Asymmetries in Interpersonal Coordination:

recruiting degrees-of-freedom stabilizes coordination

by

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ABSTRACT

The current paper presents two studies that examine how asymmetries during interpersonal coordination are compensated for. It was predicted that destabilizing effects of asymmetries are stabilized through the recruitment and suppression of motor *degrees-of-freedom* (df). Experiment 1 examined this effect by having participants coordinate line movements of different orientations. Greater differences in asymmetries between participants yielded greater spatial deviation, resulting in the recruitment of *df.* Experiment 2 examined whether coordination of movements asymmetrical in shape (circle and line) yield simultaneous recruitment and suppression of *df*. This experiment also tested whether the initial stability of the performed movement alters the amount of change in *df*. Results showed that changes in *df* were exhibited as circles decreasing in circularity and lines increasing in circularity. Further, more changes in *df* were found circular (suppression) compared to line (recruitment) movements.

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ASYMMETRIES AND INTERPERSONAL COORDINATION

Research has shown that people in dyads and groups coordinating their movements with each other exhibit similar patterns to one person coordinating multiple limbs (Fine & Amazeen, 2011; Fine, Gibbons, & Amazeen, 2013; Schmidt, Carello, & Turvey, 1990). This suggests that similar principles constrain the execution and stability of intra- and interpersonal motor coordination (Riley, Richardon, Shockley, & Ramenzoni, 2011; Schmidt, Bienvenu, Fitzparick, & Amazeen, 1998; Schmidt & Richardson, 2008). A common feature of motor coordination is that its stability is impacted by asymmetries, such as one or two people coordinating limbs at different speeds (Schmidt & Turvey, 1994), amplitudes (Fine & Amazeen, 2011; Schwartz, Amazeen, & Turvey, 1999), or directions (Richardson, Campbell, & Schmidt, 2009; Meesen, Wenderoth, Temprado, & Swinnen, 2008). In some cases, these asymmetries will lead to a transition to a new mode of coordination. However, in many cases, transitions are not exhibited and stability is maintained through alterations in local parameters (e.g., addition or suppression of spatial planes). This process has received less attention (Buchanan, Kelso, de Guzman, & Ding, 1997; Fink, Kelso, Jirsa, & de Guzman, 2000; Richardson et al., 2009). In this paper, two studies examine how asymmetries during interpersonal coordination are accommodated by changes in local movement parameters.

Coordination Dynamics

Coordination of the limbs can be captured by a single variable, their *relative phase* (Φ). This variable describes the organization of a high *degree-of-freedom* (*df*) motor system without explicitly addressing the underlying mechanisms. Without practice, in-phase ($\Phi = 0°$) and anti-phase ($\Phi = 180°$) modes of coordination are performable with minimal variability (Kelso, 1984). In-phase coordination is stable across most movement frequencies (Kay, Kelso, Saltzman, & Schoner, 1987; Kelso, 1984). When coordination is prepared anti-phase, however, the pattern becomes unstable at some critical frequency (Haken, Kelso, & Bunz, 1985; Kay et al., 1987). At this frequency, a transition from anti- to in-phase occurs. This suggests that in-phase is generally more stable than anti-phase. Akin to the intrapersonal case, in-phase interpersonal coordination is more stable than anti-phase. Furthermore, phase transitions emerge due to decreased coordination stability at critical frequencies (Schmidt et al., 1990; Schmidt et al., 1998). Such similarity between intra- and interpersonal coordination points to general dynamic principles governing the formation of coordination patterns and their respective stability (Richardson, Lopresti-Goodman, Mancini, Kay, & Schmidt, 2008). Coordination constraints are not reliant upon a specific substratum, but function across different organism-environment systems (Riley et al., 2011; Rosenblum, Pikovsky, & Kurths, 2001; Strogatz, 2003).

Movement Asymmetries and Lost Stability

When two people coordinate their movements, it is likely that certain asymmetries will exist. These asymmetries may result from individual differences (e.g., the size, mass, or preferred movement frequencies of the limbs) or task differences such as a leader-follower dance routine. Coordination asymmetries have been studied, mainly, by manipulating the natural movement frequency of each limb or person (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007; Schmidt et al., 1998). This can be accomplished by having participants coordinate pendulums with different natural oscillation frequencies (Kugler & Turvey, 1987). As the difference between pendulum frequencies increases, coordination variability (indexed by SDΦ) increases (Fuchs, Jirsa, Haken, & Kelso, 1996; Schmidt & Turvey, 1994) for two-handed intrapersonal (Kay et al., 1998; Mulvey, Amazeen, & Riley, 2005) or interpersonal coordination (Amazeen, Schmidt, & Turvey, 1995; Schmidt et al., 1998).

Coordination symmetry is also broken by spatial differences. Amazeen, Amazeen, and Turvey (1998) showed that manipulating the orientation of two pendulums (inverted or parallel) has similar consequences on SDΦ. Pendulums oriented in an inverted manner yielded greater variability. A similar interpersonal case has been found when two individuals coordinate spatially orthogonal arm movements (Fine et al., 2013; Richardson et al., 2009). Similarly, an individual producing increasingly different orientations or shapes with each hand (e.g., one hand moving circularly and the other linearly) will exhibit increased coordination variability. Each hand adopts spatial characteristics of the other; a line becomes might become circular and vice versa (Swinnen, Dounskaia, Levin, & Duysens, 2001; Franz, Zelaznik, & McCabe, 1991).

These tasks have been instrumental in uncovering two major tendencies during asymmetric coordination: effectors express their autonomy by performing close to the expected frequency or pattern, but also deviate in the direction of their counterpart's overall pattern in timing or space (Schmidt et al., 1998). The latter point indicates that coordination stability is maintained through local changes (e.g., frequency or spatial adaptation). These findings present the question about what is controlled during coordination (Latash, 2008; Scholz & Schoner, 1999). Because coordination characteristically requires asymmetric contributions from each person or hand (Treffner & Turvey, 1996), it is necessary to consider how each person or effector accommodates the other so as to achieve some movement goal with minimal deviation.

Changing *df* Stabilizes Coordination

When coordination stability is compromised through asymmetric arrangements (e.g., anti-phase), the motor system can globally reorganize the motor *df* (*degrees-of-freedom*) through phase transitions. Given that many real world activities can't be accomplished without a specific coordination pattern, global reorganization does not always present an ideal solution. This suggests that alternative mechanisms must be employed to stabilize coordination. Because the motor system is a high-dimensional system composed of redundant *degrees-of-freedom* (Bernstein, 1967), an alternative solution to the stability problem is the suppression and recruitment of motor *df* (Kelso, 1995; Kelso, Buchanan, de Guzman, & Ding, 1993).

