Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 September 2022 doi:10.20944/preprints202203.0316.v2

The Collective Mind: An Experimental Analysis of Imitation and Self-organization in Humans

Emmanuel Olarewaju [1*]

[1] Department of Biological Sciences, University of Manitoba
* Correspondence: umolaree@myumanitoba.ca
* Correspondence: emmanuel.olarewaju@mail.mcgill.ca

Abstract: I present an experimental paradigm to explore the interpersonal dynamics generating a collective mind. I hypothesized that collective organization is based on dual interpersonal modes: (1) symmetrical and (2) anti-symmetrical. I specified the geometric topology of these modes by detecting the spatiotemporal patterns that embed cooperative agents in a three-dimensional matrix. I found that the symmetrical mode is executed automatically and without guidance. Conversely, the anti-symmetrical mode required explicit direction and recruited attention for execution. I demonstrate that self-other mirror-symmetry stabilized group dynamics, enabled fast and efficient symmetrical imitation that optimized information transmission, whereas anti-symmetrical imitation was comparatively slow, inefficient, and unstable. I determined that the anti-symmetrical mode spontaneously transitioned to the symmetrical mode under perturbations. Crucially, this renormalization mechanism never transitioned from symmetrical to anti-symmetrical. These self-organizing dynamics speak to interpersonal symmetry-breaking. In the present work, spontaneous group choice mandated that agents synchronize cooperative cycles in symmetrical space under internal or external perturbations. I provide examples to illustrate that this self-regulating pullback attractor manifests in invertebrates and vertebrates alike. I conclude by suggesting that inter-agent symmetry provides the social stability manifold through which attention-driven interactions enable intrapersonal and interpersonal change.

Keywords: 1; Social interaction 2; Self-organization 3; Imitation 4; Coordination dynamics 5; Group normalization 6; Interpersonal symmetry

1. General Introduction

This paper focuses on the sensory-motor dynamics that coordinate interpersonal perceptions and actions. In particular, my investigations provide evidence that cooperating individuals are comparable to a living system capable of informational coupling and generating automatic responses when perturbed [1]. These system dynamics rely on coordination between self and others to maintain the perceptual architecture that underlies interconnected brains across space and time. I propose that these spatiotemporal interconnections enable the nervous system to integrate the observer and the observed by encoding interpersonal symmetries whose geometric topographies facilitate prosocial responsivity and shared identity. With these underpinnings, I experimentally demonstrate that mirror-symmetrical associations between individuals are at the core of fast and efficient cooperation. In other words, the perceptual interconnectedness that enables cooperative activity requires individuals to represent a shared model based on mirror-symmetric alignments between the observer and the observed. I suggest that these self-similar alignments function as the foundation of a stable collective whose dynamic structure enables perceptions about the self to emerge from cooperative interactions with others.

The implication here is that perceptual stability about the self develops through temporal exchanges with spatially-symmetrical others. My experimental findings support this view by demonstrating that cooperation relies on mirror-symmetrical associations that maximize the spatiotemporal associations between individuals while concurrently optimizing information processing. To examine these interpersonal dynamics, I employ the synergetics approach [2] to discern the symmetrical and anti-symmetrical modes of cooperative imitation, which in this context denotes the spatiotemporal correlations overlapping the observer and the observed. In the present research, I specify this system's geometric topography by orienting dyads face-to-face and measuring the temporal responses generated during egocentric imitation. To demonstrate that mirror-symmetry underlies fast and efficient cooperative dynamics, I present an experimental framework that utilizes mirrored reference frames to investigate the effects of changing interpersonal symmetries on information processing and transmission.

To accomplish the above, I test the hypothesis that imitation encodes a collective (generative) model by regulating perception-action cycles via cooperation [2-6]. In systems neuroscience and statistical physics, theoretical and empirical works that affirm these behavioural postulates reveal that order at higher (group) scales is formed based on coordination at lower (individual) scales [5, 7]. This multiscale organization's maintenance relies on spatiotemporal connectivity to align scale-invariant dynamics at criticality [8]. Criticality is an emergent property of self-organizing systems that undergo phase transitions and spontaneous realignment when perturbed [8-11]. My experiments evaluate these scale-invariant dynamics via the analysis of cognitive demand induced perceptual symmetry-breaking [12, 13] and spatial entrainment [14] during cooperative imitation [4-6, 15]. Here, I task research subjects to engage in coordination while face-to-face. This mirrored reference frame enables the investigation of topological mapping [14] and group renormalization [16] during perturbations. Ultimately, this experimental approach demonstrates that cooperative imitation generates a spatiotemporal matrix in which individuals bind perceptually through symmetries that induce a shared (collective) model of interpersonal expectations.

