synchronized (since individuals can be synchronized, but out of phase), using a Hilbert transform for each pair of positions. To determine the confidence of these estimates I computed a sample of 1000 bootstrapped means of the relative phase lag for each position pair across all eight groups and recorded the upper and lower 25th percentile as confidence intervals. However, this was not considered to be a primary variable of interest for these experiments due to the circular nature of relative phase means. Such calculations are inconsequential for variable coordination and do not reflect a meaningful synchrony relationship.

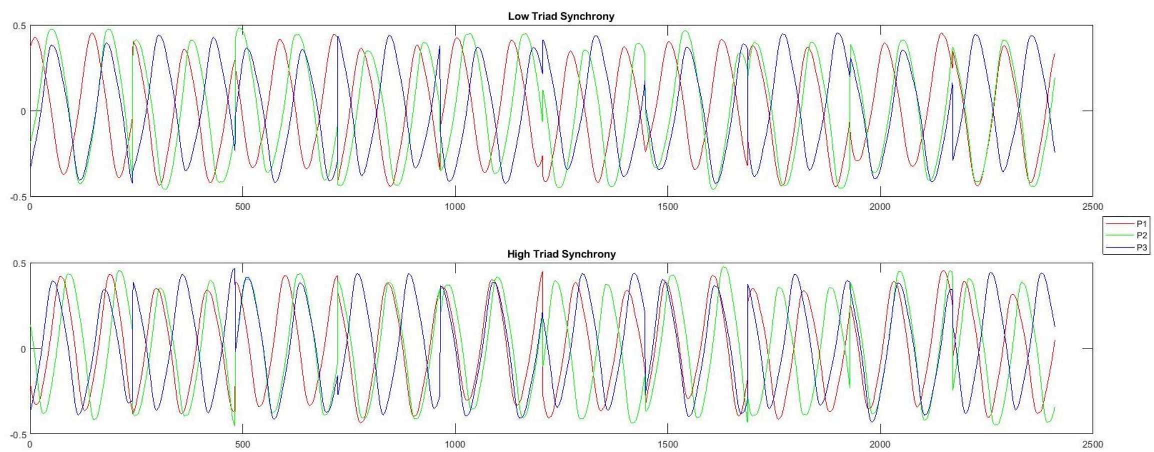


Figure 8: Example Low and High Synchrony Data. Seen here are the PCA values across all three triad members during the diagonal segment of the walking path from two different trials that resulted in low and high group synchrony.

Results

Group Synchrony

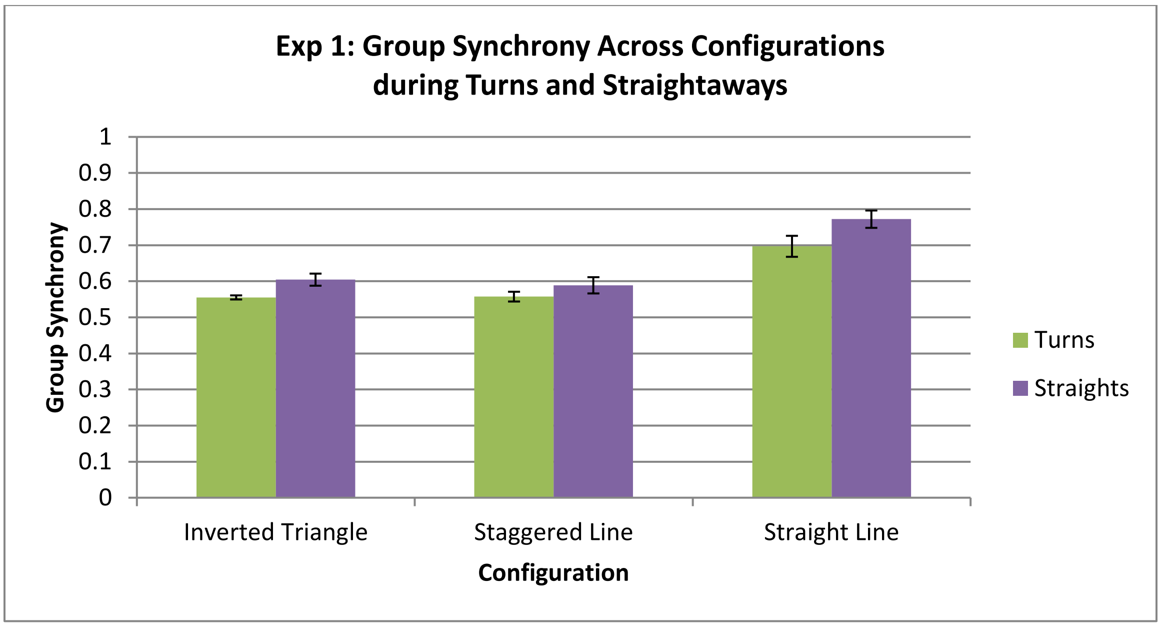


Figure 9: Experiment 1 Group Synchrony (mean ± SEM) across configuration during Turns and Straightaways. A two-way repeated measures ANOVA revealed main effects of configuration *F* (2, 14) = 42.750, p < .001 and movement type of *F* (1, 7) = 24.111, p = .002, p = .001, but no interaction *F* (2, 14) = 1.764, p = .207.

A 2x3 repeated measures ANOVA was conducted to examine the effects of configuration (InvT, StgL, and StrL) and movement type (Turns, Straights) on group synchrony (See Figure 9). The interaction effect between configuration and movement type on group synchrony was not statistically significant, *F* (2, 14) = 1.764, p = .207;

however, there was a significant main effect of configuration, *F* (2, 14) = 42.750, p < .001, which demonstrates that mean group synchrony was higher for the StrL configuration (*M* = .74, CI [.68, .79]) than it was for the StgL (*M* = .57, CI [.54, .61])) and the InvT. (*M* = .58, CI [.56, .60]) configurations. The main effect of movement type yielded an F ratio of *F* (1, 7) = 24.111, p = .002, indicating that the mean change score was significantly greater for straightaways (*M* = .66, CI [.62, .69]) than for turns (*M* = .60, CI [.58, .63]).

Dyadic Synchrony

A 2x3x3 repeated measures ANOVA was conducted to determine the effects of movement type (turns/straights), position pairs (P1 with P2, P1 with P3, and P2 with P3), and configuration (InvT, StgL, and StrL) on dyadic synchrony (See Figure 10). While there was not a significant three-way interaction, *F* (4, 28) = 1.293, p = .297, there was a significant two-way interaction between configuration and position pairs, F(4,28) = 8.646, p < .001. Subsequent simple main effects analysis showed that for the InvT configuration, dyadic synchrony was higher between P1 and P3 (M = .69, CI [.67, .71]) than it was for P1 and P2 (M = .67, CI [.66, .67]), p = .037. In addition, for the StrL configuration, dyadic synchrony was significantly higher between P1 and P2 (M = .81, CI [.77, .85]) than it was for P1 and P3 (M = .73, [.69, .78], p = .013) or P2 and P3 (M = .76, CI [.71, .81], p = .002).

In addition, there was a significant main effect of configuration, *F* (2, 14) = 29.267, p <.001, such that the mean group synchrony for the StrL (*M* = .77, CI [.73, .81]) was higher than for the InvT (*M* = .68, CI [.66, .70]) or the StgL (*M* = .68, CI [.66, .71]). Also, there was a main effect of movement type, F (1, 7) = 13.756, p = .008, where synchrony was higher for straights (M = .73, CI [.70, .76]) than turns (M = .69, CI [.67, .71]).

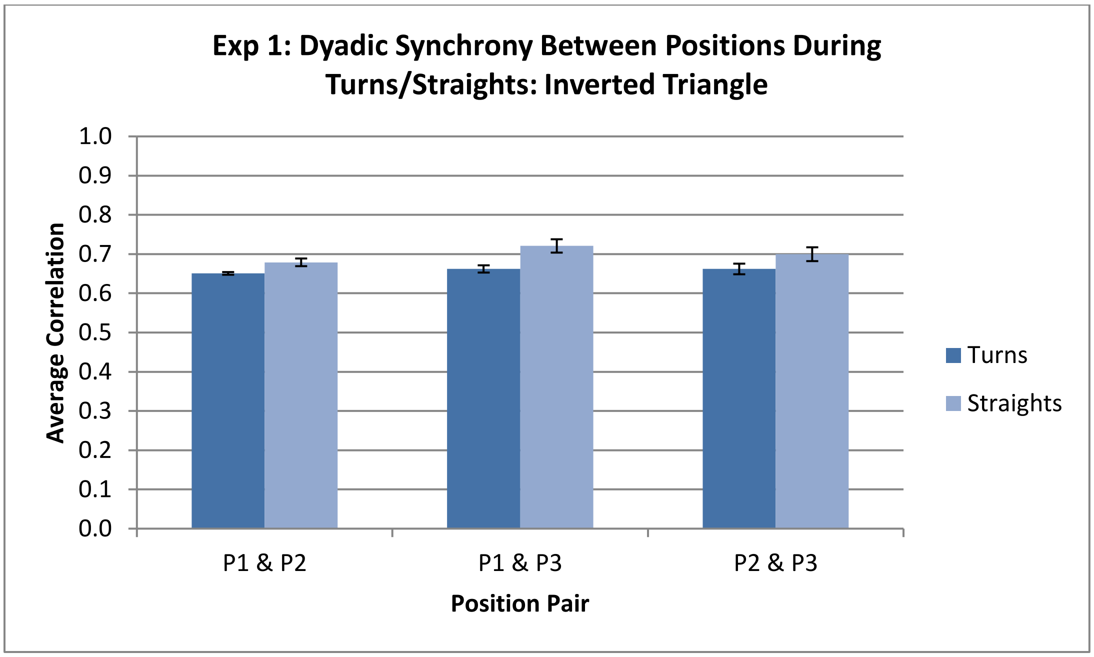
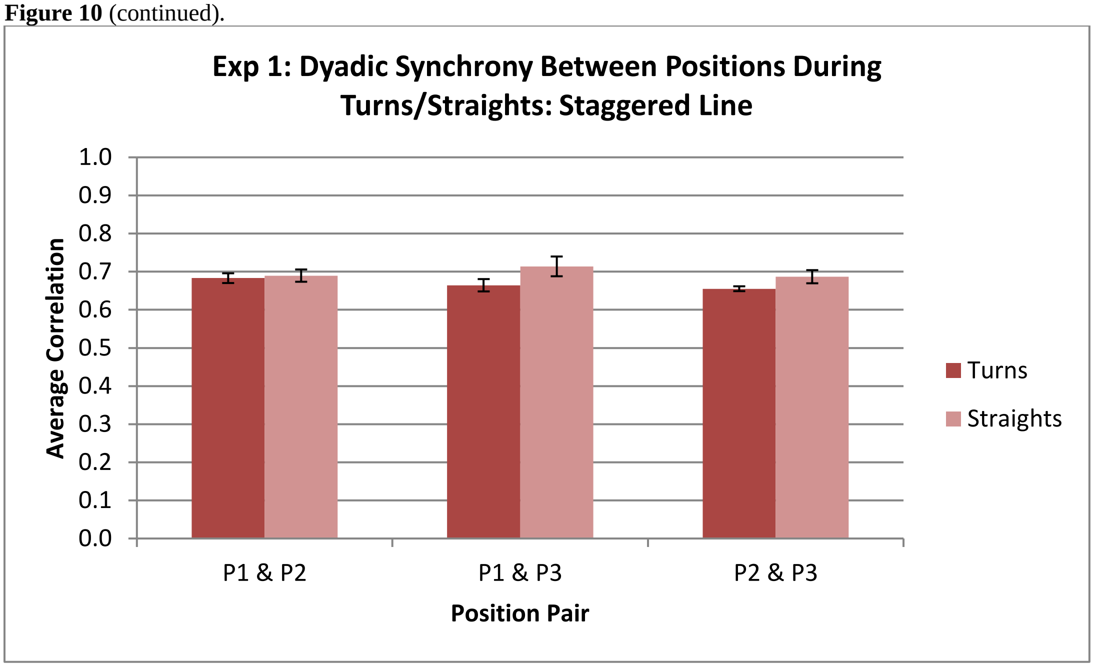


Figure 10 (continued).



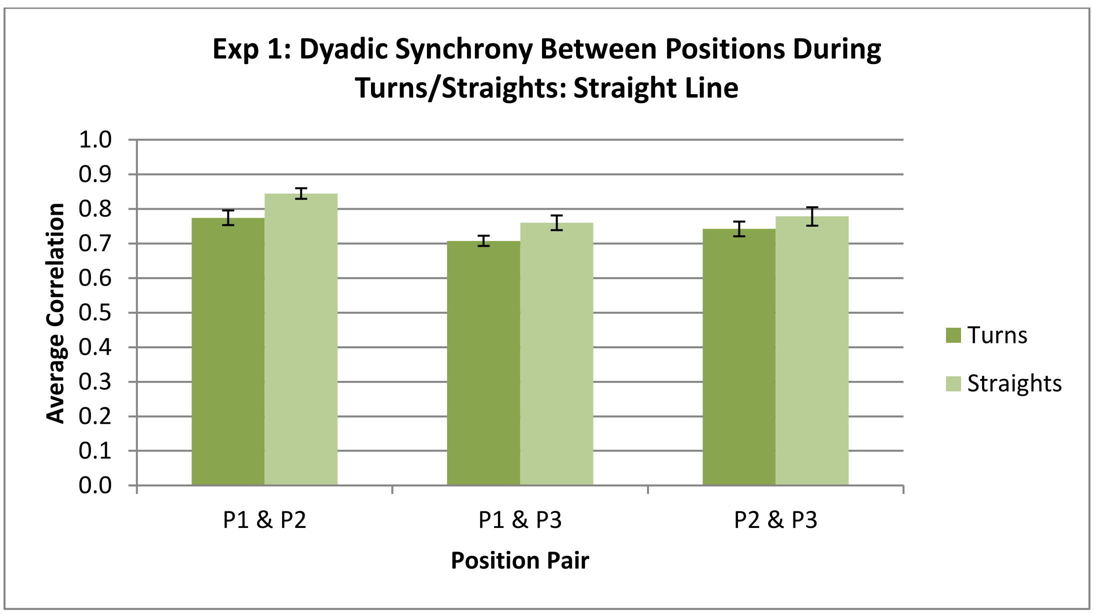


Figure 10: Experiment 1 Dyadic Synchrony in each configuration (mean ± SEM). While there was not a significant three-way interaction, F (4, 28) = 1.293, p = .297, there was a significant two-way interaction between configuration and position pairs, F(4,28) = 8.646, p < .001. Subsequent simple main effects analysis showed that for the InvT configuration, dyadic synchrony was higher between P1 and P3 (M = .69) than it was for P1 and P2 (M = .66), p = .037. In addition, for the StrL configuration, dyadic synchrony was significantly higher between P1 and P2 (M = .81) than it was for P1 and P3 (M = .73, p = .013) or P2 and P3 (M = .76, p = .002).

Relative phase lag was measured in degrees. Values close to zero represent high in-phase synchrony, whereas values close to 180 degrees represent an out of phase relationship. Across all configurations, all position pairs demonstrated behavior that was largely in-phase (see Table 2, Table 3, and Table 4). Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25th percentiles.