An example of *df* recruitment is seen when individuals' movements are not constrained to a specific plane during anti-phase (asymmetric) bimanual coordination (Fink et al., 2000); there is not always a transition from anti- to in-phase at high frequencies (Buchanan & Kelso, 1999; Kelso et al., 1993). Instead, movement spatial trajectories increased in the number of movement dimensions (2D (planar) to 3D (elliptical)). In the case of bimanual coordination, these shifts are accompanied by the recruitment of forearm movement (Buchanan & Kelso, 1999; Fink et al., 2000). This behavior does not appear if the forearm movement is restricted, yielding transitions instead. The tendency to adopt spatial characteristics of the contralateral hand when coordinating the drawing of asymmetric (e.g., circle & line) shapes (Franz, Zelaznik, & McCabe, 1991; Swinnen, Dounskaia, Levin, & Duysens, 2001) is another example of *df* recruitment. When producing single-handed (unimanual) movements, recruitment and suppression processes serve a similar purpose (Buchanan & Kelso, 1999; Buchanan, Kelso, de Guzman, 1997). Buchanan et al. (1997) had individuals trace arcs of different curvatures with a specified phase relationship between joints. The pattern was maintained by recruiting or suppressing movements from the shoulder or wrist joints.

Similar conclusions have been drawn about interpersonal coordination (Richardson et al., 2009). The proposal is that the alterations of *df* during asymmetric coordination presents, like phase transitions, a solution for a coupled system of effectors to stabilize. For example, Kilner, Pauligan, & Blakemore (2003) and Richardson et al. (2009) had participants coordinate spatially congruent and incongruent arm movement with a confederate (see Fig. 1). In both studies, when movements were incongruent, the participant's movement in the unintended (orthogonal) plane increased markedly. Kilner et al. (2003) interpreted this effect as motor error or neural interference between the perceived movement and the participant's intended; this conclusion is an extension of that typically applied to bimanual coordination (Swinnen et al., 2001; Ivry et al., 2004). Richardson et al. (2009), however, demonstrated that the participants' unintended movements were oscillatory and coordinated with the intended movements of the confederate. Despite research showing that changes in the *df* stabilize coordinated movements, there is little understanding about whether these changes are absolute or scale with movement asymmetries. Furthermore, it is unclear as to whether asymmetrically coordinating systems will always trend towards recruitment (or suppression) of *df*.

Experiment 1: Spatial Symmetry Breaking

This goal of this experiment was to examine the effects of one-dimensional spatial asymmetries during interpersonal coordination (Kilner et al., 2003; Richardson et al., 2009). The aim was to establish that increasing the degree of spatial asymmetry (incongruence) between participants is complemented by the recruitment and suppression of spatial *df.* A paradigm similar to Kilner et al. (2003) and Richardson et al. (2009) was implemented. Two individuals coordinated linear movements of the same and different orientations. The main prediction was that increased differences in orientation (asymmetry) should yield recruitment of *df*. The angular orientation of each participant's trajectory was expected to shift towards the other participant's intended orientation. Further, the size of this shift was expected to increase with the degree of asymmetry. Because the spatial deviations or unintended movements are proposed to represent changes in the *df,* the unintended movements of one person are expected to entrain (e.g., frequency locked) to the other person's intended movements.

Methods

Participants. Ten dyads (fourteen men and six women, mean age = 20.2 years) from Arizona State University were recruited for this experiment for fulfillment of an

Introductory Psychology class requirement. All participants were classified as right-hand dominant using self-report.

Design. Participants coordinated arm movements in six different orientations (see Fig.1). The design consisted of 36 conditions, resulting from a combination of Participant-A Orientation (-90^o, -60^o, -30^o, 0^o, 30^o, & 60^o) and Participant-B Orientation (-90^o, -60^o, -30^o, 0^o, 30^o, & 60^o). To reflect the influence of asymmetries on movement performance, the measures described below were analyzed with a 6 Performer Orientation (-90^o, -60^o, -30^o, 0^o, 30^o, & 60^o) x 6 Orientation Asymmetry (-60^o, -30^o, 0^o, 30^o, 60^o, and 90^o) repeated-measures design. Performer Orientation refers to the movement orientation of the person's data being analyzed; each person's data was analyzed separately to capture effects of orientation on their movement goal. Orientation Asymmetry refers orientation difference (deg) between the person's data analyzed under the Performer Orientation variable and the other participant's orientation. To establish whether the anticipated effects of recruitment and suppression of *df* are due to the coordination of both performers, baseline conditions with only one performer were also examined. If performance variability is due to performing the movements under a coordination constraint, then dependent measures should differ with respect to baseline. In these trials, individuals produced continuous movements of each line orientation without a partner. These conditions were analyzed with a single factor design of Performer Orientation (-60^o, -30^o, 0^o, 30^o, 60^o, & 90^o). There was one trial per condition, for a total of 48 trials. Based on past studies examining similar behaviors (Kilner et al., 2003; Richardson et al., 2009), movements were performed at a frequency of 1.2 Hz.

Materials. Movement trajectories and experimental stimuli were controlled using a custom computer program. The program recorded the *x* and *y-plane* movement trajectories (sampling rate = 100 Hz) of each participant from infrared diodes (IREDS; diameter = 1mm) attached to the distal end of a participant's finger. Data capture was controlled by an Optotrak 3020 motion capture system (Northern Digital Inc.). All movement information was displayed at the participants' eye-height using a projector.

[Insert Figure 1 about here]

Procedure. Each dyad was instructed to coordinate movements, while maintaining their assigned movement orientation. Participants were instructed to coordinate via simultaneous arrival of the two closest endpoints of each person's oriented lines. At the beginning of each trial, participants were shown a display of two lines corresponding to one of the possible orientations (see Fig. 1). They were shown which endpoints coincided for the purpose of coordination. For baseline trials, only one movement orientation was displayed. A metronome was played at the beginning of each trial to set the target frequency. After a five second period, the lines and metronome were removed. Each trial lasted 45 seconds.

Results

Intended Coordination. To obtain a measure of coordination, each participant's *x* and *y* movements were rotated using principal components analyses (PCA). This yielded two separate trajectories (reconstructed components); the first component was the trajectory containing the majority of variance after PCA. The reconstructed trajectories containing the majority of variance from each person's movements was used to calculate cross-spectral coherence (frequency correlation), which provides an index of coordination (intended) strength. Coherence was analyzed using a 6 Performer Orientation (-90°, -60°, -30°, 0°, 30°, & 60°) x 6 Orientation Asymmetry (-60°, -30°, 0°, 30°, 60°, and 90°) repeated-measures ANOVA. Using a Greenhouse-Geiser correction, only the main effect of Orientation Asymmetry was significant, $F(3.39,30.55)= 7.92$, $p < .05$, $\eta_p^2 = .46$. Comparing the mean coherence (Figure. 2) collapsed across Performer Orientation reveals that greater asymmetries yielded reduced coordination.

[Insert Figure 2 about here]

Analysis of changes in *df*. Based on the prediction that spatial asymmetries will lead to recruitment of spatial *df* to stabilize coordination, it is anticipated that an individual's deviation from their intended orientation should be highest at maximum asymmetry (e.g., combination of 0° and 90°). Trajectory accuracy was assessed using the average angular orientation for each person's movement trajectory. Angles were found by fitting a line to the data on each movement cycle, and converting the slope to an angle ($\theta \text{ (orientation)} = \tan^{-1}\left(\frac{y_i - y_0}{x_i - x_0}\right)$). The signed difference between the performed and intended orientation ($\theta_{intended}$- θ_{actual}) provided a measure of constant error. Angular deviation was analyzed using a 6 Performer Orientation (-90°, -60°, -30°, 0°, 30°, &60°) x 6 Orientation Asymmetry (-60°, -30°, 0°, 30°, 60°, and 90°) repeated-measures ANOVA.