Table 2
Experiment 1 InvT Mean Relative Phase Lag between Position Pairs

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	11.27	-3.58	25.15
		P1 with P3	-6.32	-26.08	13.67
		P2 with P3	-10.68	-24.03	1.26
	Corner 2	P1 with P2	1.66	-18.86	23.44
		P1 with P3	0.02	-22.35	25.24
		P2 with P3	-16.44	-27.69	-5.69
	Corner 3	P1 with P2	-7.73	-25.11	11.57
		P1 with P3	-0.37	-8.74	10.60
		P2 with P3	5.00	-9.79	20.36
	Corner 4	P1 with P2	-6.55	-24.15	7.49
		P1 with P3	-2.57	-15.48	9.99
		P2 with P3	1.49	-17.48	19.94
Straights	Leg 1	P1 with P2	-22.36	-44.63	0.02
		P1 with P3	-2.87	-27.94	20.08
		P2 with P3	1.28	-22.87	24.88
	Diagonals	P1 with P2	2.83	-14.89	24.52
		P1 with P3	-0.45	-11.41	10.98
		P2 with P3	1.69	-4.85	8.37
	Leg 3	P1 with P2	12.99	-1.62	26.64
		P1 with P3	-14.51	-35.44	11.12

Table 2 (Continued).

		P2 with P3	21.13	-1.90	39.90

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25th percentiles.

Table 3

Experiment 1 StgL Mean Relative Phase Lag between Position Pairs

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	-6.23	-17.24	6.49
		P1 with P3	11.36	-4.10	24.75
		P2 with P3	3.36	-9.85	15.03
	Corner 2	P1 with P2	9.57	-5.33	26.27
		P1 with P3	9.32	-7.66	25.87
		P2 with P3	14.01	3.91	23.00
	Corner 3	P1 with P2	-5.10	-25.42	14.11
		P1 with P3	-0.33	-14.54	14.25
		P2 with P3	-12.41	-24.63	-1.43
	Corner 4	P1 with P2	-15.85	-32.74	0.65
		P1 with P3	17.24	4.47	29.44
		P2 with P3	-16.85	-25.59	-8.14
Straights	Leg 1	P1 with P2	-17.78	-34.29	-4.15
		P1 with P3	14.08	-0.71	29.84
		P2 with P3	-3.56	-27.07	20.44
	Diagonals	P1 with P2	-5.60	-15.82	7.69
		P1 with P3	22.36	-1.07	42.87
		P2 with P3	-4.92	-17.55	9.43
	Leg 3	P1 with P2	0.50	-25.62	21.31
		P1 with P3	6.94	-10.16	26.08
		P2 with P3	-13.11	-33.06	6.65

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25th percentiles.

Table 4
Experiment 1 StrL Mean Relative Phase Lag between Position Pairs

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	8.92	-23.92	47.33
		P1 with P3	10.97	-6.59	25.98
		P2 with P3	27.78	9.25	43.22
	Corner 2	P1 with P2	27.34	3.79	46.34
		P1 with P3	9.38	-3.94	30.88
		P2 with P3	15.28	-0.86	34.91
	Corner 3	P1 with P2	17.21	-8.11	44.95
		P1 with P3	18.41	6.61	30.70
		P2 with P3	19.70	-4.93	46.05
	Corner 4	P1 with P2	25.26	3.01	47.48
		P1 with P3	0.62	-16.57	17.88
		P2 with P3	27.15	5.95	49.97
Straights	Leg 1	P1 with P2	41.88	24.24	61.61
		P1 with P3	-10.42	-28.84	8.44
		P2 with P3	22.64	2.17	43.00
	Diagonals	P1 with P2	33.48	22.67	44.40
		P1 with P3	-5.57	-23.98	13.10
		P2 with P3	25.25	13.70	38.29
	Leg 3	P1 with P2	32.04	21.38	41.07
		P1 with P3	-7.16	-21.56	7.77
		P2 with P3	11.20	-9.73	31.44

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25th percentiles.

Discussion

Experiment 1 investigated how spatial configuration effected group synchrony as a function of access to varying levels of visual cues with the InvT, StgL, and StrL.

Group Synchrony

Overall, it was predicted that synchrony would differ across walking configurations, and that synchrony would be best when the greatest number of synchrony cues were available to the follower (InvT configuration). While there were differences between configurations, highest group synchrony was achieved during the StrL, rather than the InvT. Essentially, synchrony was increased when followers were required to couple their movements with fewer visual cues, rather than a greater number of cues, like those available in either the StgL or the InvT configurations. The timing strategies that each configuration produced paralleled the timing strategies illustrated in Honisch et al. (2016); since P3 could adopt an integrator role in the InvT or the StgL this introduced a more challenging signal processing task which ultimately resulted in a decrease in group synchrony. The StrL, on the other hand, restricted visual information to a single source (the person if front of you) which is similar to the timing strategy used by the participants in the chain of Honisch et al. (2016) such that they were able to focus on reducing their own asynchrony variance with the preceding cue.

In addition, group synchrony during straights was higher than during turns. Turning as a group in this paradigm required maintenance of step synchrony with the group as well as the groups' spatial configuration with respect to one another. This process involves spatial and temporal prediction about how each individual in the triad will step through the turn, in order to keep their position in the configuration. This additional change in step size which depends on position in the configuration likely led to an increase in intrapersonal variability, and an overall decrease in group synchrony that was not present during straightaways. This finding is in line with previous research which shows that less reliable cues in terms of increased variance of the estimated onset times result in lower correction gains and increased asynchrony (Wright & Elliott, 2014).

Dyadic Synchrony

The second question explored how dyadic synchrony could change as a function of the number of synchrony sources to pay attention to within each configuration. As with group synchrony, dyadic synchrony was higher during straights than during turns.

When walking in the StrL configuration, I predicted a decrease in synchrony along the chain; P1 and P2 would be more synchronized than P1 and P3 due to limited visual synchrony sources and the injection of noise along the chain of walkers (Honisch et al., 2016). This hypothesis was supported, as dyadic synchrony between P1 and P2 was significantly higher than the dyadic synchrony between P1 and P3 and between P2 and P3.

For the StgL configuration, I predicted a number of possible dyadic patterns: P3 could have been more in synch with P2 than P1, because P2 is closer to them, providing a more salient cue. P3 could have alternated stepping in time with P1 and P2, demonstrating moments where they are more in synch with one or the other. Lastly, P3 could have attempted to integrate cues from P1 and P2, resulting in a decrease in synchrony with P1 and P2, but an increase in the stability of their own intrapersonal stepping (Honisch et al., 2016). Because dyadic synchrony was lower than other configurations overall, and no significant differences in dyadic synchrony emerged between each of the position pairs especially with respect to P3, it does not appear that distance and cue salience drove an increase in synchrony between P2 and P3 (Chauvigné, Walton, Richardson, & Brown, 2019). It is more likely that the availability of multiple cue sources in P1 and P2 led to swapping attention between the two leaders or accommodation on the part of P3 to integrate both signals (Wright & Elliott, 2014).

Lastly, the InvT configuration allowed P1 and P2 peripheral visual cues while P3 had equal access to P1 and P2. In this scenario, similar to the StgL, I predicted that P3 could attempt to integrate signals from P1 and P2, P3 could also direct their attention solely to P1 or P2, or alternate stepping in time with P1 or P2. Unlike the StgL, P1 and P3 showed higher dyadic synchrony than P1 and P2, which suggests that P3 was following P1, potentially due to the decrease in synchrony between the two leaders. By limiting their attention to a single position, P3 could optimize the timing of their movements with a single source (Repp & Su, 2013).

CHAPTER THREE – EXPERIMENT 2

Research investigating gait synchrony has most often been measured along a straight path or side by side on a treadmill (Zivotofsky & Hausdorff, 2007). This excludes the inherent variability introduced by a more natural path, which would include turning behavior. Both experiment 1 and 2 present the opportunity to compare synchrony while turning and while walking along straightaways as a group, which furthers the current state of the literature.

In experiment 1, the individual(s) assigned to the leading positions remained in the leading position(s) over the duration of the trial. This addresses one walking scenario where there is a designated leader, perhaps who possesses knowledge of the group's goal direction or final location and therefore, remains at the front of the group. Here, group members would be required to predict and adapt to the signals of those in leading positions. For example, if making a 90 degree turn while walking parallel to another person, the inner individual will have to take smaller steps while the outer individual will need to take larger ones, in order to remain parallel. This situation likely increases prediction demands and movement variability within the group that would not otherwise be necessary when walking a straight line, and ultimately resulted in a decrease in group synchrony while turning.

Experiment 2 explored a different walking scenario: one where collective knowledge of the path to a goal location exists, so no explicit individual needs to lead the way. Rather than following a leader, the role of leader is possessed by whoever happens to be in front based on their spatial location as the group takes a turn. This manner of turning is expected to be more efficient as it would reduce each individual's turning radius and where each person would take the same approximate step to maintain the group configuration. This could increase signal reliability and minimize the interpersonal predictions one would have to make about how the rest of the group will take the turn (Vesper et al., 2013a); although, it also introduced the potential variability that could arise due to fluctuating leadership.

Experiment 2 altered the stability of leadership roles by allowing it to fluctuate within a trial, depending on the direction of travel to inform how fluctuating leadership would affect group synchronization. In this scenario, it was hypothesized that overall synchrony could increase due to a reduced turning radius for each individual or decrease due to fluctuating visual synchrony cues for each individual.

Methods

Participants

Participants included 24 right-handed female undergraduate students with normal or corrected vision from George Mason University and the surrounding community, for a total of eight groups made up of three participants (age range 18-26; average age 20;

ethnicity: 33% Asian, 21% Black/African American, 21% White/Caucasian, 13% Hispanic/Latino, 8% Other, 4% Native Hawaiian or other Pacific Islander). They were new individuals (different from experiment 1), recruited from the George Mason University campus and community using flyer, emails, and social media posts. Participants signed a consent form in accordance with the Declaration of Helsinki and the Human Subjects Review Board at George Mason University and were compensated for their time either through course credit or cash.

Task Design

As in experiment 1, marker setup remained the same. The manner in which the participants moved throughout the space and path, however, was changed. Rather than maintaining their order within the configuration, the participants were instructed to keep their spatial relationship with respect to one another constant but allow the leadership role to change as they traversed the space. In other words, individuals pivoted around their own individual central axis, rather than the axis of the group (see Figure 11).

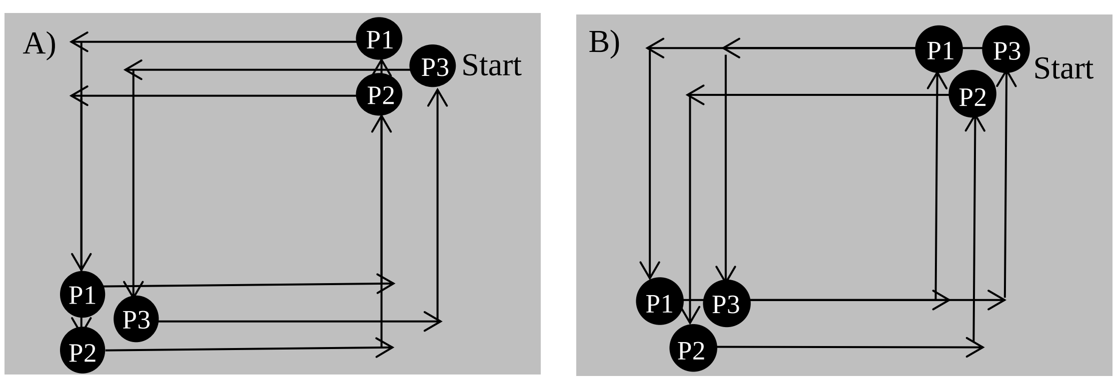


Figure 11: Fluctuating Leadership and Walking Path.A) Along the first and third legs, participants walk in the inverted triangle pattern, while along the second and fourth legs, they form a staggered line. B) Along the first and third legs, participants

Given this particular design, two separate configurations, the staggered line and the inverted triangle, occurred in a single trial. For example, participants would travel the first leg of the path in the inverted triangle configuration, but when they changed direction to follow the second leg, the group configuration transformed into the staggered line. Each position assumed a leadership role within a trial. Rather than following the "X" pattern from experiment 1, participants walked a square path around the room, to ensure that each member of the triad would lead for a portion of time. For this experiment, the straight line configuration was not included, as it did not involve the same exchange in leadership when operating under these design rules.

Procedure

First, participants were grouped into triads, matched for approximately for height with no pre-existing relationship to their other group members. Upon arrival to each experimental session, participants were outfitted with full body motion capture suits, and tracked using 41 retro-reflective markers placed onto the participant's body (see Figure 1). Markers of particular interest for analysis in this experiment included the right and left heel, as well as the four hip markers which defined the participant's center of mass, although all markers were placed to recreate the human skeleton accurately within the Motiv software (Motive, Version 2.0, 2017). Each session took place in a dance studio in George Mason University's School of dance, which houses the 20-camera Optitrack

Motion Capture System (Motive, Version 2.0, 2017) that recorded participant movements at a rate of 120 frames per second.

As in experiment 1, after each participant received their instructions and practiced the walking path with the experimenter while applying the instructed movement rule, the triad was positioned at the start of the path in the inverted triangle or the staggered line configuration (starting configuration was randomized across groups). Half of the trials began in the inverted triangle configuration and the other half of the trials began in the staggered line configuration. Participants were prompted to start walking simultaneously while the motion capture system recorded their walking behavior. Since this scenario combined two of the configurations and excludes the straight line, participants executed all order permutations (n = 6) of the fluctuating leadership configuration two times, resulting in a grand total of 12 trials which took approximately one hour. The experiment was repeated with eight triad groups total.

Data Acquisition and Analysis

Procedures for signal pre-processing, data reduction, PCA, and categorization of movement type were identical to those used in experiment 1.

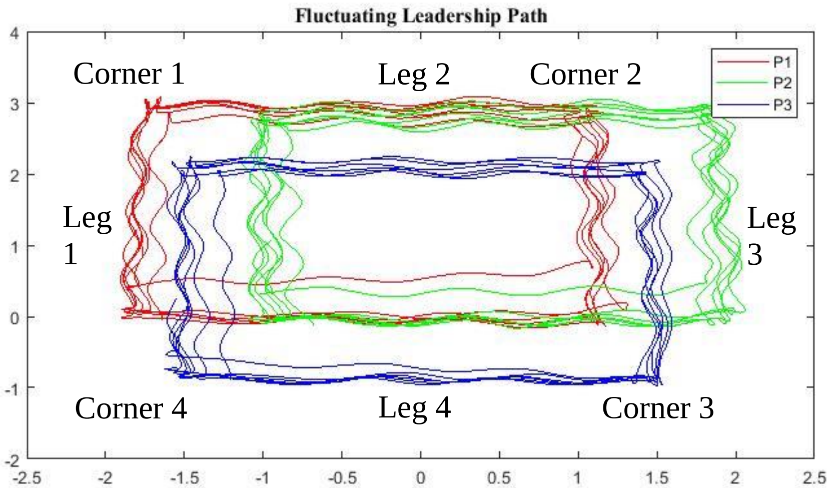


Figure 12: Experiment 2 Example Configuration Paths. Plotted is the center of mass for each member of one triad over the full course of one trial in each configuration.

Group and Dyadic Synchrony

As in experiment 1, the primary measures of interest included two forms of synchrony: group synchrony and dyadic synchrony. These measures were applied in two ways: firstly, across all twelve trials independent of configuration to investigate overall synchrony during fluctuating leadership, and also split by configuration (using the respective straight legs and corners associated with the StgL and InvT) to better understand whether configuration played a role in group synchrony within a trial. The procedures for processing group and dyadic synchrony and relative phase lag were identical to those used in experiment 1.