Where necessary, Greenhouse-Geiser corrected results are presented for violations of variance homogeneity. Analyses revealed both main effects of Performer Orientation, $F(1.87, 16.87) = 39.99$, $p < .05$, $\eta_p^2 = .42$, and Orientation Asymmetry, $F(2.75, 24.76) = 32.16$, $p < .05$, $\eta_p^2 = .78$, were significant. The interaction of both factors was also significant, $F(5.16, 46.43) = 3.47$, $p < .05$, $\eta_p^2 = .28$. Follow-up contrasts revealed the source of the interaction was due to the $0^o$and 60^o Performer Orientation differing from the other orientations at the -30^o and -60^o Orientation Asymmetries ($p < .05$). This result is seen in Figure 3. Baseline angular deviation was analyzed using a one-way, repeated measures ANOVA with a single factor of Performer Orientation (-90^o, -60^o, -30^o, 0^o, 30^o, &60^o). There was a significant effect of Performer Orientation, $F(1.52, 13.72) = 4.52$, $p < .05$, $\eta_p^2 = .34$. The angular deviation means for coordination and baseline trials are shown in Figures. 3 and 4, respectively.

[Insert Figure 3 about here]

[Insert Figure 4 about here]

Following past studies (Fine et al., 2013; Richardson et al., 2009), a measure of unintended coordination, orthogonal to the intended plane has been used as a measure of *df* recruitment. In other words, if the changes in a person's movement are due to the changes in motor *df*, it is expected that these emerging, non-dominant movements will demonstrate task specific properties (Fine et al., 2003; Richardson et al., 2009); this includes rhythmic behavior and coordination with the other person's dominant rhythmic movements (c.f., Kilner et al., 2003). This analysis requires comparing each person's dominant movement to the other person's non-dominant movement. Unintended coordination was assessed by calculating the mean spectral coherence of each person's dominant trajectory and the other person's non-dominant trajectory. The dominant (intended) and non-dominant (unintended) movement trajectories were created using reconstructed components after PCA. The trajectory with the lowest variance (2nd reconstructed component) was considered the non-dominant movement. Unintended coordination was analyzed using a 6 Performer Orientation (-90°, -60°, -30°, 0°, 30°, & 60°) x 6 Orientation Asymmetry (-60°, -30°, 0°, 30°, 60°, and 90°) repeated-measures ANOVA. The effects of Performer Orientation, $F(5, 95) = 2.86$, $p < .05, \eta_p^2 = .13$, and Orientation Asymmetry, $F(5, 95) = 22.41$, $p < .05, \eta_p^2 = .54$, were both significant. The two-way interaction was also significant, $F(25,475) = 3.35$, $p < .05, \eta_p^2 = .15$. The interaction is due to coherence differences between levels of Performer Orientation at the 90° level of Orientation Asymmetries ($p < .05$, using simple contrasts).

[Insert Figure 5 about here]

Discussion

Previous research on bimanual (Swinnen, Jardin, Verschueren, Meulenbroek, Franz, Dounskaia, & Walter, 1998) and interpersonal coordination (Fine et al., 2013; Richardson et al., 2009) has shown that coordinating directionally orthogonal movements leads to coordination between a person's unintended and another person's intended movements (Fine et al., 2013; Richardson et al., 2009). Past studies have only examined conditions where movement orientations were the same or maximally different (equivalent to 90^{o} asymmetry).

Considering the effects of symmetry breaking on coordination (Amazeen, Amazeen, & Turvey, 1998), we predicted that coordination strength and changes in *df* should scale with the degree of asymmetry between a dyad's movements. This hypothesis was tested by incrementally changing the degree of asymmetry between individual's movement angles. As seen in Fig. 2, the 0^{o} Asymmetry Orientation exhibited a level of coherence expected from stable coordinated movements. Shifting out towards either -60^{o} or 90^{o}, the intended coordination coherence decreased as Orientation Asymmetry increased. Comparing the Figures (2 & 5) and results for the intended and unintended coherence suggests, though, that coordination did not disappear globally. The intended coordination (Figure. 2) coherence was highest at the 0^{o} Orientation Asymmetry, while unintended coherence was minimal at this point. Examining both graphs (Figures 2 & 5) across levels of Orientation Asymmetry reveals a trade-off, with one increasing (unintended coordination) and the other decreasing (intended coordination). The increased unintended coordination suggests that alteration of these *df* stabilized the overall coordination task.

Because the predictions were based on spatial asymmetries, alterations in the motor *df* were expected to occur in the direction of the Orientation Asymmetry (Fine et al., 2013). Importantly, the angular deviation results mirror findings of *df* recruitment during bimanual coordination (Fink et al., 2000), except across two people. The main effect of angular deviation (Figure. 3) scaled with the degree of Asymmetry Orientation, and the deviation's sign was consistent with the sign of the asymmetry; negative asymmetries exhibited negative deviations from the intended angle and vice versa. Overall, the effects of the unintended coordination strength and angular deviation support the findings of past research (Fine et al., 2013; Fink et al., 2000; Richardson et al., 2009). Namely, unintended movements found during spatially asymmetric coordination reflect directionally and amplitude specific alterations in the motor *df*. These findings point towards recruitment and suppression processes as a task specific change that stabilizes coordination.

Experiment 2: changing *df* depends on initial stability

The intent of this experiment, following past results and experiment 1, was two-fold. First, to demonstrate that spatial adaptation for different shapes occurs during interpersonal coordination. Because the coordination is between two individuals, it stands to reason that adaptation represents changes in the *df*. During bimanual coordination of line and circle movements (Franz et al., 1991), motor *df* change (spatial adaptation) in the form of recruited (lines become more circular) or suppressed dimensionsality (circles become more linear). In this case, movements are asymmetrical in their shape. Researchers have also suggested that this spatial adaptation is due to neural interference of motor programs (Diedrichsen, Ivry, Hazeltine, Kennerley, & Cohen, 2003; Diedrichsen, Nambisan, Kennerley, & Ivry, 2004) or abstract spatial representations (Hommel, Musseler, Aschersleben, & Prinz, 2001; Franz, Zelaznik, Swinnen, & Walter,

2001) of the shapes. During interpersonal coordination, however, there is no centralized controller.

In a coupled system of effectors, recruitment and suppression processes can provide stability to accommodate asymmetric task goals. When the goals are, for example, to draw a circle with one hand and a line with another, it is clear that the hands mediate stability through recruitment and suppression of *df.* Though the amount that one hand changes with respect to the other is likely not equivalent. To stabilize the global coordination task, one hand will likely change more than the other, suggesting an unequal bidirectional coupling (Treffner & Turvey, 1995). Using an asymmetric shape coordination task, we tested whether line movements change more than circle movements. Given the coupling between effectors, we predicted that movements of lower dimensionality (e.g., drawing a line) will exhibit less recruitment of *df* than systems of higher dimensionality (e.g., drawing a circle) exhibit suppression of *df*. This prediction is based on the assumption that higher dimensional (circle) movements become less stable when coupled to a lower dimensional (line) movement.