Results

Group Synchrony – All Trials

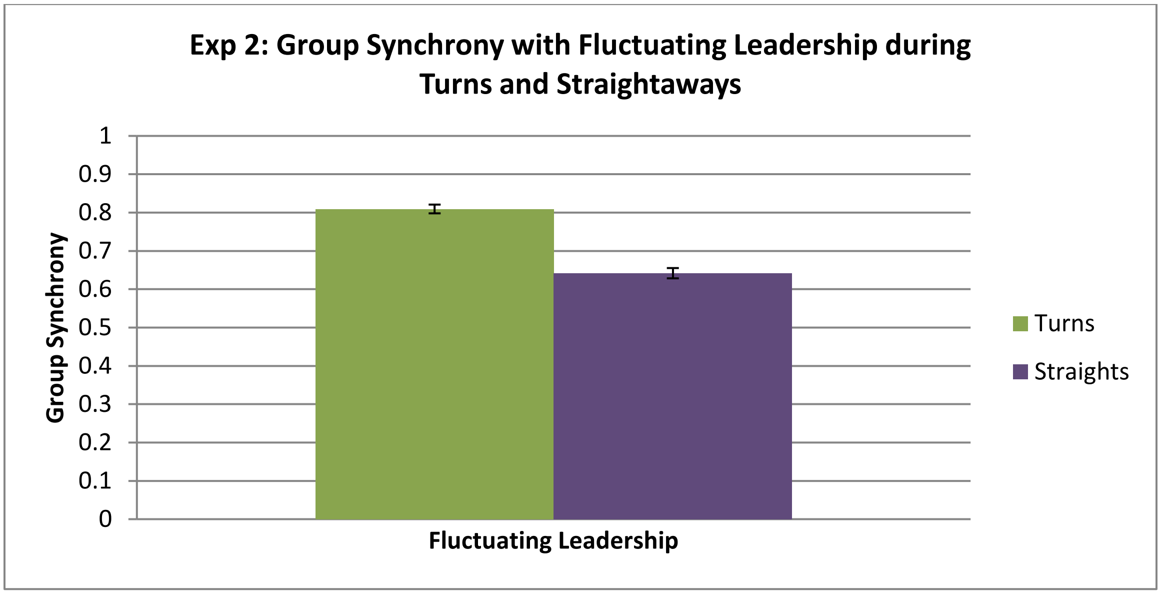


Figure 13: Experiment 2 Group Synchrony with Fluctuating Leadership (mean ± SEM). A paired-samples t-test showed there was a significant difference in the degree of synchrony during turns and straightaways, t(7) = 8.587, p <.001, such that synchrony during turns (*M*= .81, *SD*= .03) was higher than it was during straightaways (*M*= .64, *SD*= .04).

A paired-samples t-test was conducted to compare group synchrony across all trials during turns and straightaways (See Figure 13). There was a significant difference in the degree of synchrony during turns and straightaways, *t* (7) = 8.587, p <.001, such that synchrony during turns (*M*= .81, *SD*= .03) was higher than it was during straightaways (*M*= .64, *SD*= .04).

Dyadic Synchrony – All Trials

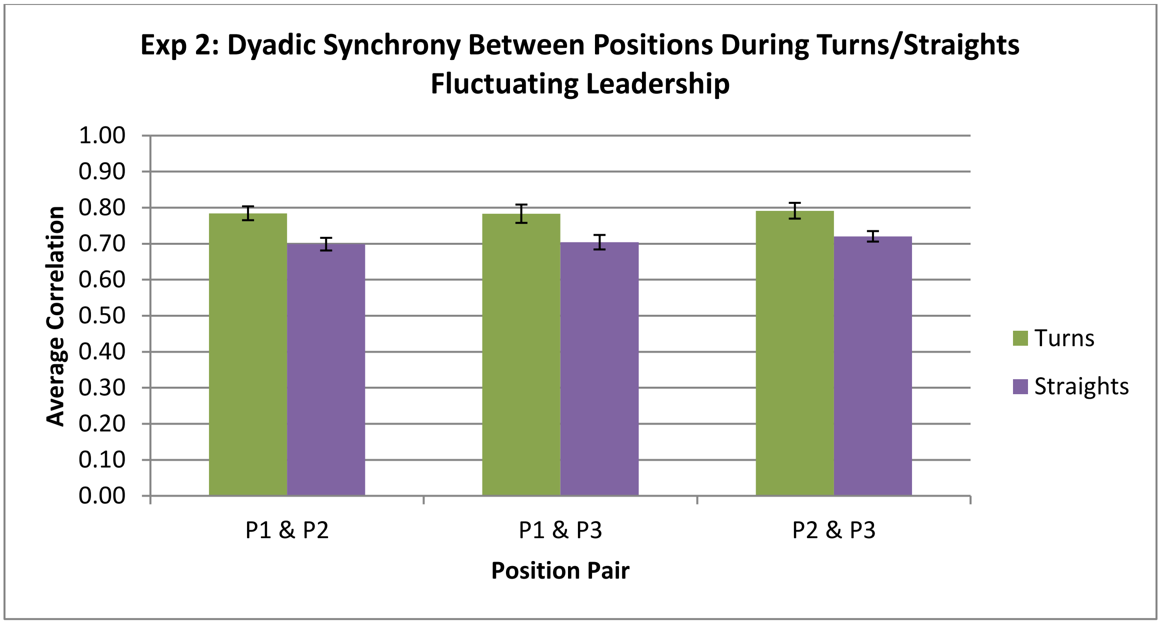


Figure 14: Experiment 2 Dyadic Synchrony with Fluctuating Leadership (mean ± SEM). A significant main effect of movement type was found, *F* (1, 7) = 12.690, p = .009, where dyadic synchrony was higher for turns (*M* = .76, CI [.75, .83]) than it was for straights (*M* = .71, CI [.68, .74]). Neither the main effect for position pair (P1 and P2, P1 and P3, or P2 and P3), *F* (2, 14) = .258, p = .776, nor the interaction position pair and movement type were found to be significant *F* (2, 14) = .294, p = .749.

A 2x3 ANOVA was conducted to examine the effects of movement type (Turns, Straights) and position pairs (P1 with P2, P1 with P3, and P2 with P3) on dyadic synchrony (See Figure 14). A significant main effect of movement type was found, *F* (1, 7) = 12.690, p = .009, where dyadic synchrony was higher for turns (*M* = .76, CI [.75, .83]) than it was for straights (*M* = .71, CI [.68, .74]). Neither the main effect for position pair (P1 and P2, P1 and P3, or P2 and P3), *F* (2, 14) = .258, p = .776, nor the interaction position pair and movement type were found to be significant *F* (2, 14) = .294, p = .749.

Relative phase lag was measured in the same way as experiment 1. Again, across all trials, all position pairs demonstrated behavior that was largely in-phase (see Table 5). Due to the change in shape of the walking path, location was split into each of the four corners and the four straight legs.

Table 5
Experiment2 All Trials, Mean Relative Phase Lag between Position Pairs

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	5.22	-5.69	15.86
		P1 with P3	-2.31	-16.24	11.15
		P2 with P3	-7.79	-21.05	4.57
	Corner 2	P1 with P2	2.08	-6.18	9.32
		P1 with P3	4.16	-7.11	15.98
		P2 with P3	2.09	-8.16	10.65
	Corner 3	P1 with P2	-4.13	-11.35	2.56
		P1 with P3	4.10	-5.78	14.59
		P2 with P3	2.77	-2.77	9.92
	Corner 4	P1 with P2	-1.82	-6.90	2.85
		P1 with P3	-10.38	-23.09	2.50
		P2 with P3	-4.65	-13.99	4.18
Straights	Leg 1	P1 with P2	2.24	-11.24	15.48
		P1 with P3	-0.48	-12.56	10.60
		P2 with P3	13.16	0.17	24.00
	Leg2	P1 with P2	-12.37	-21.38	-1.93
		P1 with P3	3.52	-4.81	11.44
		P2 with P3	8.60	-0.43	17.10
	Leg 3	P1 with P2	-1.35	-17.80	14.02
		P1 with P3	16.40	4.71	28.06
		P2 with P3	-26.50	-43.90	-9.70
	Leg 4	P1 with P2	0.11	-10.36	9.72
		P1 with P3	-0.32	-10.17	7.71
		P2 with P3	0.17	-11.17	13.64

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25^{th} percentiles.

Group Synchrony – Split By Configuration

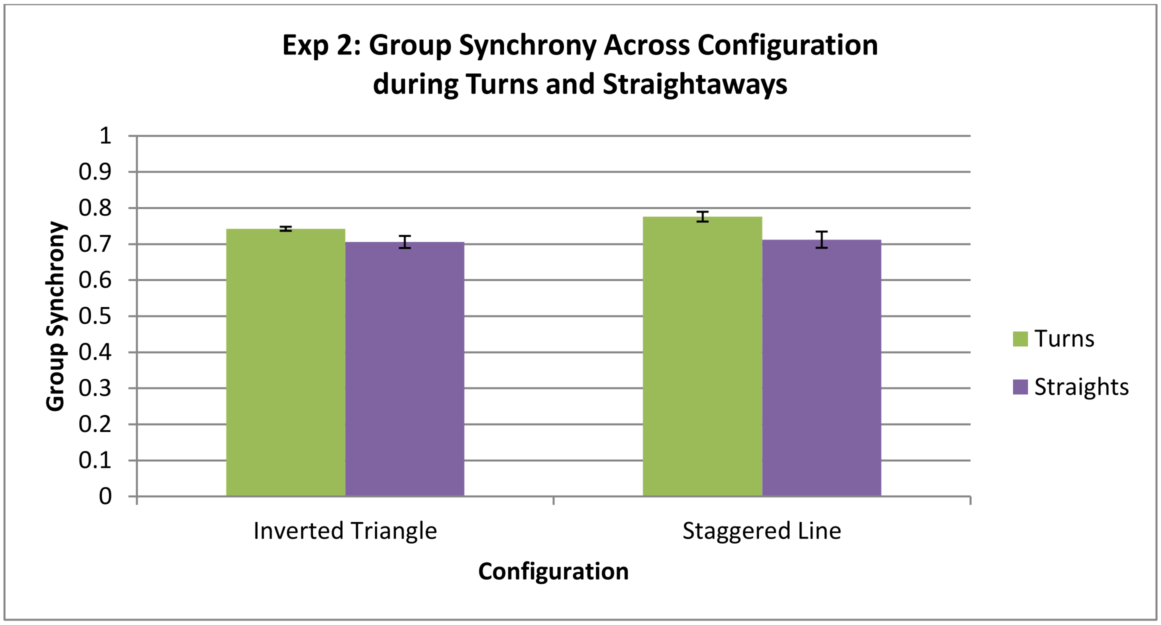


Figure 15: Experiment 2 Group Synchrony Split by Configuration (mean ± SEM). The interaction effect between configuration and movement type on group synchrony was not statistically significant, *F* (1, 7) = 1.072, p =.335; however, there was a significant main effect of movement type, *F* (1, 7) = 10.444, p =.014, indicating that the mean for Turns (M = .76, CI [.74,.79]) was significantly higher than for straightaways (M = .71, CI [.67, .75]). There was not a significant main effect of configuration, *F* (1, 7) = 2.042, p =.196.

A 2x2 repeated measures ANOVA was conducted to examine the effects of configuration (InvT, StgL) and movement type (Turns, Straights) on group synchrony (See Figure 15). The interaction effect between configuration and movement type on group synchrony was not statistically significant, *F* (1, 7) = 1.072, p =.335; however, there was a significant main effect of movement type, *F* (1, 7) = 10.444, p =.014, indicating that the mean for Turns (M = .76, CI [.74,.79]) was significantly higher than for straightaways (M = .71, CI [.67, .75]). There was not a significant main effect of configuration, *F* (1, 7) = 2.042, p =.196.

Dyadic Synchrony – Split By Configuration

A 2x2x3 repeated measures ANOVA was conducted to examine the effects of movement type (Turns, Straights), configuration (InvT, StgL), and position pairs (P1 with P2, P1 with P3, and P2 with P3) on dyadic synchrony (See Figure 16). This analysis revealed that there was not a significant three-way interaction between movement type, configuration, and position pairs, *F* (2, 14) = 2.230, p = .144. In addition, no two way interactions were found to be significant. There was only one significant main effect of configuration, *F* (1, 7) = 11.932, p =.011, which showed that dyadic synchrony was higher in the StgL configuration (*M* = .77, CI [.74, .80]) than in the InvT (*M* = .74, CI [.72, .76]). Both the main effects for movement type, *F* (1, 7) = 3.554, p =.101, and position pairs, *F* (2, 14) = 2.013, p = .170, were not significant.

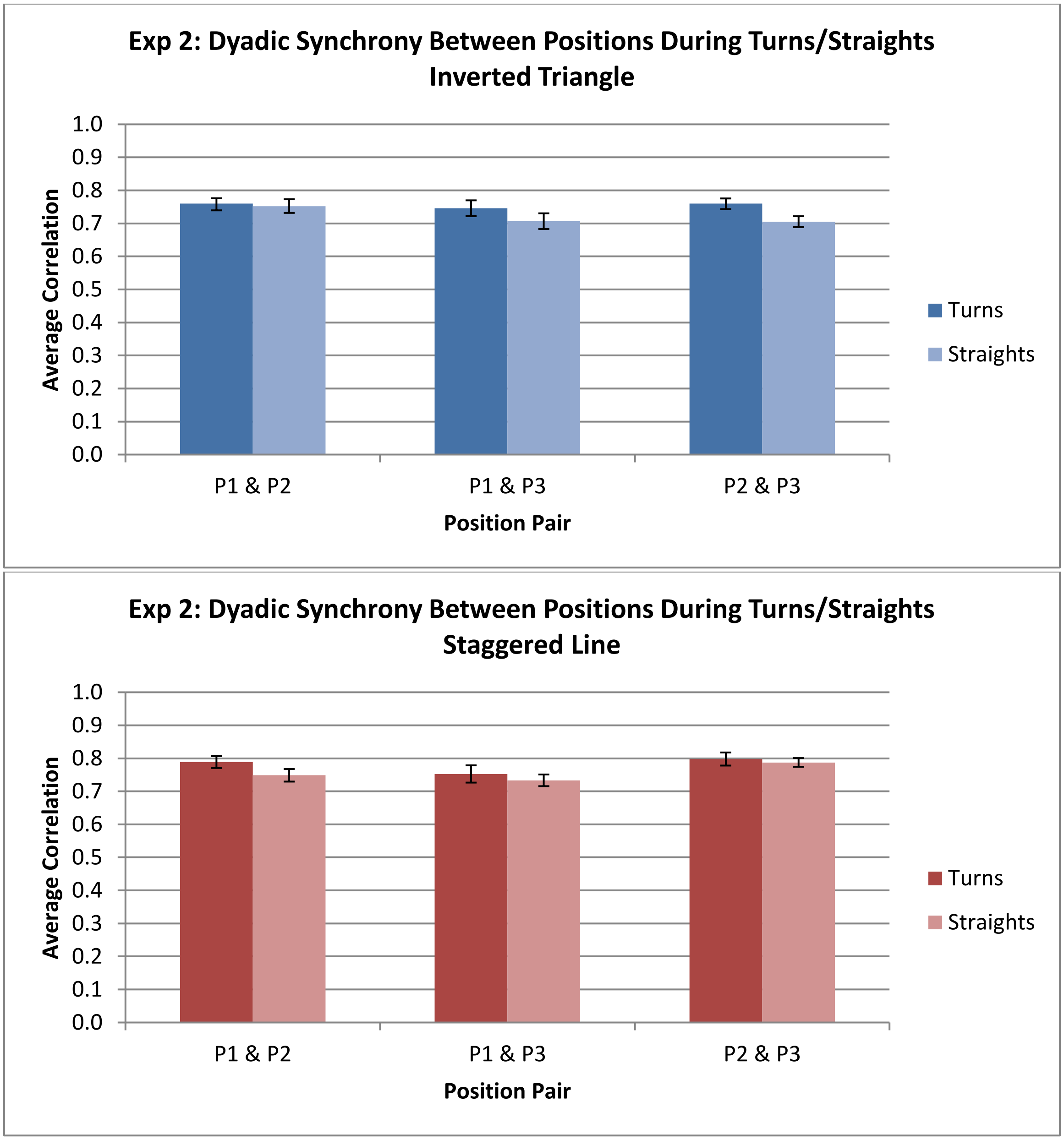


Figure 16: Experiment 2 Dyadic Synchrony Split by Configuration (mean ± SEM). There was only one significant main effect of configuration, F (1, 7) = 11.932, p =.011, which showed that dyadic synchrony was higher in the StgL configuration (M = .77, CI [.74, .80]) than in the InvT (M = .74, CI [.72, .76]). Both the main effects for movement type, F (1, 7) = 3.554, p =.101, and position pairs, F (2, 14) = 2.013, p = .170, were not significant.

Respective configuration legs and corners were relatively equal when considering phase lag between dyads. All position pairs demonstrated behavior that was largely in-phase (see Table 6 and Table 7).

Table 6
Experiment 2 InvT Mean Relative Phase Lag between Position Pairs

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	1.15	-12.95	18.40
		P1 with P3	-16.01	-31.79	0.79
		P2 with P3	-8.26	-25.42	7.81
	Corner 2	P1 with P2	3.53	-10.33	16.00
		P1 with P3	6.45	-13.81	25.00
		P2 with P3	0.07	-17.51	17.66
	Corner 3	P1 with P2	-13.25	-24.96	-1.01
		P1 with P3	-13.14	-23.57	-2.52
		P2 with P3	4.38	-1.19	9.78
	Corner 4	P1 with P2	2.64	-8.04	13.69
		P1 with P3	-8.24	-28.92	12.81
		P2 with P3	9.02	-6.22	24.53
Straights	Leg 1	P1 with P2	-15.54	-52.40	22.37
		P1 with P3	-11.75	-29.09	9.70
		P2 with P3	29.01	2.72	53.51
	Leg2	P1 with P2	-16.80	-31.96	-2.71
		P1 with P3	16.20	-3.03	35.87
		P2 with P3	14.81	-3.34	33.73
	Leg 3	P1 with P2	12.66	-24.66	46.33
		P1 with P3	35.32	25.13	47.88
		P2 with P3	-41.23	-72.05	-15.54
	Leg 4	P1 with P2	-5.68	-20.06	10.46
		P1 with P3	-6.37	-24.75	13.04
		P2 with P3	-8.00	-30.40	16.86

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25th percentiles.

Table 7
Experiment 2 StgL Mean Relative Phase Lag between Position Pairs

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	9.29	-1.74	19.93
		P1 with P3	11.40	-7.38	29.68
		P2 with P3	-7.32	-18.79	3.64
	Corner 2	P1 with P2	0.62	-23.39	22.89
		P1 with P3	1.86	-5.14	9.58
		P2 with P3	4.10	-11.76	16.94
	Corner 3	P1 with P2	5.00	-12.52	20.10
		P1 with P3	21.33	-0.52	44.16
		P2 with P3	1.17	-10.97	18.21
	Corner 4	P1 with P2	-6.27	-12.50	-0.65
		P1 with P3	-12.51	-30.01	6.94
		P2 with P3	-18.32	-26.25	-9.21
Straights	Leg 1	P1 with P2	20.03	-0.23	37.97
		P1 with P3	10.78	-4.39	21.04
		P2 with P3	-2.68	-14.34	9.10
	Leg2	P1 with P2	-7.93	-20.63	5.15
		P1 with P3	-9.16	-20.89	2.80
		P2 with P3	2.40	-4.56	9.84
	Leg 3	P1 with P2	-15.36	-28.85	-2.39
		P1 with P3	-2.52	-29.42	26.42
		P2 with P3	-11.77	-31.78	9.59
	Leg 4	P1 with P2	5.90	-7.56	21.08
		P1 with P3	5.72	-9.07	23.27
		P2 with P3	8.33	-3.56	19.78

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25th percentiles.

Discussion

Experiment 2 altered the stability of leadership roles by allowing it to fluctuate within a trial, depending on the direction of travel to inform how fluctuating leadership would affect group synchronization. In this scenario, it was hypothesized that overall synchrony could increase due to a reduced turning radius for each individual or decrease due to fluctuating visual synchrony cues for each individual. Results from experiment 2 provide support for the former hypothesis, rather than the latter.

Group Synchrony

As opposed to the results from experiment 1, whether across all trials or split by configuration (InvT and StgL), group synchrony was higher during turns than it was during straights. Interestingly (although not directly compared due to procedural design differences) straightaway synchrony was approximately equal to straights in experiment 1, indicating that synchrony during turns improved in experiment 2 and not that straightaway synchrony decreased.

The manner in which the group turned in experiment 2 varies in an important way when compared to experiment 1. While both experiments still require maintenance of step synchrony as well as the groups' spatial configuration with respect to one another; the ability to turn synchronously relied on accurate prediction of how the other two triad members would step through the turn in terms of step size and speed. In experiment 2, leadership changed with the direction of the turn, which each allowed each person to pivot in the same manner to make a 90 degree turn. This fashion of turning resulted in greater consistency and regularity regardless of the leader (Vesper, van der Wel, Knoblich, & Sebanz, 2011), because there was less of a need to predict the movements of others, and a strategy of minimizing one's own movement variability emerged.

The resulting increase in synchrony may relate to triad member's ability to simulate the same turn in time and space, which arises from their own cognitive-motor system and not the prediction of another person's. This temporal coordination of action is similar to a study which had pianists practice one part of several unfamiliar duets, then were subsequently asked a few months later to play the complementary second part. It was shown that pianists synchronized best with a recorded version of the first part if they had played it themselves (Keller, Novembre, & Hove, 2014b). In both cases, synchrony is highest when the task relies on the prediction of one's own movements, as opposed to the movements of another person.

Dyadic Synchrony

With respect to dyadic synchrony, once again, turns were more synchronized than straights, but there were no significant differences between position pairs. In this context, it is possible that coordination was achieved by each position moving as predictably as possible, which allowed for the creation of procedural common ground (Brennan & Clark, 1996) and highly synchronized walking between all position pairs. In addition, because the availability of visual cues was continuously in flux, triads were forced to synchronize even when visual feedback about others was changing or even presumed unavailable. Furthermore, it is possible that shared responsibility of leadership within a trial enhanced the mutual goal of group synchrony, and like those in Vesper et al. (2011), resulted in greater intentional synchronization and increased top-down modulation of motor performance which kept them on their toes.

In addition, dyadic synchrony, while not different between positions, was higher for the trial portions where triads were walking in a StgL as opposed to an InvT. One difference that exists between these two configurations is the directness of visual cues with which to synchronize: in the StgL, P2 is offset, but behind P1 and P3 follows both P1 and P2, whereas in the InvT P1 and P2 are parallel and P3 is equidistant behind both P1 and P1. It is possible that the peripheral cues available to P1 and P2 in the InvT were less available which led to a decrease in synchrony that was not apparent in the StgL, where P2 and P3 have equal visual access to at least one other individual.

CHAPTER FOUR – EXPERIMENT 3

Experiment 1 and 2 explored leadership as it emerged from spatial location with respect to the other triad members, but another way leadership can arise is through assignment, regardless of their position in relation to the rest of the group. This situation is more similar to those seen in small quartets, where acting jointly is accomplished by way of a designated leader and the remaining musical group members anticipating and coordinating their actions with the nonverbal cues elicited by that leader.

Synchrony success in an assigned leadership scenario is related to the structural elements of the situation (Chang, Livingstone, Bosnyak, & Trainor, 2017). With respect to the design of experiment 3, this refers to whether or not the assigned leader and their subsequent cues are visually accessible to the other group members. For example, if P2 is assigned to be the leader and the group is walking in a StrL configuration, P3 can see the leader, but P1 cannot without effort, which would lead to a decrease in overall group synchrony. Imagine the same scenario again, but now P1 is assigned to be the leader, and although P3 does not have direct visual access to the leader, P2 does, which could still produce a highly synchronized effort.

Experiment 3 added a hidden auditory signal to the experimental design to explore how an auditory signal, denoting assigned leadership, interacted with position (as described in experiment 1) during group synchronization. The ability to identify, match, and transmit the signal (i.e., effectiveness in the leadership role) was expected to depend on participant position within each configuration. When the signal was sent to a position in view to all other positions, synchrony was expected to be highest.

Methods

Participants

Participants included 24 right-handed female undergraduate students with normal or corrected vision from George Mason University and the surrounding community, for a total of eight groups made up of three participants (age range 18-27; average age 21; ethnicity: 54% White/Caucasian, 17% Black/African American, 17% Other, 8% Asian, 4% Hispanic/Latino). They were new individuals (different from experiment 1 and 2) recruited from the George Mason University campus and community using flyer, emails, and social media posts. Participants signed a consent form in accordance with the Declaration of Helsinki and the Human Subjects Review Board at George Mason University and were compensated for their time either through course credit or cash.

Task Design

Marker setup, walking path, and spatial configurations (See figures 2-4) matched experiment 1. Again, one trial lasted three minutes, and participants completed one trial per order permutation in each configuration; however, rather than freely synchronizing their walking with one another, one of the three participants was provided with a metronome beat, with which to synchronize their steps to. The other two participants did not hear the metronome signal, but instead heard white noise. Each participant heard a spoken cue, either “leader” or “follower” to prompt whether or not they would receive the metronome signal. The “leader” was whoever happened to be the metronome signal receiver, regardless of their position in any configuration. The primary goal of the participant in possession of the metronome beat was to synchronize their steps with the tempo of the metronome, while those who do not hear the signal, were required to synchronize their movements with one another, as a group. In order to prevent acclimation to the metronome beat across trials, the metronome signal that was presented via wireless Bluetooth headphones varied between 106 and 130 beats per minute. Styns and colleagues (2007) established this range as optimal for walking synchronization (Styns, van Noorden, Moelants, & Leman, 2007).

Procedure

First, participants were grouped into triads, matched approximately for height with no pre-existing relationship to their other group members. Upon arrival to each experimental session, participants were outfitted with full body motion capture suits, and tracked using 41 retro-reflective markers placed onto the participant’s body (see Figure 1). Markers of particular interest for analysis in this experiment included the right and left heel, as well as the four hip markers which defined the participant’s center of mass, although all markers were placed to recreate the human skeleton accurately within the Motiv software (Motive, Version 2.0, 2017). Each session took place in a dance studio in George Mason University’s School of dance, which houses the 20-camera Optitrack Motion Capture System (Motive, Version 2.0, 2017) that recorded participant movements at a rate of 120 frames per second.

As in experiment 1, after each participant received their instructions and practiced the walking path with the experimenter to an example beat, the triad was positioned at the start of the path in one of the three proposed configurations (configuration order was randomized). Participants were prompted to start walking simultaneously while the motion capture system recorded their walking behavior (See Figure 17). As previously described, participants executed all order permutations (n = 6) in each configuration (n = 3), resulting in a grand total of 18 trials which took approximately one hour. The participant with the hidden auditory signal was balanced across position (not individuals), such that P1, P2, and P3 in each configuration had the signal twice. The order that each position got the signal was randomized across triads. The experiment was repeated with eight triad groups total.

Data Acquisition and Analysis

Procedures for signal pre-processing, data reduction, PCA, and categorization of movement type, were identical to those used in experiment 1. In addition, at the end of each trial, participants discreetly reported on paper who they believed the leader to be.

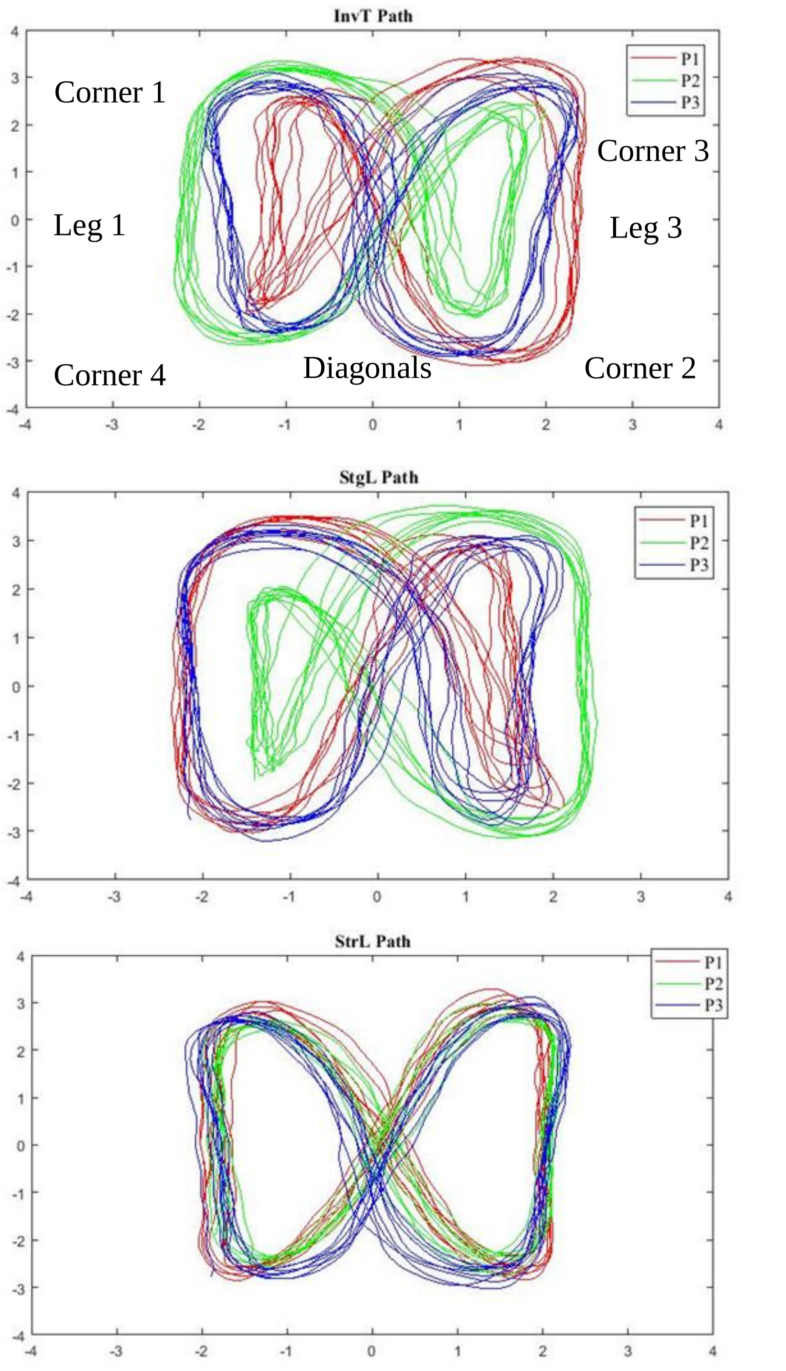


Figure 17: Experiment 3 Example Configuration Paths. Plotted is the center of mass for each member of one triad over the full course of one trial in each configuration.

Due to the complex nature of implicit leadership signals and the elusive effects that had on group synchrony, I conducted an extended exploratory analysis beyond looking at synchrony as I have throughout this dissertation (independent of the assigned leadership component). I approached the question about the influence of the assigned leader in two ways: 1) based on whether or not the followers could see the leader and 2) more specifically, how many followers could see the leader (See Figure 18).