To test these predictions, participants coordinated line and circle movements. In all conditions, one individual produced a line of differing orientation and the other person a circular movement. These conditions were expected to yield recruitment (line movements) and suppression (circle movements) of spatial *df*. Circle drawings should exhibit decreased circularity, while line drawings should increase in circularity; further, circle drawings were expected to suppress along the plane parallel to the line drawing.

Methods

Participants. Ten dyads (nine men and eleven women, mean age = 19.4 years) from Arizona State University were recruited for this experiment for fulfillment of an Introductory Psychology class requirement. All participants were classified as right-hand dominant.

Materials. Movement trajectories and experimental stimuli were controlled using a custom computer program. The program recorded the *x* and *y-plane* movement trajectories (sampling rate = 100 Hz) of each participant from infrared diodes (IREDS; diameter = 1mm) attached to the distal end of their finger. Data capture was controlled by an Optotrak 3020 motion capture system (Northern Digital Inc.). All movement information was displayed at the participants' eye-height using a projector.

Design. Participants coordinated right-arm movements by drawing different shapes (line and circle). Movements were performed with the same end-to-end amplitude of 20 cm. Similar to experiment 1, line movements were performed in six orientations (-60^o, -30^o, 0^o, 30^o, 60^o, & 90^o; see Fig. 3). To confirm whether recruitment and suppression of *df* are due to the coordination of both performers, baseline conditions similar to experiment 1 were also examined. During these trials, individuals produced continuous movements of each line orientation and circle movements without a partner. Using two different designs, the measures described below are analyzed separately for line and circle movements. This yields a single-factor design of Orientation (-60^o, -30^o, 0^o, 30^o, 60^o, & 90^o). All movements were performed at 1.2 Hz.The total design includes

26 conditions because each person in a dyad had to perform circle and line drawings together and separately. Each trial was repeated once, for a total of 52 trials.

Procedure. The same computer setup from experiment 1 was employed. Each coordination trial started with a display consisting of two template trajectories (line and circle), each corresponding to the participant's assigned position. Baseline trials started with a display of just one line or circle. The shapes and metronome were played for five seconds before removal. Participants were instructed to begin coordinating once the templates appeared and to continue after removal. Each trial lasted 45 seconds, and the whole session lasted approximately one hour.

Results

Intended Coordination. The same coordination analysis from experiment 1 was used. Each participants *x* and *y* movements were rotated using principal components analyses. The reconstructed trajectories with the highest variance were used to calculate the cross-spectral coherence. Coherence was analyzed with a one-way repeated-measures ANOVA, with a single factor of Line Orientation (-60^o, -30^o, 0^o, 30^o, 60^o, & 90^o). Analyses revealed a significant effect of Line Orientation, $F(5,95)= 7.92$, $p < .05$, $\eta_p^2 = .25$. Examination of the mean coherence (Figure. 6) shows that the 0^o Line Orientation yielded the least stable coordination, while coordination strength increased in regions closest to 90^o

[Insert Figure 6 about here]

Analysis of changes in *df*. Two measures were used to analyze changes in *df*. Based on the first prediction that alterations would occur as spatial changes, we analyzed the degree of deviation from a movement's intended geometry. This was accomplished by finding the best fitting ellipse for each set of *x* and *y* movements, and calculating the circularity of line and circle movements. The ratio of the principal axes (semi-minor/semi-major) of each ellipse provided a measure of circularity, where a ratio of 1 indicates a circle and 0 a line. This measure was then converted into a deviation measure (constant error) for line movements (difference from 0) and for circles (1- circularity). Mean deviation was analyzed using a 2 Movement Type (Line & Circle) x 6 Line Orientation (-60^o, -30^o, 0^o, 30^o, 60^o, & 90^o) repeated-measures ANOVA. Analyses yielded significant main effects of Movement Type, $F(1,20)= 149.08$, $p < .05$, $\eta_p^2 = .98$, and Line Orientation, $F(5,95)= 8.15$, $p < .05$, $\eta_p^2 = .30$. The two-way interaction of both factors was also significant, $F(5,95)= 4.78$, $p < .05$, $\eta_p^2 = .20$. Simple contrasts revealed that mean deviation was significantly greater for the circle than the line in the -30^o, 0^o, and 30^o Line Orientation conditions ($p < .05$ for all contrasts). The mean deviations are plotted in Figure 7, and their baseline counterparts are in Figure 8.

[Insert Figure 7 about here]

[Insert Figure 8 about here]

Because the Line Orientation is predicted to affect the axis of recruitment and suppression, it is necessary to consider the movement orientations. For circle movements, orientation angle (degrees) was calculated as the rotation of the ellipse's semi-major (longest) axis, away (±) from the *x-axis* origin. For line movements, the same line fitting procedure used in experiment 1 was used. The mean Orientation Angles were analyzed using a 2 Movement Type (Line & Circle) x 6 Line Orientation (-60°, -30°, 0°, 30°, 60°, & 90°) repeated-measures ANOVA. Analyses yielded significant main effects of Movement Type, $F(1,19) = 211.89$, $p < .05$, $\eta_p^2 = .89$, and Line Orientation, $F(2.79, 53.07) = 459.35$, $p < .05$, $\eta_p^2 = .92$. The two-way interaction was also significant, $F(2.77, 51.72) = 180.58$, $p < .05$, $\eta_p^2 = .85$. Follow-up contrasts showed that the interaction was due to differences between the line and circle movements at all levels of Line orientation ($p < .05$), except 0°. The mean orientation angles for coordination trials are shown in Figure 9. Baseline orientation angles for line movements are shown in Figure 10; the mean baseline orientation for circles was 2.4°.

[Insert Figure 9 about here]

[Insert Figure 10 about here]

Lastly, coherence between each person's dominant and the other person's non-dominant movement was calculated to capture unintended coordination. The procedure for calculating unintended coordination was identical to experiment 1. Mean coherence was analyzed using a single factor of Line Orientation (-60°, -30°, 0°, 30°, 60°, & 90°) with a repeated-measures ANOVA. The analysis yielded a main effect of Line Orientation, $F(5,95) = 4.13$, $p < .05$, $\eta_p^2 = .18$.

[Insert Figure 11 about here]

Discussion

The current experiment's results extend the findings of experiment 1 and past research (Fine et al., 2013; Richardson et al., 2009) — spatially asymmetric coordination yielded spatial adaptations between two coordinating persons. The common interpretation is that neural interference between motor programs for producing each shape causes distortion in movements (Swinnen & Wenderoth, 2004). Interpersonal coordination does not afford this type of direct interference, though. What emerged, like experiment 1, was a cooperation or trade-off between intended and unintended coordination. In other words, while the intended coordination task destabilized, unintended coordination emerged at the same time; this trade-off represents the recruitment or suppression of *df*. Examination of Figure. 6 and 11 reveals this effect. Intended coordination strength (indexed by coherence; Fig. 6) was weakest at the 0^{o} Line Orientation, while unintended coordination strength (Figure. 11) was strongest at the 0^{o} Line Orientation. These differences are not surprising, given that circular movements tended to complete a cycle at the top of the circle (equivalent to a 90^{o} line orientation). Therefore, when the Line Orientation was 90^{o}, there existed a high spatial coupling between the endpoints of the circle and line movements; the opposite emerged for 0^{o} oriented line movements.

Because recruiting and suppressing motor *df* stabilizes coordination, it is necessary to consider what properties will drive a system's potential to produce these changes. It was proposed that the amount and type (recruitment or suppression) of change depends on the initial stability of an intended movement. These predictions are supported by the deviation measure; mean deviation was greater for circle compared to line movements during coordination (Figure. 7). Mean deviation of circle movements was also greater than line movements during baseline. This finding suggests a principled manner for predicting how movements of different complexity will accommodate one another when coupled. Movement types lower in stability (circles) should display greater recruitment of suppression in *df* to stabilize global performance when coupled with more stable movement types (lines). Presumably, a movement type is lent its generalized stability by the number of movement dimensions that need controlling for performance; other factors, such as differences in movement difficulty (Fine & Amazeen, 2011) or timing (Amazeen, Schmidt, & Turvey, 1995) between the hands may play a similar role. Generally, these findings suggest that coordinating effectors facing destabilizing influences (e.g., movement asymmetries) will collectively alter the control of *df* between effectors, while changing differentially within effectors. Importantly, spatial movement asymmetries are non-specific factor to manipulate because they show similar effects at an intra- and interpersonal level of analysis (Fine et al., 2013).

GENERAL DISCUSSION

It is typically assumed that spatial or timing adaptations that emerge between two hands reflect motor program interference at the neural planning level. However, experiments 1 and 2, and other studies (Fine et al., 2013; Richardson et al., 2009), demonstrated similar effects across the hands of two people. Both studies examined whether unintended movements (spatial adaptions) due to spatial asymmetries reflect local changes produced by coupled, autonomous systems to maintain global task stability. The global task in this paper was coordinating rhythmic arm movements of either differing orientations or shapes (line or circle) and dimensionality. Contrary to typical interpretations, the current and past results (Fine et al., 2013; Richardson et al., 2009; Romero, Coey, Schmidt, & Richardson, 2012) suggest these changes are not error or interference (Kilner et al., 2003; Stanley, Gowen & Miall, 2007). By inspecting participant's unintended movements, we found that those movements are coordinated with the intended movements of the other person. Moreover, changes in spatial (experiment 1), or dimensional and spatial (experiment 2) deviation scaled with the degree of asymmetry between partners' movements. Comparing movements of differing dimensionality revealed that higher dimensional movements exhibit more local changes than lower dimensional movements, especially when coupled together. Taken together, these findings suggest that spatial deviations exhibited during these and other studies (Kilner et al., 2003; Franz et al., 1991) reflect, contrary to interference, coordinated recruitment and suppression of previously dormant or currently active motor *df*.

Sources of Coordination Stability

During asymmetric coordination, overall performance is characterized by decreased coordination stability (Amazeen et al., 1995) and increased spatial deviation (Fink et al., 2000). For example, Swinnen et al. (2001) demonstrated that coordinating line movements of different orientations leads to results similar to experiment 1. Movement angles drifted in the direction of the other hand's orientation. They concluded (see also, Swinnen & Wenderoth, 2004) that these changes are due to neural interference between motor programs assigned to each of the hands. Information regarding each hand's movement parameters are shared across the corpus-callosum. The finding that spatial interference effects don't occur for split-brain patients supports this proposal (Franz, Eliassen, Ivry, Gazzaniga, 1996). However, similar effects of asymmetries on interpersonal coordination necessitate reconsidering an interference explanation (Diedrichsen et al., 2003; Franz et al., 1991). Two coordinating individuals neither share hemispheres, intact or not, nor a single cortex.

Another explanation is that spatial changes represent the recruitment or suppression of motor *df*. The current and other interpersonal coordination studies support this proposal. Fine et al. (2013; see also Richardson et al., 2009) demonstrated that spatially orthogonal movements between a participant and actor yields unintended coordination. Participants exhibited increased movements opposite of their instructed movement direction. When orthogonal to the actor's movements, the participant's unintended movements were coordinated with the actor's intended movements. The movements exhibited a structured movement pattern and were coherent at a similar frequency to the intended movements. Experiment 1 extended these findings by demonstrating that alterations to the *df* are driven by the degree of spatial asymmetry. Under conditions of little or no orientation asymmetry, intended coordination strength was high, while unintended coordination strength increased as asymmetry increased.

Akin to Swinnen et al.'s findings (2001), the first experiment also showed that the direction of spatial deviation is specific to the orientation of the other person's movement. Fink et al. (2000) demonstrated a similar recruitment of spatial *df* during bimanual coordination. The current and past findings (Fine et al., 2013; Richardon et al., 2009) suggest that recruitment processes are marked by increased rhythmic, coordinated behavioral changes. Demonstrations of this general stability mechanism, though, are usually assessed by capturing the mean coordination between dominant and non-dominant movements, for example, through coherence measures. Understanding this mechanism's ability to stabilize coordination requires further studies into how long these processes take to occur once a critical instability is reached, thus analyzing the time course of recruitment processes. Furthermore, consideration of how strongly these mechanisms hold up to unexpected perturbations to performance is also necessary for future study. Regardless, the similarity of findings across unimanual (Buchanan et al., 1999, Ryu & Buchanan, 2004), bimanual (Fink et al., 2000), and interpersonal (Fine et al., 2013; Richardson et al., 2009) coordination experiments supports the existence of emergent, stabilizing dynamics.

Broken Symmetry Redistributes Stability

Accepting the possibility that timing or spatial deviations represent changes of a system's *df* suggests a different interpretation of coordination stability. Measured deviations are typically construed as coordination destabilization (Swinnen et al., 2001) or performance failures. The intended coordination coherence and spatial deviation measures (i.e., angular deviation and circularity) in isolation implies a similar conclusion. For example, greater orientation asymmetries in experiment 1 lead to weaker intended coordination strength and increased deviation from the intended orientation. Coordination stability in this case, however, relies solely on the intended movements. The unintended coordination coherence suggests that overall stability is not globally lost, but is maintained and redistributed among the intended and unintended movements.