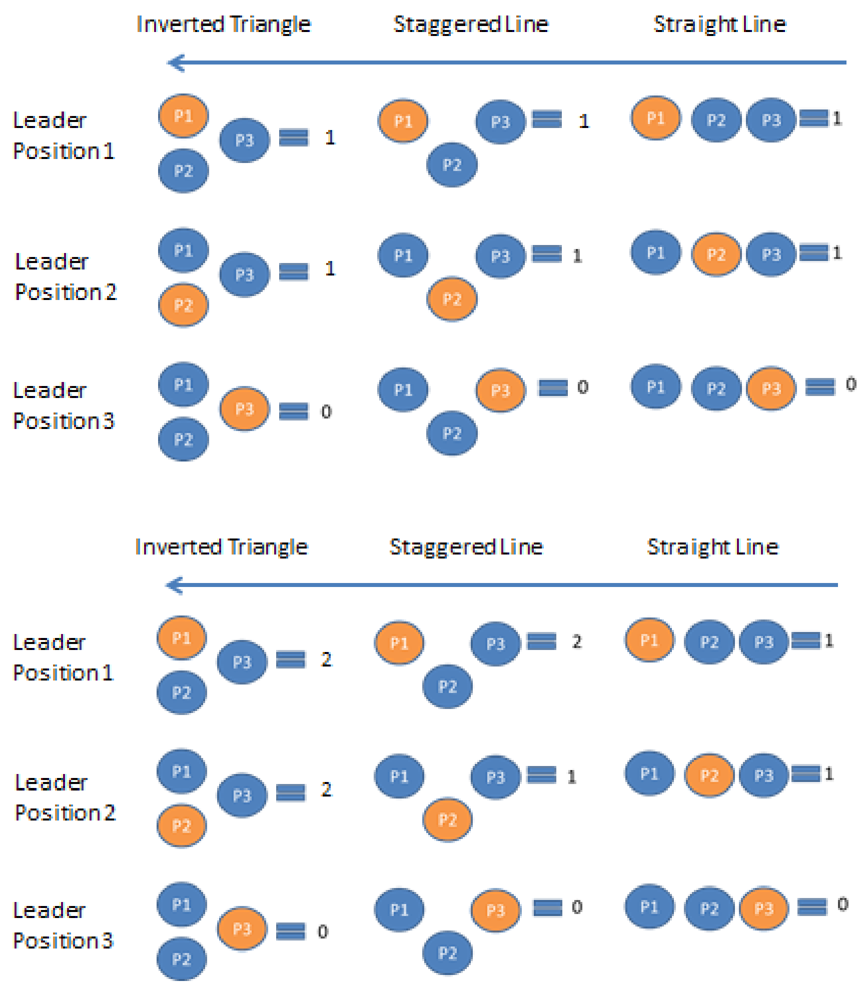


Figure 18: Assigned Leadership Definition. A) Dichotomous View B) Specific Number of Followers

An additional factor that came into play was the followers' ability to identify the assigned leader on any given trial, and as such, I analyzed follower accuracy depending on their configuration and position. Lastly, I parsed trials where the leader was incorrectly reported to see if synchrony would increase based on the position of the "suspected" leader.

Results

Group Synchrony – Independent of the Assigned Leader

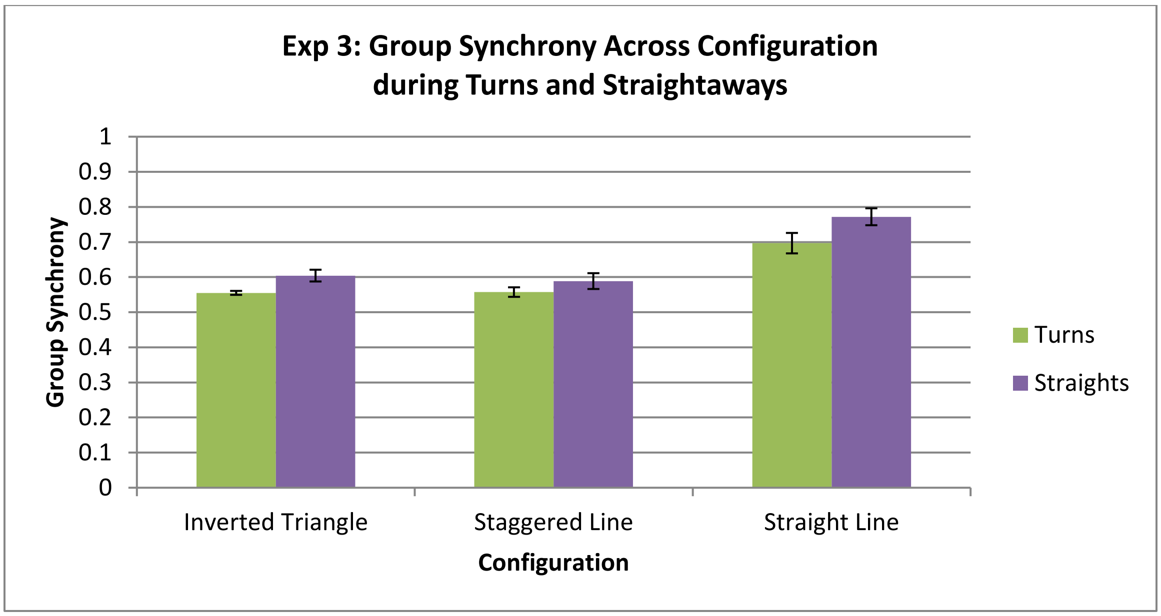


Figure 19: Experiment 3 Group Synchrony, Independent of the Assigned Leader (mean ± SEM). The interaction effect between configuration and movement type on group synchrony was statistically significant, F (2, 14) = 6.824, p = .009.

A 2x3 repeated measures ANOVA was conducted to examine the effects of configuration (InvT, StgL, and StrL) and movement type (Turns, Straights) on group synchrony (see Figure 19). The interaction effect between configuration and movement type on group synchrony was statistically significant, F (2, 14) = 6.824, p = .009.

Simple main effects analysis showed that during turns, synchrony was highest for the StrL (*M* = .60, CI [.56,.63]) when compared to the InvT (*M* = .56, CI [.54,.58], p = .043) or the StgL (*M* = .54, CI [.52,.55], p = .005). Additionally, group synchrony for the InvT was found to be higher than the StgL, p = .006.

For straights, a similar pattern emerged, such that group synchrony in the StrL (M = .66, CI [.60, .73]) was greater than it was for the InvT (*M* = .57, CI [.55,.58], p = .011) or the StgL (*M* = .58, CI [.56,.59], p = .008).

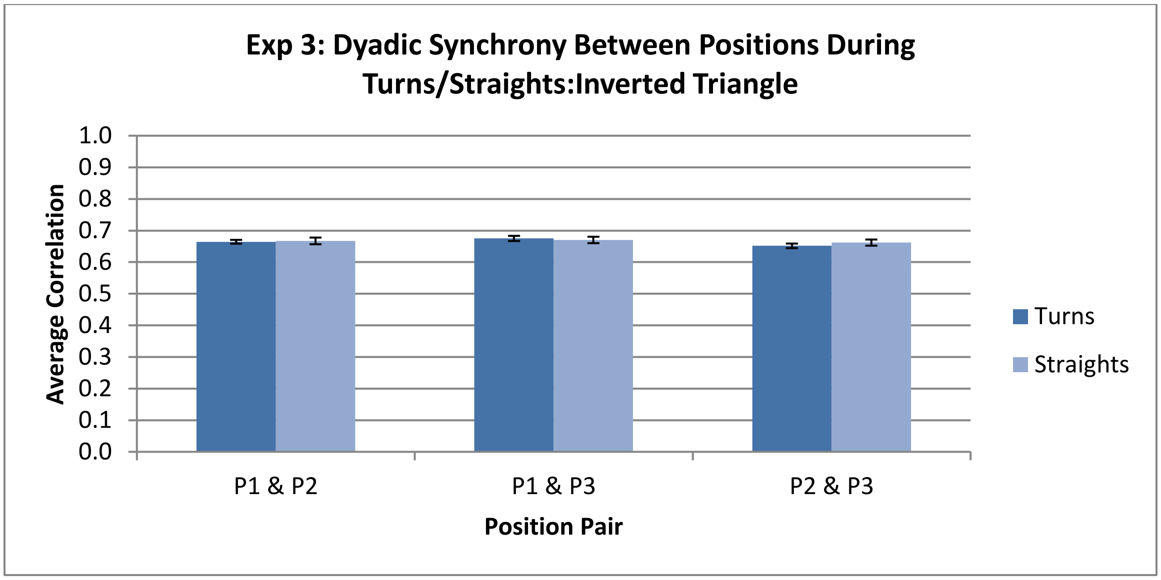
Main effects showed a significant effect of movement type, *F* (1, 7) = 20.539, p = .003, where straights (M = .60, CI [.57, .63]) led to higher synchrony than turns (*M* = .56, CI [.55, .58]). There was also a main effect of configuration, *F* (2, 14) = 13.167, p = .007; the StrL (M = .63, CI [.58, .68]) configuration was more synchronized than the InvT (M = .56, CI [.55,.58]) or the StgL (M = .56, CI [.54, .57]).

Dyadic Synchrony – Independent of the Assigned Leader

A 2x3x3 repeated measures ANOVA was conducted to examine the effects of movement type (Turns, Straights), configuration (InvT, StgL, StrL), and position pairs (P1 with P2, P1 with P3, and P2 with P3) on dyadic synchrony (see Figure 20). This analysis revealed that there was not a significant three-way interaction between movement type, configuration, and position pairs, *F* (4, 28) = .146 , p = .963; although there was a significant two-way interaction between movement type and position pairs, $F(2, 14) = 14.005$, $p < .001$.

Simple main effects analysis revealed that for turns, both the StrL (M = .69, CI [.67,.71], p = .005) and the InvT (M = .66, CI [.65,.68], p = .017) resulted in higher dyadic synchrony than the StgL (M = .65, CI [.64,.66]). For straights, the dyadic synchrony for the StrL (M = .72, CI [.70, .75]) configuration was higher than it was for either the InvT (M = .67, CI [.65, .68], p = .001) or the StgL (M = .67, CI [.67,.68], p = .008).

Of the main effects, configuration, $F(2, 14) = 18.227$, $p = .002$, and movement type, $F(1, 7) = 86.605$, $p < .001$, were found to be significant. For configuration, the StrL (M = .70, CI [.68, .73]) was higher in dyadic synchrony than the InvT (M = .67, CI [.65,.68]) or the StgL (M = .66, CI [.65, .67]). For movement type, straights (M = .69, CI [.67, .70]) resulted in higher dyadic synchrony than turns (M = .67, CI [.66, .68]).


Exp 3: Dyadic Synchrony Between Positions During Turns/Straights:Inverted Triangle
Average Correlation
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
P1 & P2
P1 & P3
P2 & P3
Position Pair
Turns
Straights

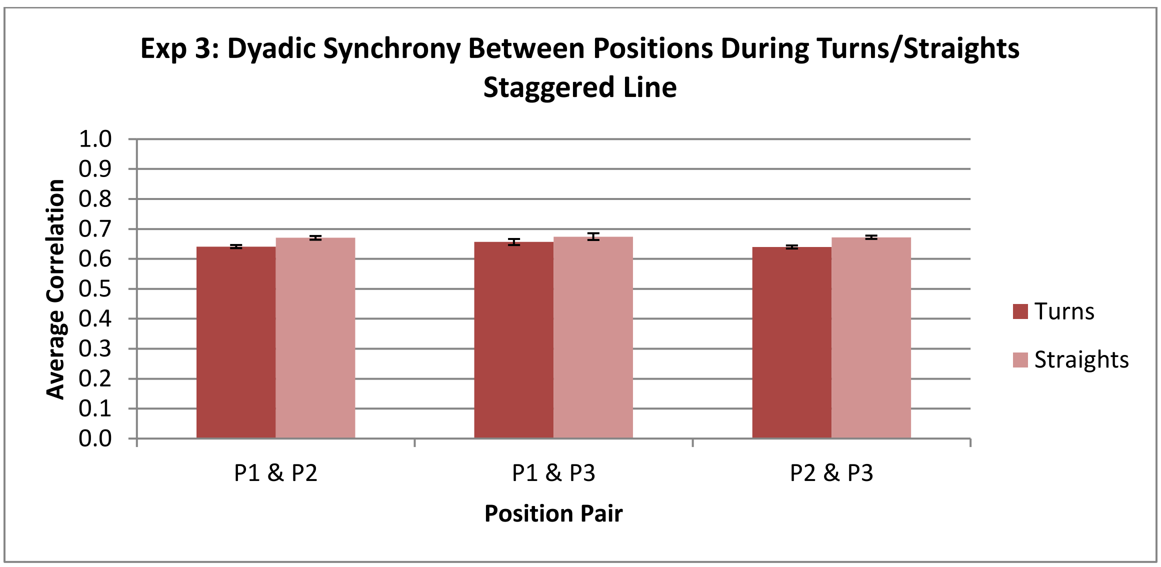

Exp 3: Dyadic Synchrony Between Positions During Turns/Straights Staggered Line
Average Correlation
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
P1 & P2
P1 & P3
P2 & P3
Position Pair
Turns
Straights

Figure 20 (Continued).

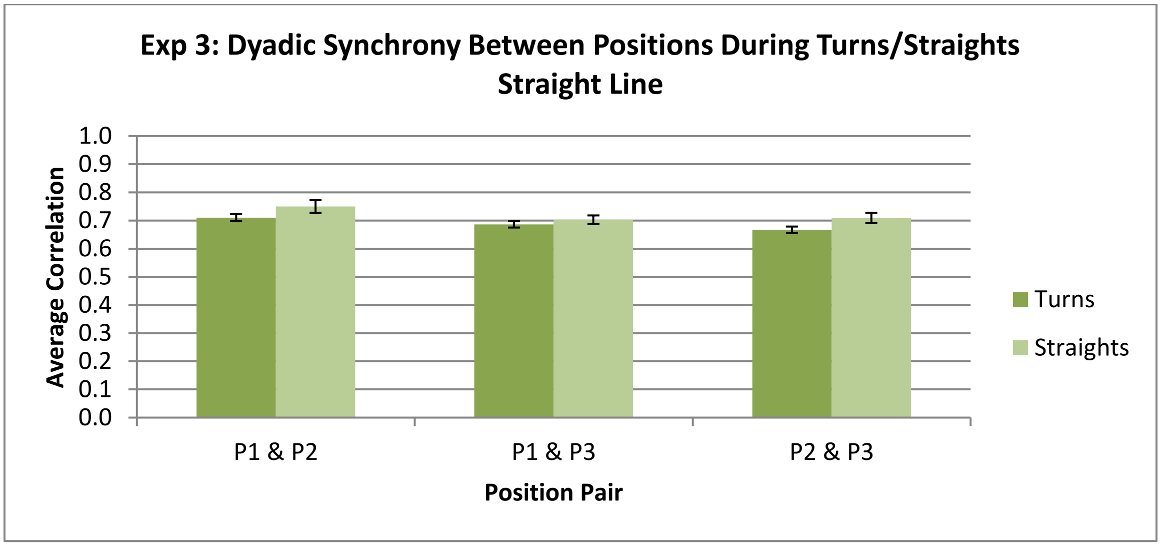


Figure 20: Experiment 3 Dyadic Synchrony across configuration, Independent of the Assigned Leader (mean ± SEM). There was a significant two-way interaction between movement type and position pairs, F (2, 14) = 14.005, p < .001.Simple main effects analysis revealed that for turns, both the StrL (M = .69, CI [.67,.71], p = .005) and the InvT (M = .66, CI [.65,.68], p = .017) resulted in higher dyadic synchrony than the StgL (M = .65, CI [.64,.66]). For straights, the dyadic synchrony for the StrL (M = .72, CI [.70, .75]) configuration was higher than it was for either the InvT (M = .67, CI [.65, .68], p = .001) or the StgL (M = .67, CI [.67,.68], p = .008).