Studying how systems maintain task stability through changes *df* is not novel to the study of coordination, but has remained largely ignored (c.f., Buchanan et al., 1997; Kelso, 1995). Coordination research has focused mainly on phase transitions, a depiction of global *df* rearrangement. These dynamics are generically described in terms of inverted pitchfork bifurcations (Kelso, 1984; Park & Turvey, 2008), referring to systems that undergo symmetry breaking and shift to another state (anti- to in-phase). Local changes in the *df* refer to another kind of symmetry breaking bifurcation, termed Hopf bifurcations (Collins & Stewart, 1993). Generally, this type of bifurcation refers to a shift in an oscillator's behavior from a stationary fixed-point to a limit cycle (Stewart & Golubitsky, 1992; Strogatz, 1994). In terms of movement, a Hopf bifurcation refers to a shift from no movement to periodic, cyclical behavior or the other way; this depends on whether it is a super- or subcritical bifurcation (Ryu & Buchanan, 2004; Kelso et al., 1993). The current and past results (Fine et al., 2013; Fink et al., 2000; Richardson et al., 2009) on spatially asymmetric coordination are an example of Hopf bifurcations. Specifically, the recruitment of *df* are seen as unintended movements that become increasingly periodic as asymmetry increases (indexed by unintended coherence); there exists a switch from either fixed-point or unstable limit-cycle attractors to a stable limit cycle, that is coupled to the intended movement *df*. Conversely, the switch from an unstable or stable limit-cycle to a fixed point attractor is indicative of *df* suppression.

Although changes in *df* offer a general solution to maintaining stability, these *df* are not necessarily all spatial; it depends on the medium of coupling (Schmidt et al., 1998) and form of asymmetry (Mulvey et al., 2005). In the case of interpersonal coordination (Coey, Varlet, Schmidt, & Richardson, 2011; Fine et al., 2013; Richardson et al., 2009; Riley et al., 2011), coupling is purely informational through vision, and asymmetries are spatial or timing based. Thus, recruitment and suppression processes serve to stabilize the perceptual differences between perceived and produced movements. For intrapersonal coordination, strong couplings exist for visual and peripheral feedback (Amazeen, Da Silva, Amazeen, 2008; Li, Levin, Carson, & Swinnen, 2004; Park, Collins, & Turvey, 2001), giving way to more changes in *df*. These differences in coupling explain why deviations in the current experiments are driven purely by spatial asymmetries. However, it is still unclear in bimanual coordination whether these effects are driven by congruence in muscle activation (Carson, Riek, Smethurst, Parraga, & Byblow, 2000; Li et al., 2004; Salter, Wishart, Lee, & Simon, 2004), visual information (Meschner, Kerzel, Knoblich, & Prinz, 2001), or a mixture (Amazeen et al., 2008).

Initial stability Drives Recruitment and Suppression.

Clearly systems undergo changes to stabilize coordination, it is not clear why certain movements or limbs are affected more during coordination. For example, when specified movement amplitudes differ between persons, the person producing the greater amplitude will decrease their amplitude more than the other person will increase their amplitude (Fine & Amazeen, 2011). Similar behavior occurs during bimanual coordination. Swinnen et al. (2001) had individuals produce star movements with one hand and either a small or large line movement with the other hand. They found that large line movements were more variable, and deviated more from the intended amplitude. These findings mirror the current studies. Specifically, experiment 2 showed that circular movements always exhibited greater deviation than line movements (Figure. 7). Circular movements were also less stable at baseline. Whether the changes in *df* exhibit recruitment or suppression, the amount of change is driven by the initial stability of the intended movements. Experiment 2 suggests that initial stability is partially determined by movement dimensionality. It remains an open question, though, what other factors comprehensively determine a system's initial stability.

Conclusions

Two experiments are carried out to examine how instabilities created by coordination asymmetries are stabilized by local changes in movement parameters, rather global breakdowns in performance. It has been proposed by some (Swinnen & Wenderoth, 2004) that spatial (Franz et al., 1991) and amplitude (Swinnen et al., 2001) adaptations found during bimanual coordination is due to neural interference or cross-talk across the Corpus Callosum (Franz et al., 2001; Swinnen, 2002). Findings of similar spatial effects during asymmetric unimanual (Romero et al., 2012) and interpersonal coordination (Fine et al., 2013, Richardson et al., 2009) contradict a strictly neural interference conclusion. The current studies extended these past findings by the manipulating the degree of symmetry breaking and initial stability (movement dimensions) during coordination. Results suggest that unintended movements or spatial deviations likely represent the dynamics of coupled systems tendency to recruit or suppress *df* under unstable conditions (e.g., spatial or timing asymmetries). These local changes allow bypassing total reorganization of a system's components, especially under circumstances involving quick or unpredictable movement requirements.

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Figure. 1

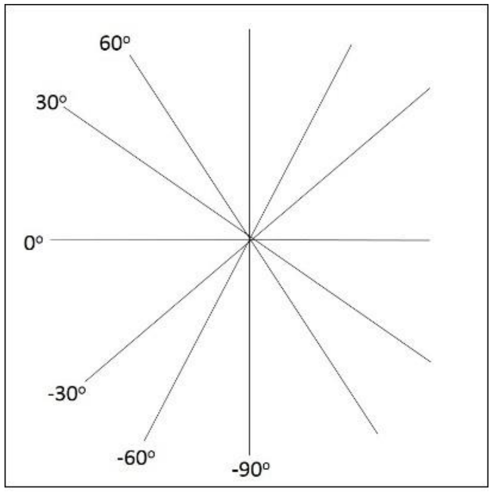
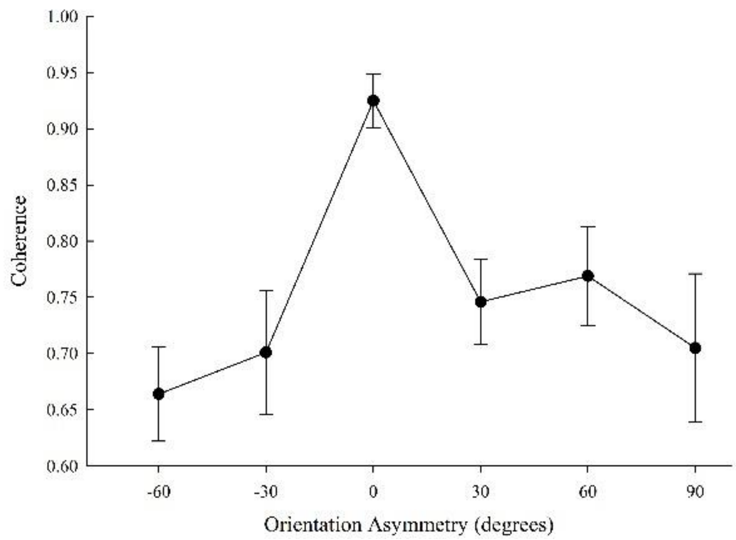


Figure. 2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0.95
0.90
0.85
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Coherence
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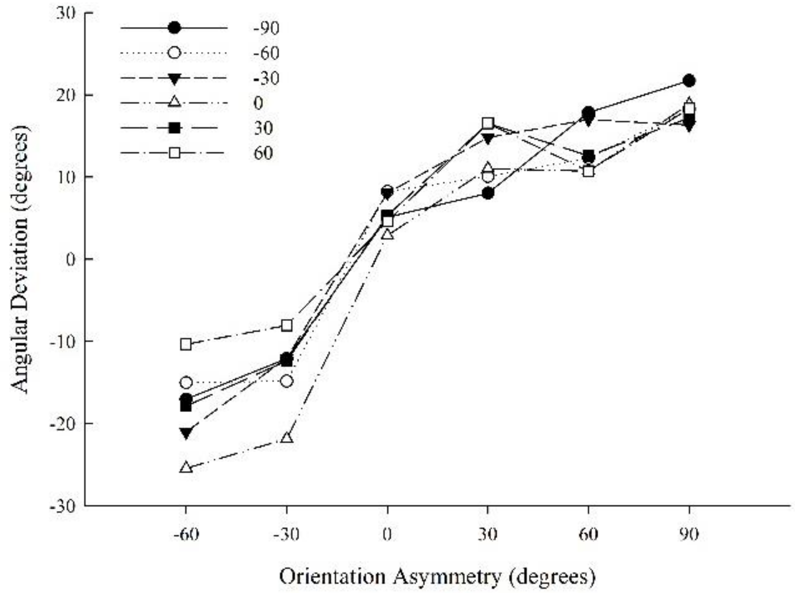
0
30
60
90
Orientation Asymmetry (degrees)

Figure. 3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Angular Deviation (degrees)
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30
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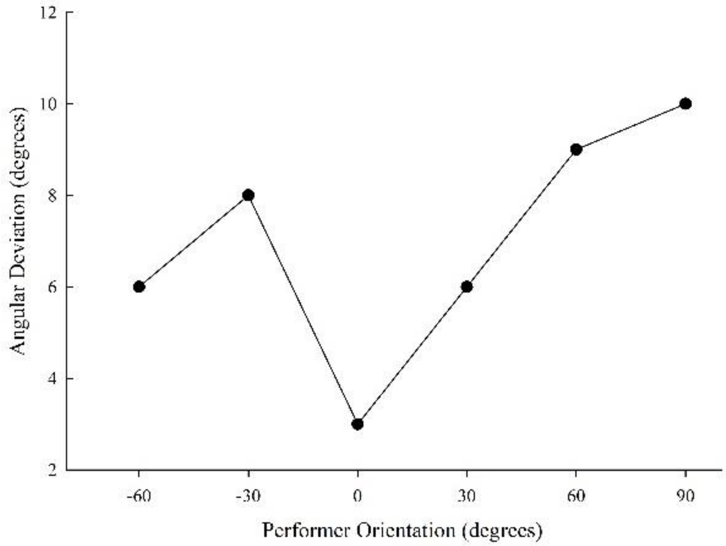
90
Orientation Asymmetry (degrees)

Figure. 4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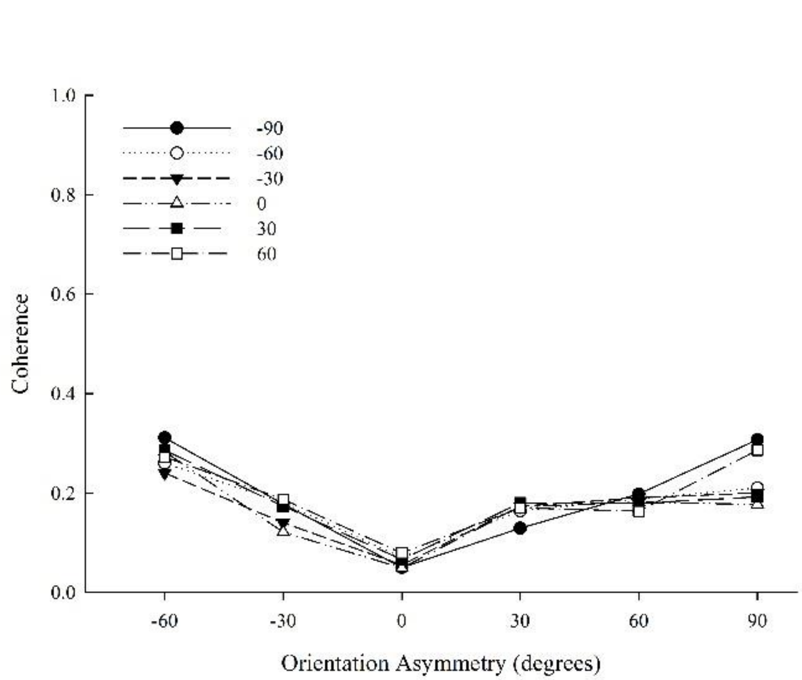
Performer Orientation (degrees)

Figure. 5



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Coherence
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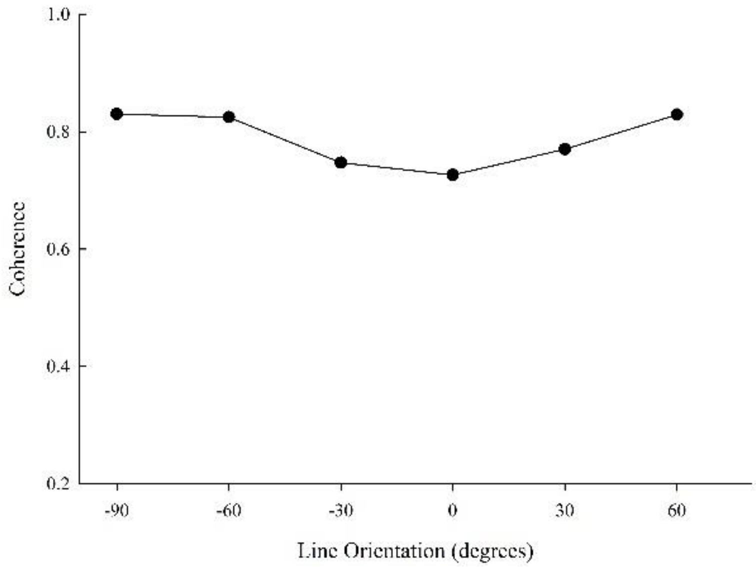
30
60
90
Orientation Asymmetry (degrees)

Figure. 6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0
30
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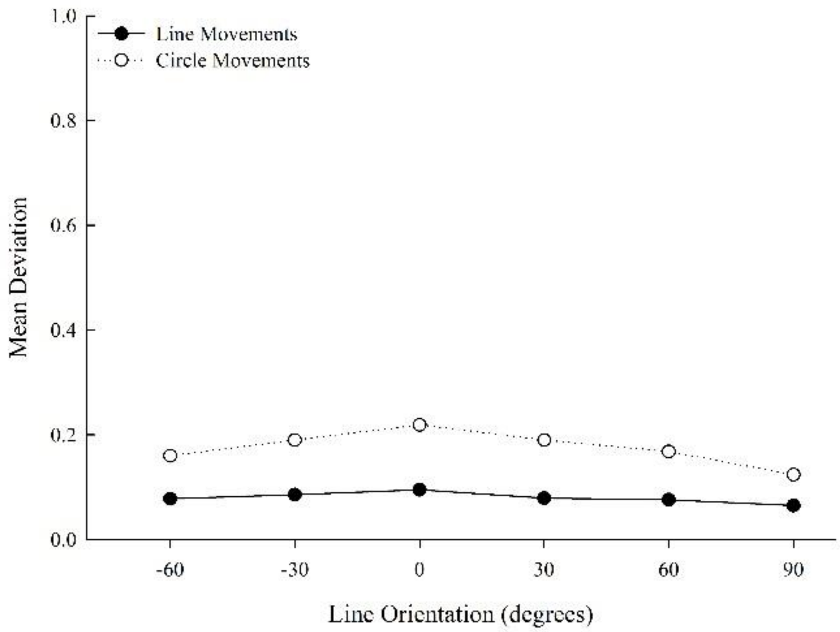
Line Orientation (degrees)