Relative phase lag was measured in the same way as experiment 1. Again, across all trials, all position pairs demonstrated behavior that was largely in-phase (see Table 8-10).

Table 8
Experiment 3 InvT Mean Relative Phase Lag between Position Pairs

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	-3.23	-19.13	9.95

Table 8 (Continued).

		P1 with P3	-3.54	-10.94	4.32
		P2 with P3	-4.05	-17.50	7.03
	Corner 2	P1 with P2	1.12	-12.37	11.87
		P1 with P3	9.32	-0.61	17.26
		P2 with P3	-6.86	-13.08	-0.19
	Corner 3	P1 with P2	3.89	-6.52	14.24
		P1 with P3	-3.13	-12.10	6.13
		P2 with P3	-7.18	-21.83	7.53
	Corner 4	P1 with P2	0.56	-12.21	16.77
		P1 with P3	7.43	-2.47	16.40
		P2 with P3	-8.09	-23.39	6.37
Straights	Leg 1	P1 with P2	-4.35	-20.60	10.73
		P1 with P3	1.54	-10.88	14.01
		P2 with P3	2.37	-17.44	24.40
	Diagonals	P1 with P2	-6.71	-15.71	2.44
		P1 with P3	5.42	-5.06	15.01
		P2 with P3	3.94	-9.45	15.03
	Leg 3	P1 with P2	9.36	-9.08	25.84
		P1 with P3	-16.79	-27.54	-3.56
		P2 with P3	-18.32	-40.92	4.90

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25th percentiles.

Table 9

Experiment 3 StgL Mean Relative Phase Lag between Position Pairs

Table 9 (Continued).

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	2.76	-7.56	12.83
		P1 with P3	4.21	-11.61	21.41
		P2 with P3	1.62	-9.92	15.04
	Corner 2	P1 with P2	9.67	-0.05	21.32
		P1 with P3	14.33	-3.34	31.41

Table 9 (Continued).

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
		P2 with P3	12.06	-1.71	25.41
	Corner 3	P1 with P2	-2.98	-13.23	9.97
		P1 with P3	3.21	-8.73	14.97
		P2 with P3	5.24	-5.85	20.44
	Corner 4	P1 with P2	7.65	-6.50	19.61
		P1 with P3	-7.52	-18.67	-0.84
		P2 with P3	4.67	-4.30	13.19
Straights	Leg 1	P1 with P2	-0.56	-16.91	15.04
		P1 with P3	5.02	-6.91	16.97
		P2 with P3	-15.28	-30.12	0.39
	Diagonals	P1 with P2	-1.21	-8.86	6.55
		P1 with P3	4.76	-6.17	15.62
		P2 with P3	6.00	-8.52	21.54
	Leg 3	P1 with P2	9.20	-9.84	27.80
		P1 with P3	-25.50	-39.47	-11.11
		P2 with P3	2.09	-14.35	14.86

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25th percentiles.

Table 10
Experiment 3 StrL Mean Relative Phase Lag between Position Pairs

Movement Type	Location	Position Pairs	*M*	Lower CI	Upper CI
Turns	Corner 1	P1 with P2	12.90	0.99	22.28
		P1 with P3	3.90	-10.95	21.48
		P2 with P3	12.55	-7.21	31.17
	Corner 2	P1 with P2	-4.64	-21.65	11.33
		P1 with P3	4.80	-8.41	17.42
		P2 with P3	13.09	3.41	24.91
	Corner 3	P1 with P2	19.12	-3.11	43.91
		P1 with P3	8.86	-3.61	21.06
		P2 with P3	2.38	-11.28	15.90
	Corner 4	P1 with P2	3.82	-20.99	32.43
		P1 with P3	9.23	1.31	17.28
		P2 with P3	-3.23	-21.42	14.33

Table 10 (Continued).

Straights	Leg 1	P1 with P2	-9.26	-17.81	1.74
		P1 with P3	-15.27	-23.95	-5.01
		P2 with P3	10.57	-14.20	36.00
	Diagonals	P1 with P2	-9.21	-22.95	5.03
		P1 with P3	-3.15	-16.09	9.19
		P2 with P3	-11.25	-28.08	7.21
	Leg 3	P1 with P2	14.87	-7.93	37.81
		P1 with P3	-6.24	-19.05	5.73
		P2 with P3	6.58	-15.25	27.45

Note. Comparisons were made with respect to the first position of the pair listed. Results were bootstrapped 1000 times to uncover the mean phase lag between position pairs in each location along the path. Confidence limits were constrained to the lower and upper 25^{th} percentiles.

Group Synchrony – Relative to the Position of the Assigned Leader

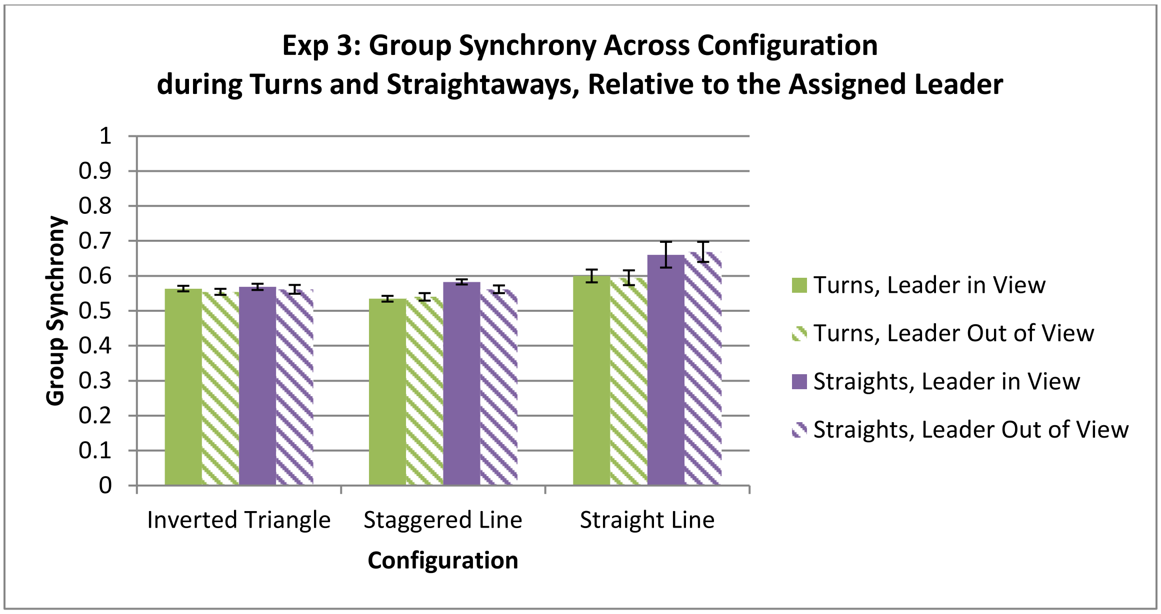


Figure 21: Experiment 3 Group Synchrony across configuration, Relative to the Assigned Leader (mean ± SEM).

A 2x2x3 repeated measures ANOVA was conducted to examine the effects of movement type (Turns, Straights), leader visibility (In View, Out of View), and configuration (InvT, StgL, StrL) on dyadic synchrony (see Figure 21). This analysis revealed that there was not a significant three-way interaction between movement type, leader visibility, and configuration, $F(2, 14) = 2.230$, $p = .144$; although there was a significant two-way interaction between movement type and configuration, $F(2, 14) = 8.631$, $p = .004$.

Simple main effects analysis revealed that for turns, both the StrL (M = .60, CI [.56,.63], p = .008) and the InvT (M = .56, CI [.54,.58], p = .013) resulted in higher No synchrony than the StgL (M = .54, CI [.52,.55]). For straights, the group synchrony for the StrL (M = .67, CI [.60, .72]) configuration was higher than it was for either the InvT (M = .57, CI [.55,.58], p = .008) or the StgL (M = .57, CI [.56,.59], p = .003).

Of the main effects, configuration, F (2, 14) = 13.912, p = .006, and movement type, F (1, 7) = 17.374, p =.004, were found to be significant. For configuration, the StrL (M = .63, CI [.59, .68]) was higher in group synchrony than the InvT (M = .56, CI [.55,.57]) or the StgL (M = .56, CI [.54, .57]). For movement type, straights (M = .60, CI [.58, .63]) resulted in higher group synchrony than turns (M = .56, CI [.55, .58]).

Dyadic Synchrony – Relative to the Position of the Assigned Leader

A 2x3x3x3 repeated measures ANOVA was conducted to examine the effects of movement type (Turns, Straights), leader position (P1, P2, P3), position pairs (P1 with P2, P1 with P3, and P2 with P3), and configuration (InvT, StgL, StrL) on dyadic synchrony. This analysis revealed that there was not a significant four-way interaction between movement type, leader position, position pairs, and configuration, F (8, 56) = .578, p =.791, or any three way interactions. There was a significant two-way interaction between movement type and configuration, F (2, 14) = 9.208, p = .003.

Simple main effects analysis revealed that for turns, only the StrL (M = .69, CI [.66, .71]) resulted in higher dyadic synchrony than the StgL (M = .65, CI [.64,.66], p =

.002). For straights, the dyadic synchrony for the StrL (M = .72, CI [.69, .76]) configuration was higher than it was for either the InvT (M = .66, CI [.65, .68], $p = .011$) or the (M = .67, CI [.67, .68], $p = .003$).

Of the main effects, configuration, $F(2, 14) = 11.205$, $p = .007$, and movement type, $F(1, 7) = 63.670$, $p < .001$, were found to be significant. For configuration, the StrL (M = .70, CI [.65, .69]) was higher in dyadic synchrony than the InvT (M = .66, CI [.65,.70]) or the StgL (M = .66, CI [.66, .70]). For movement type, straights (M = .68, CI [.67, .70]) resulted in higher dyadic synchrony than turns (M = .67, CI [.65, .68]).

Exploratory Analysis: Leader Identification Accuracy

A one-way repeated measures ANOVA was conducted to determine whether or not there were differences in overall identification accuracy between configurations (InvT, StgL, StrL). A significant difference was not found, $F(2, 14) = .008$, $p = .992$. Generally speaking, since participants were choosing between two possible choices, chance identification would be 50%. In this case, participants were better than chance, on average, in each configuration (see Figure 22).

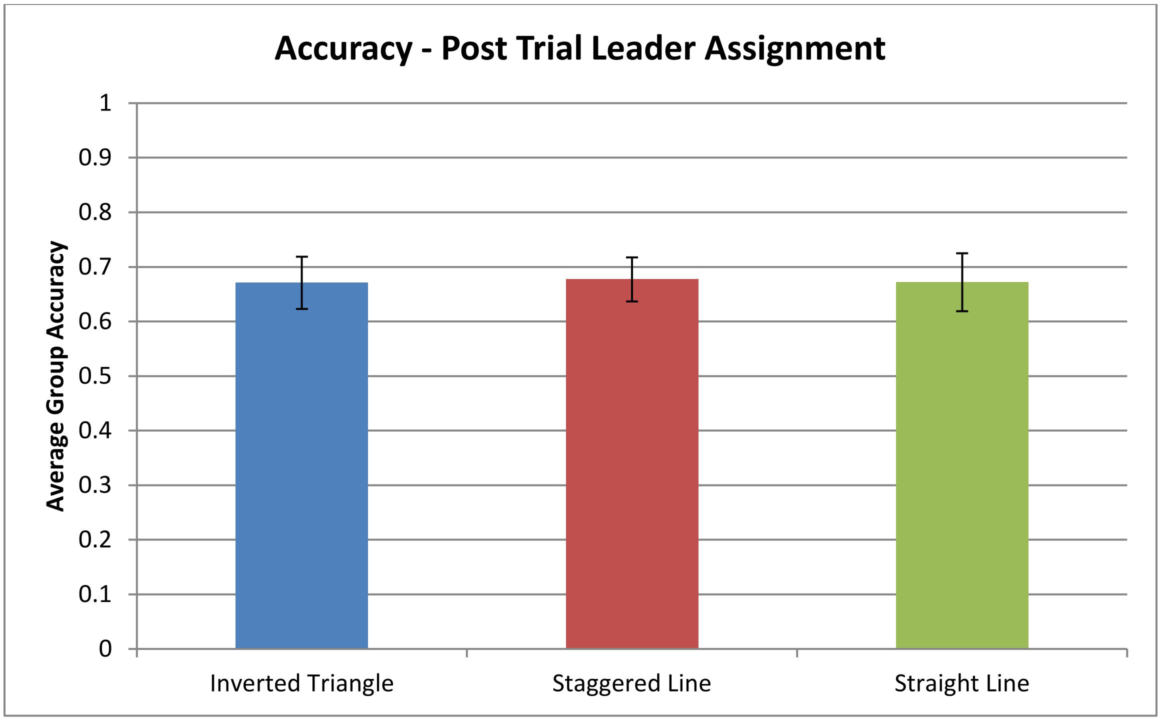


Figure 22: Overall Leader Identification Accuracy by Configuration.

A 3x3 repeated measures ANOVA was conducted to examine the effect of position and configuration on leadership identification accuracy (see Figure 22 and 23). No significant differences were found between configuration and position, $F(4, 28) = 1.292$, $p = .303$.

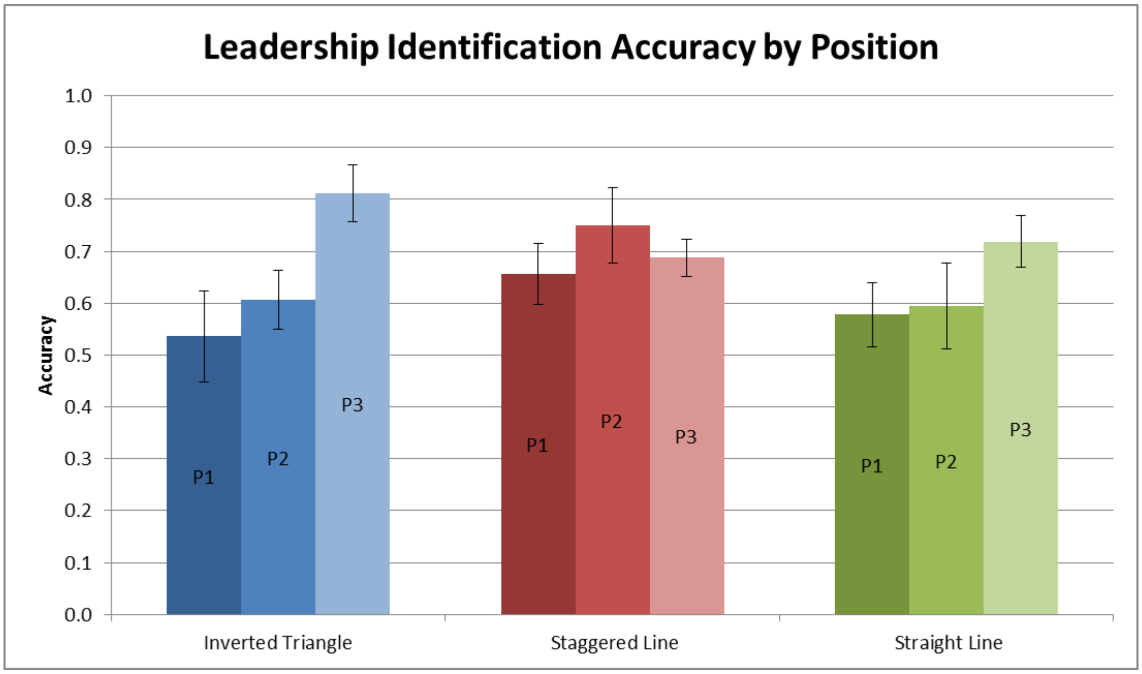


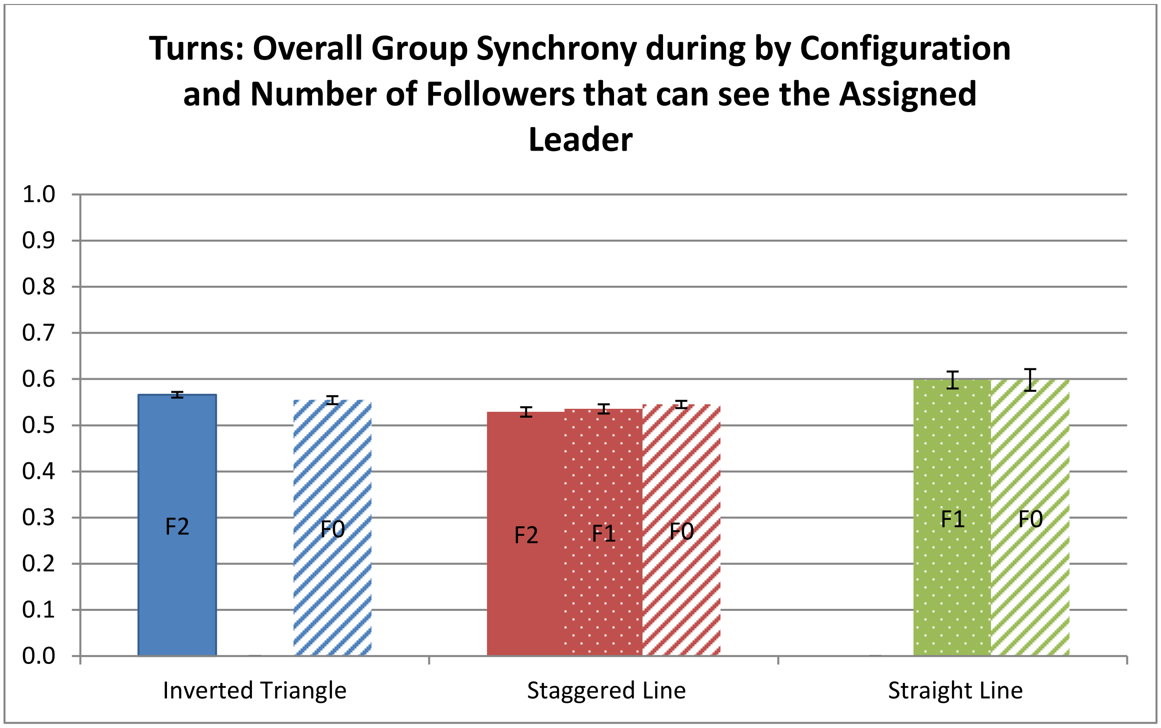
Figure 23: Leadership Identification Accuracy by Position and Configuration.

Exploratory Analysis: Number of Followers

Separate two-way repeated measures ANOVA were run for each configuration (InvT, StgL, StrL) to examine the effect that the specific number of followers in view of the leader (2, 1, or 0) had on group synchrony during turns and straights (see Figure 24). For the InvT, there was not a significant interaction between movement type (Turns, Straights) and number of followers in view of the leader (2 or 0), F (1, 7) = .762, p = .762, or any significant main effects: movement type, F (1, 7) = .157, p = .704, or number of followers in view of the leader, F (1, 7) = .2.877, p = .134.

For the StgL, there was not a significant interaction between movement type (Turns, Straights) and number of followers in view of the leader (3, 2, or 0), $F (2, 14) = .1.595$, $p = .238$; however, there was a significant main effect of movement type, $F (1, 7) = 18.030$, $p = .004$, where straights (M = .57, CI [.56, .59]) were significantly better than turns (M = .54, CI [.52, .55]), but the main effect of number of followers was not significant, $F (2, 14) = .055$, $p = .946$.

For the StrL, there was not a significant interaction between movement type (Turns, Straights) and number of followers in view of the leader (1 or 0), $F (1, 7) = .244$, $p = .636$; however, there was a significant main effect of movement type, $F (1, 7) = 18.412$, $p = .004$, where straights (M = .66, CI [.60, .73]) were significantly better than turns (M = .60, CI [.56,.63]), but the main effect of number of followers was not significant, $F (1, 7) = 024$, $p = .880$.



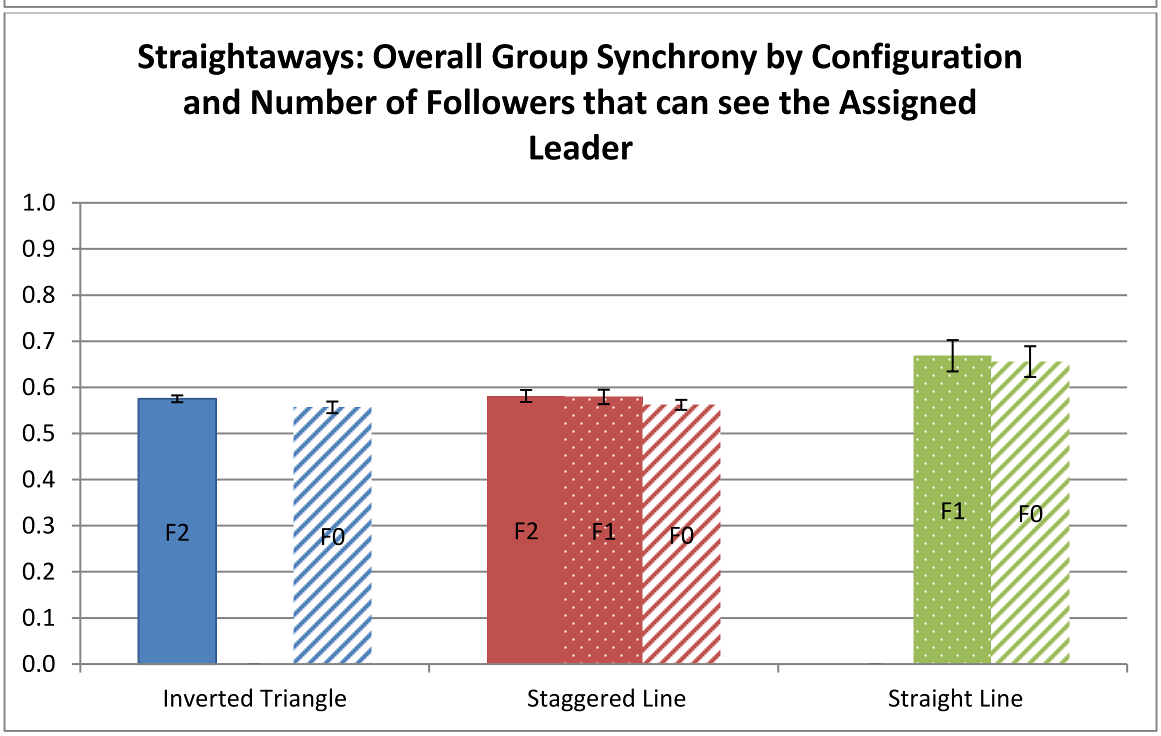


Figure 24: Group Synchrony by Specific Number of Followers. Separate two-way repeated measures ANOVA were run for each configuration (InvT, StgL, StrL) to examine the effect that the specific number of followers in view of the leader (2, 1, or 0) had on group synchrony during turns and straights. For the InvT, there was not a

significant interaction between movement type (Turns, Straights) and number of followers in view of the leader (2 or 0), F (1, 7) = .762, p = .762, or any significant main effects: movement type, F (1, 7) = .157, p = .704, or number of followers in view of the leader, F (1, 7) = .2.877, p = .134.

Exploratory Analysis: Correctly Assigned versus Incorrectly Reported

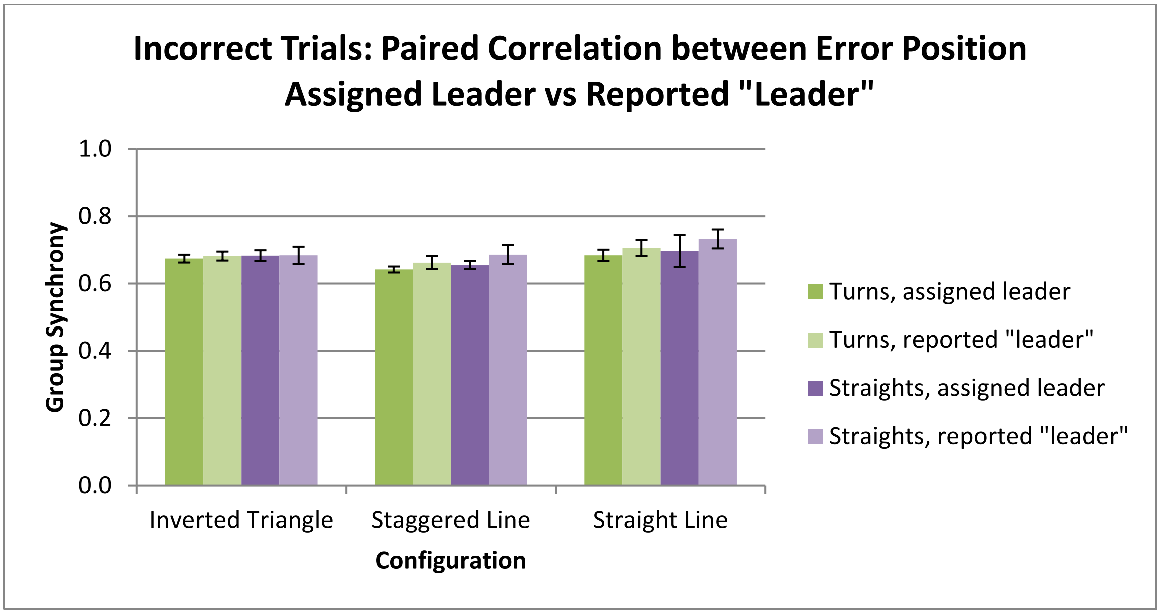


Figure 25: Correctly Assigned versus Incorrectly Reported Leader Synchrony.

A 2x2x3 repeated measures ANOVA was conducted to examine the effect of movement type (Turns, Straights), leader authenticity (correctly assigned or incorrectly reported), and configuration (InvT, StgL, and StrL) on group synchrony (see Figure 25). A response was categorized as “correctly assigned” if a follower wrote down the name of the person who was actually sent the metronome beat and “incorrectly reported” if they wrote down the name of another follower for that trial. No significant interaction was found, F (2, 14) = .088, p = .916, nor any main effects: configuration, F (2, 14) = .3.548, p = .057, leadership authenticity, F (1, 7) = 1.196, p = .310, or movement type, F (1, 7) = .3.390, p = .108.

Discussion

Experiment 3 added a hidden auditory signal to the design from experiment 1 to explore how an auditory signal, denoting assigned leadership, interacted with position during group synchronization. The ability to identify, match, and transmit the signal was expected to depend on participant position within each configuration. When the signal was sent to a position in view to all other positions, synchrony was expected to be highest. Despite several analysis approaches, the overall results for experiment 3 failed to support this hypothesis, possibly due to errors in leader identification; the visual availability of the leader to their followers did not significantly affect synchrony success.

Group and Dyadic Synchrony

Whether independent of or relative to the leader's position, group synchrony manifested similarly to experiment 1; with respect to movement type, straights were more synchronized than turns and regarding configuration, the StrL resulted in higher group synchrony than the StgL or InvT. The fact that the leader was assigned was not expected to influence the degree of synchrony depending on movement types, so the result that straights were more synchronized than turns was in line with the discussion from experiment 1. In addition, there were no significant differences found between position pairs with respect to dyadic synchrony, which was contrary to the expectation followers would be more synchronized with the leader when they were in view.

For experiment 3, if the effective relay of the leader's signal depended on their position within a configuration, it would follow that the configuration that provided the greatest visual access to the leader in the most positions (InvT) would produce the highest degree of synchrony and those that provide the least would be at a disadvantage. This was not the case, but it is not a complete surprise that the StrL synchrony was high overall. Despite P3's inability to directly see P1 (if they were the leader) in the StrL, given the high degree of synchrony between P1 and P2 and the short length of the chain, the total group synchrony would not suffer in the way that it would if P2 introduced a greater asynchrony variance or if there were more people in the StrL (Chauvigné et al., 2019). This may have led to behavior that resembles having two followers in view of the leader, rather than one, due of the effective transmission of synchrony information along the chain.

Two possible circumstances may underlie the finding that dyadic synchrony was relatively equal between the assigned leader and all other positions. First, if the leader was in view, known, and all positions were able to accurately synchronize with the leader, there would not be a difference between position pairs. For example, in the InvT, if P1 were the leader and P2 synchronized well with P1, P3 could follow the cues of either position and it would wash out any advantage of specific attention to the assigned leader, P1. Second, in the event that the leader was in P3 and completely out of view, there is no guarantee that a) P3 synchronized with the audio signal provided through their headphones over the visual cues they were receiving from P1 and P2 or b) even if they were trying to synchronize their steps with the audio signal, that they did so well enough to produce the expected asynchrony.

Exploratory Analyses

Accuracy

While participants were able to discern who the leader was on a trial to trial basis better than would be expected for chance (which does indicate that leaders were identifiable based on their visual cues to an extent), there is no record of how reliable leaders were at synching with the beat. Asynchronous stepping could have been perceived by followers as an increase in variance which made the other triad member appear as a more reliable cue to follow, thereby increasing synchrony with another member that is not the assigned leader and additionally, leading to errors in identification of the leader even when they are in view. Even though there were not significant differences in leader identification across configuration or positions within each configuration, this does not preclude the aforementioned scenario and the potential for muddying of effects.

In order to determine whether or not errors in identification of the leader played a role in the decrease in dyadic synchrony with the leader, I also investigated if on average individuals who inaccurately identified the leader within a trial, were more synchronized with the individual they reported to be the leader, but no reliable differences were found.

Due to the limited number of trials in which this occurred, the likelihood of finding a significant difference was reduced.

Definition of Followers in View

Two variants of how the number of followers in view of the leader was defined was also explored in experiment 3. Initially, it was expected that a dichotomous categorization of whether or not the leader could be seen at all would be sufficient to capture any effects on group synchrony. This method was selected first because not all configurations were balanced in terms of how many followers could see the leader depending on their position at any given time; however, since an effect was not detected, it was also prudent to further define synchrony explicitly by the number of followers that could be seen. The hypothesis was that synchrony would be highest when the leader was in view of both followers. By combining the synchrony behavior associated with only one follower in view (which you would expect to decrease synchrony), the effect of leader in view may have been too broadly defined; even though no significant effects of the number of followers were found with the more specific definition.

CHAPTER FIVE – SUMMARY AND GENERAL DISCUSSION

Summary

This dissertation is comprised of three experiments aimed to broadly examine several different aspects the dynamics of group synchronization while walking in groups of three individuals. The first experiment investigated how patterns of spatial configuration affect group synchrony. The second experiment explored leadership stability by allowing leadership to fluctuate depending on the direction of movement and sought to measure the subsequent changes in synchrony. Lastly, the third experiment built upon the methods of the first, but also explored how a hidden (only provided to one individual of the three) auditory synchrony signal could alter group synchrony by assigning leadership. All of which ultimately led to the following conclusions:

1) Synchrony was highest in the StrL, when followers were required to couple their movements with *fewer* visual cues, rather than a greater number of cues, like those available in either the StgL or the InvT configurations. The potential for cue integration that was present in the StgL and InvT configurations led to a more challenging signal processing task which ultimately resulted in a decrease in group synchrony. The StrL, on the other

hand, restricted visual information to a single source (the person if front of you) with which they were able to focus on reducing asynchrony variance with the preceding cue leading to a high degree of synchrony.