Figure. 7



Line Movements
Circle Movements
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Mean Deviation
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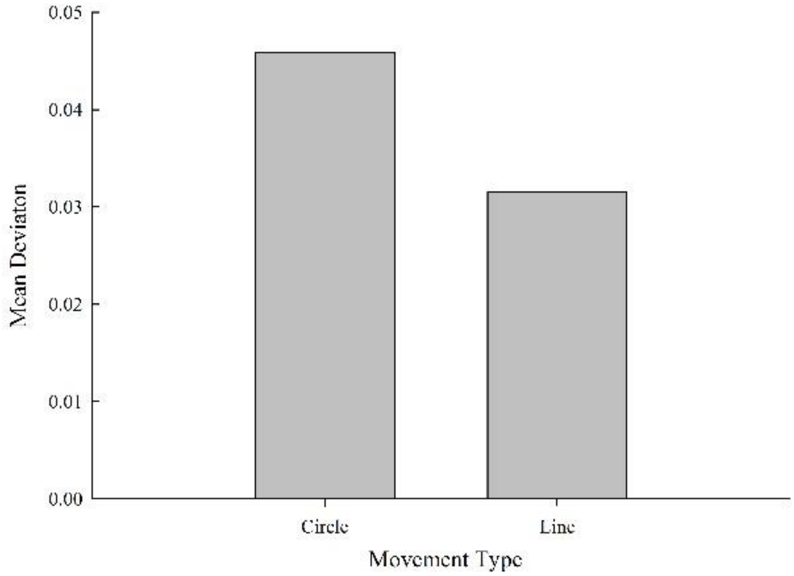
0
30
60
90
Line Orientation (degrees)

Figure. 8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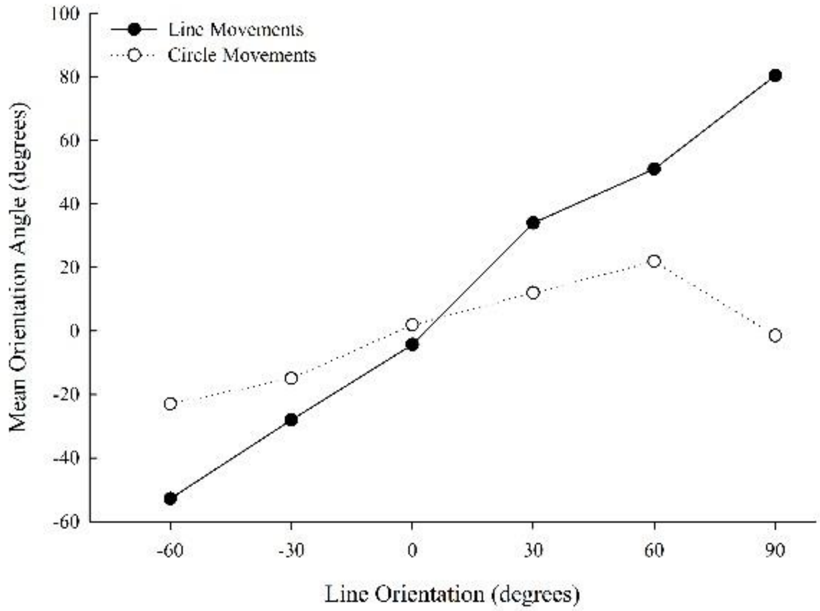
Mean Deviaton
Circle
Line
Movement Type

Figure. 9


Line Movements
Circle Movements
Mean Orientation Angle (degrees)
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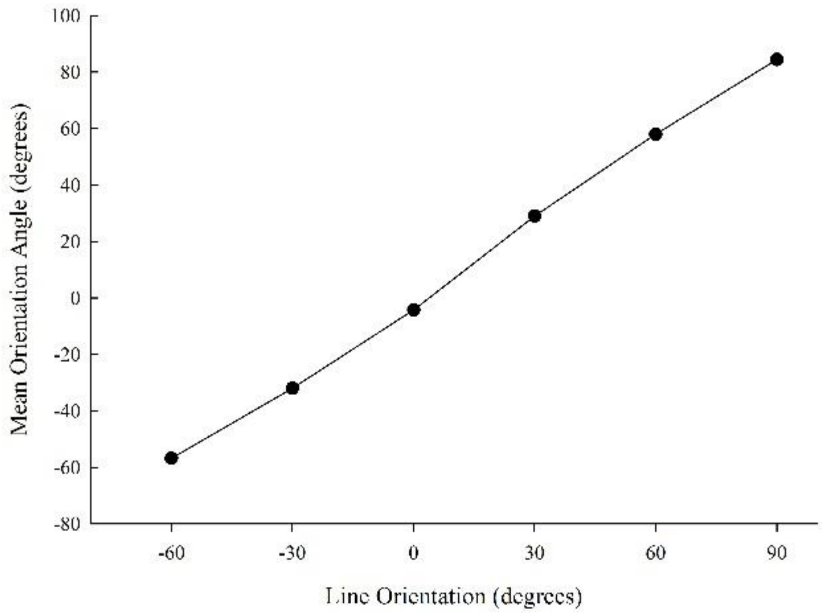
0
-20
-40
-60
-60
-30
0
30
60
90
Line Orientation (degrees)

Figure. 10



100
80
60
40
20
0
-20
-40
-60
-80
Mean Orientation Angle (degrees)
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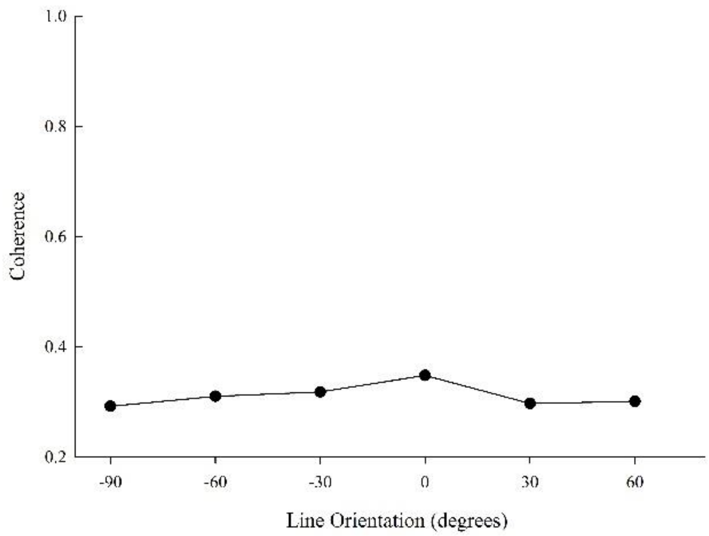
0
30
60
90
Line Orientation (degrees)

Figure. 11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Coherence
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0
30
60
Line Orientation (degrees)