2) The way in which a group turns changes group synchrony. When collective knowledge of the path was shared and leadership was caused to fluctuate based on direction, turning resulted in higher synchrony regardless of the number of people in front, likely due to the reduced need to predict the movements of others, and a strategy of minimizing one's own movement variability emerged. Turning synchrony was lower in experiment 1 when compared to straightaways, where individuals were required to maintain their positions with respect to one another, making leadership static.

3) Assigned leadership as measured in this dissertation had little impact on group synchrony. Accuracy with respect to leader identification played a minor role in terms of follower ability to synchronize with the leader and the group as a whole.

General Discussion

More (visual) cues for synchrony is not necessarily better

Coordinated movement between individuals relies on perceptual, cognitive, and motor processes that support interpersonal synchrony (Knoblich, Butterfill, & Sebanz,

2011) and the success of that effort depends on each individual's access to information about their own other people's movements (Vesper, van der Wel, Knoblich, & Sebanz, 2013) and their willingness and ability to put that knowledge into use when acting jointly. Experiment 1 illustrated how the availability of more visual sources of information with which to synchronize does not necessarily lead to greater group synchrony and provided an excellent example of how one-way interactions as described by Honisch et al. (2016) can lead to global synchrony despite a unidirectional flow of information. Less group synchrony was achieved under task conditions that required P3 to manage the demands of synchronizing visually with two variable cues simultaneously which was also evident in the results of experiment 3.

This behavior harkens back to an old adage called Segal's law: a man with one watch knows exactly what time it is; however, a man with two watches is never quite sure. Heuristics also offer an explanation for the concept that less information is sometimes better for making judgments about the world. Gigerenzer et al. (2011) described the less-is-more effect where there is an inverse-U-shaped relationship between accuracy and the amount of information one needs to make a judgment. In some instances, more information is not better, but is actually harmful (Gigerenzer & Gaissmaier, 2011)

Since the scope of visual attention is limited, the addition of synchrony cues in a different modality could have increased the capacity group members to utilize more than one source of information simultaneously. For example, Chauvigné et al. (2019) investigated the contribution of different sensory channels to group synchrony in a dancing paradigm. In this study, 13 expert folk dancers performed to the beat of music (auditory coupling) while holding hands in a circle (haptic coupling) and seeing their fellow dancers (visual coupling) and found the greatest advantage for haptic coupling, which provided each dancer with movement information about both dancers on either side of them simultaneously over visual or auditory cues. Expansion of attention through different modalities appears to increase synchrony capacity and could have enabled P3 to integrate multiple source cues in a different way.

Sharing Space and Attention

Interestingly, across experiment 1 and 2, synchrony relating to turning as a group changed, which may relate to task demands and consequently, differing levels of success. In militaristic terms, the type of turn participants performed in experiment 2 is similar to what is described as a “flanking” maneuver, where each individual is expected to turn at the same time. Since each person was allowed to pivot around their own central axis, it reduced the need to predict the actions of others through a turn resulting in a subsequent increase in temporal synchrony that was not observed in experiment 1. This is in contrast to a “corpen” turn performed in experiment one and three, where individuals are expected to turn at the same place or location, which takes longer to and is more difficult to execute. This result highlights how accuracy increases when the task more heavily relies on regulating our own movements rather than predicting those of another. Previous research has shown that the movement of another person’s limbs follows the same mathematical principle as the movement of one’s own limbs (R. Schmidt & Richardson,

2008) which is likely supported by a mechanism that applies predictive models of one's own motor system to the observed actions of another to increase temporal prediction of an action outcome (Sebanz, Bekkering, & Knoblich, 2006). Our ability to synchronize well with others is based on our own motor expertise and experience (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005) which ultimately led to high degrees of group synchrony.

Contrary to previous research which suggests an advantage to continuous visual sources of information during coordinated action (Chauvigné et al., 2019), the demands of fluctuating leadership in experiment 2 did not result in decreased group synchrony; rather, participants likely adopted a strategy for improving synchronous movement when cues were unreliable that involved moving as predictably as possible, which allowed for the creation of procedural common ground and highly synchronized walking between all position pairs (Brennan & Clark, 1996). Despite the fact that the availability of visual cues was continuously in flux, triads were highly synchronized even when visual feedback about others was changing or even unavailable. Each of these results emphasizes the flexibility of the human perceptual-motor system to employ various timing strategies implicitly to accommodate the reliability and availability of relevant task cues.

Limitations and Future Directions

The results of the experiments in this dissertation highlight the complexities of coordinated movement in a small group of three people and provide a broad look at factors that can influence synchrony at the group and dyad levels; however, this research only begins to uncover the inter-personal characteristics that arise during a group walking paradigm.

A limitation of the present study was the inability to track how well the assigned leaders in experiment 3 were able to synchronize with the audio cue that was provided to them via wireless headphones. If audio signals could be synced and flagged within the motion capture software as an event, I could have derived a measure of the success with which an individual was able to match their metronome beat and exclude the possibility that assigned leaders were either failing to reliably follow or ignoring their signal. In addition, I would also consider making leadership assignment explicit, so as to remove any variance associated with incorrect identification of the leader.

One advantage of the present set of studies was the rich dataset provided by the 3-D motion capture system which allowed for the simultaneous recording of multiple people and body segments. Future research should investigate how other segments of the body provide cues for group synchronization, beyond the feet. For example, heading direction could provide an additional measure of visual attention such as how often leaders checked on their followers and shoulder orientation could indicate directional cues in a task where the path was not designated. Another aspect of movement that would contribute to a better understanding of group synchrony is the influence of intra-personal variability. Some measure of reliability of each individual's movements could inform how valuable a cue they provide within a group movement scenario, which was not assessed in this dissertation.

REFERENCES

Bluedorn, A. C. (2002). *The Human Organization of Time: Temporal Realities and Experience*. Stanford University Press.

Brennan, S. E., & Clark, H. H. (1996). Conceptual pacts and lexical choice in conversation. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *22*(6), 1482–1493.

Calvo-Merino, B., Glaser, D. E., Grèzes, J., Passingham, R. E., & Haggard, P. (2005). Action Observation and Acquired Motor Skills: An fMRI Study with Expert Dancers. *Cerebral Cortex*, *15*(8), 1243–1249. https://doi.org/10.1093/cercor/bhi007

Cappella, J. N. (1997). Behavioral and judged coordination in adult informal social interactions: Vocal and kinesic indicators. *Journal of Personality and Social Psychology*, *72*(1), 119.

Chang, A., Livingstone, S. R., Bosnyak, D. J., & Trainor, L. J. (2017). Body sway reflects leadership in joint music performance. *Proceedings of the National Academy of Sciences*, *114*(21), E4134–E4141. https://doi.org/10.1073/pnas.1617657114

Chauvigné, L. A. S., Walton, A., Richardson, M. J., & Brown, S. (2019). Multi-person and multisensory synchronization during group dancing. *Human Movement Science*, *63*, 199–208. https://doi.org/10.1016/j.humov.2018.12.005

Daffertshofer, A., Lamoth, C. J. C., Meijer, O. G., & Beek, P. J. (2004). PCA in studying coordination and variability: a tutorial. *Clinical Biomechanics*, *19*(4), 415–428. https://doi.org/10.1016/j.clinbiomech.2004.01.005

Dunbar, R. I. M. (2012). Bridging the bonding gap: the transition from primates to humans. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1597), 1837–1846. https://doi.org/10.1098/rstb.2011.0217

Elliott, M. T., Wing, A. M., & Welchman, A. E. (2014). Moving in time: Bayesian causal inference explains movement coordination to auditory beats. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1786). https://doi.org/10.1098/rspb.2014.0751

Franek, M., van Noorden, L., & Rezny, L. (2014). Tempo and walking speed with music in the urban context. *Frontiers in Psychology*, *5*. https://doi.org/10.3389/fpsyg.2014.01361

Frith, C. (2009). Role of facial expressions in social interactions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1535), 3453–3458. https://doi.org/10.1098/rstb.2009.0142

Gigerenzer, G., & Gaissmaier, W. (2011). Heuristic Decision Making. *Annual Review of Psychology*, *62*(1), 451–482. https://doi.org/10.1146/annurev-psych-120709-145346

Goebl, W., & Palmer, C. (2009). Synchronization of Timing and Motion Among Performing Musicians. *Music Perception: An Interdisciplinary Journal*, *26*(5), 427 438. https://doi.org/10.1525/mp.2009.26.5.427

Hasson, U., & Frith, C. D. (2016). Mirroring and beyond: coupled dynamics as a generalized framework for modelling social interactions. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(1693), 20150366. https://doi.org/10.1098/rstb.2015.0366

Honisch, J. J., Elliott, M. T., Jacoby, N., & Wing, A. M. (2016). Cue properties change timing strategies in group movement synchronisation. *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep19439

Kawase, S. (2014). Gazing behavior and coordination during piano duo performance. *Attention, Perception & Psychophysics*, *76*(2), 527–540. https://doi.org/10.3758/s13414-013-0568-0

Keller, P. E., Novembre, G., & Hove, M. J. (2014). Rhythm in joint action: psychological and neurophysiological mechanisms for real-time interpersonal coordination. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1658), 20130394–20130394. https://doi.org/10.1098/rstb.2013.0394

Kelso, J. A. (1984). Phase transitions and critical behavior in human bimanual coordination. *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *246*(6), R1000–R1004. https://doi.org/10.1152/ajpregu.1984.246.6.R1000

Knoblich, G., Butterfill, S., & Sebanz, N. (2011). Psychological Research on Joint Action. In *Psychology of Learning and Motivation* (Vol. 54, pp. 59–101). https://doi.org/10.1016/B978-0-12-385527-5.00003-6

Konvalinka, I., Vuust, P., Roepstorff, A., & Frith, C. D. (2010). Follow you, follow me: continuous mutual prediction and adaptation in joint tapping. *Quarterly Journal of Experimental Psychology (2006)*, *63*(11), 2220–2230. https://doi.org/10.1080/17470218.2010.497843

Marmelat, V., Delignières, D., Torre, K., Beek, P. J., & Daffertshofer, A. (2014). 'Human paced' walking: Followers adopt stride time dynamics of leaders. *Neuroscience Letters*, *564*, 67–71. https://doi.org/10.1016/j.neulet.2014.02.010

Nan, N., Jenkins, J. N., McCarty, J. C., & Wu, J. (2016). Comparison of REML and MINQUE for Estimated Variance Components and Predicted Random Effects. *Open Journal of Statistics*, *06*, 814. https://doi.org/10.4236/ojs.2016.65067

Néda, Z., Ravasz, E., Brechet, Y., Vicsek, T., & Barabási, A.-L. (2000). Self-organizing processes: The sound of many hands clapping. *Nature*, *403*(6772), 849. https://doi.org/10.1038/35002660

Nessler, J. A., & Gilliland, S. J. (2009). Interpersonal synchronization during side by side treadmill walking is influenced by leg length differential and altered sensory feedback. *Human Movement Science*, *28*(6), 772–785. https://doi.org/10.1016/j.humov.2009.04.007

Phillips-Silver, J., Aktipis, C. A., & Bryant, G. A. (2010). The ecology of entrainment: Foundations of coordinated rhythmic movement. *Music Perception*, *28*(1), 3–14. https://doi.org/10.1525/mp.2010.28.1.3

Phinyomark, A., Hettinga, B. A., Osis, S., & Ferber, R. (2015). Do intermediate- and higher-order principal components contain useful information to detect subtle changes in lower extremity biomechanics during running? *Human Movement Science*, *44*, 91 101. https://doi.org/10.1016/j.humov.2015.08.018

Phinyomark, A., Petri, G., Ibáñez-Marcelo, E., Osis, S. T., & Ferber, R. (2018). Analysis of Big Data in Gait Biomechanics: Current Trends and Future Directions. *Journal of Medical and Biological Engineering*, *38*(2), 244–260. https://doi.org/10.1007/s40846 017-0297-2

Repp, B. H., & Su, Y.-H. (2013). Sensorimotor synchronization: A review of recent research (2006–2012). *Psychonomic Bulletin & Review*, *20*(3), 403–452. https://doi.org/10.3758/s13423-012-0371-2

Richardson, M. J., Garcia, R. L., Frank, T. D., Gergor, M., & Marsh, K. L. (2012). Measuring group synchrony: a cluster-phase method for analyzing multivariate movement time-series. *Frontiers in Physiology*, *3*. https://doi.org/10.3389/fphys.2012.00405

Sanders, A. F., & Donk, M. (1996). Chapter 2 Visual search. In O. Neumann & A. F. Sanders (Eds.), *Handbook of Perception and Action* (pp. 43–77). https://doi.org/10.1016/S1874-5822(96)80019-3

Schmidt, R. C., & Turvey, M. T. (1994). Phase-entrainment dynamics of visually coupled rhythmic movements. *Biological Cybernetics*, *70*(4), 369–376.

Schmidt, Richard C., & Richardson, M. J. (2008). Dynamics of Interpersonal Coordination. In *Understanding Complex Systems*. *Coordination: Neural, Behavioral and Social Dynamics* (pp. 281–308). https://doi.org/10.1007/978-3-540-74479-5_14

Sebanz, N., Bekkering, H., & Knoblich, G. (2006). Joint action: bodies and minds moving together. *Trends in Cognitive Sciences*, *10*(2), 70–76. https://doi.org/10.1016/j.tics.2005.12.009

Shockley, K., Santana, M.-V., & Fowler, C. A. (2003). Mutual interpersonal postural constraints are involved in cooperative conversation. *Journal of Experimental Psychology. Human Perception and Performance*, *29*(2), 326–332.

Strogatz, S. H. (2000). From Kuramoto to Crawford: exploring the onset of synchronization in populations of coupled oscillators. *Physica D: Nonlinear Phenomena*, *143*(1), 1–20. https://doi.org/10.1016/S0167-2789(00)00094-4

Styns, F., van Noorden, L., Moelants, D., & Leman, M. (2007). Walking on music. *Human Movement Science*, *26*(5), 769–785. https://doi.org/10.1016/j.humov.2007.07.007

Vesper, C., van der Wel, R. P. R. D., Knoblich, G., & Sebanz, N. (2011). Making oneself predictable: reduced temporal variability facilitates joint action coordination. *Experimental Brain Research*, *211*(3–4), 517–530. https://doi.org/10.1007/s00221 011-2706-z

Vesper, C., van der Wel, R. P. R. D., Knoblich, G., & Sebanz, N. (2013). Are you ready to jump? Predictive mechanisms in interpersonal coordination. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 48–61. https://doi.org/10.1037/a0028066

Wright, R. L., & Elliott, M. T. (2014). Stepping to phase-perturbed metronome cues: multisensory advantage in movement synchrony but not correction. *Frontiers in Human Neuroscience*, *8*. https://doi.org/10.3389/fnhum.2014.00724

Zivotofsky, A. Z., & Hausdorff, J. M. (2007). The sensory feedback mechanisms enabling couples to walk synchronously: An initial investigation. *Journal of NeuroEngineering and Rehabilitation*, *4*, 28. https://doi.org/10.1186/1743-0003-4-28

BIOGRAPHY

Wendy Lee Baccus graduated from Osbourn High School, Manassas, Virginia, in 2004. She received her Bachelor of Arts from George Mason University in 2008. She was employed as Research Strategist in Chevy Chase, MD for three years and received her Master of Arts in Psychology from George Mason University in 2013.