1.1 Experimental Paradigm

To identify the shared model informing interpersonal expectations, I evaluate spatiotemporal correlations during cooperative imitation. All experiments exploit the mirror-symmetries of face-to-face exchanges to partition dyadic sensory perceptions bilaterally and self-other integration medially. This four-quadrant geometric paradigm leverages the dual-route model [17] and the human body's bilateral symmetry to assess interpersonal phase transitions and entrainment during cooperative action. These interpersonal (phase) transitions organize spatiotemporal scales that give rise to binary sensorimotor configurations: (1) in-phase (ipsilateral) and (2) anti-phase (contralateral) [1]. These configurations embody divergent interpersonal matrices: (1) symmetrical and (2) anti-symmetrical. These matrices enable the quantitative analysis of symmetrical and anti-symmetrical perception-action cycles under perturbations.

1.2. Summary

I disentangle the spatiotemporal architecture underpinning collective organization in humans. The topography and temporality of this organization suggest that cooperative imitation relies upon mirror- symmetries to overlap the observer's geometric features with the observed. This interpersonal mapping draws on a collective model to guide perceptions and actions across space and time. In this mirrored social context, cooperative exchanges are automatic, and mutual information is effectively transmitted. The realization of these perceptual efficiencies has important implications for research on human behaviour because they tell the story of social organization in terms of prediction error minimization through interpersonal symmetry-seeking. In this paradigm, cooperative processes enlist automatic imitation to embed the mind in a collective matrix. The following two experiments explore this matrix of mirrored minds by testing social cognition and cooperative action under changing interpersonal contexts.

2. Experiment 1: The Effect of Symmetrical and Anti-symmetrical Imitation on Social Cognition

2.1 Introduction

I aim to demonstrate that the fundamental patterns of synergetic coordination arise spontaneously from self-organizing dynamics. I propose that these emergent patterns arrange agents mirror-symmetrically across space and time by linking self-other perceptions about cooperative intentions. Encoding these intentions is a collective model that embeds agents within a three-dimensional matrix that overlaps the observer and the observed. I suggest that this self-other overlap enables the observer to embody observed actions through interpersonal symmetry-seeking. In this sociocognitive context, (1) information transmission is optimal, (2) actions are fast, and (3) group member interactions renormalize in symmetrical space. I propose that symmetrical and not anti-symmetrical imitation facilitates the cooperative behaviours that enable these stable interpersonal dynamics. This finding would suggest that interpersonal symmetry-seeking tunes the nervous system to preferentially engage in mirrored interactions that develop long-term spatiotemporal associations between the observer and the observed.

I employ the dual route model [17] to quantify the spatial and temporal associative links that integrate cooperative agents. This model uses stimulus-response compatibility to assess the overlapping dimensions of attentional, controlled, and automatic processes. The stimulus-response mapping afforded by this model allows the implementation of reaction time procedures to measure the long-term associative effects of symmetrical and anti-symmetrical imitation on social cognition. For this, subjects are oriented face-to-face to induce a self-other overlapping pair. In this self-reflected context, the observer and the observed are nested within a three-dimensional matrix characterized by divergent self-other cooperative dynamics: (1) symmetrical and (2) anti-symmetrical. Based on past research on the synergetics of moving bodies [1], this topological dualism implies cooperative perceptions utilize bistable (in-phase and anti-phase) actions to fulfill expectations within ipsilateral (symmetrical) or contralateral (anti-symmetrical) space. The synergetics of these coordination states impose strict order parameters on interpersonal movements wherein bidirectional in-phase (symmetrical) and anti-phase (anti-symmetrical) coupling relies on in-phase hysteresis (i.e., long-term associations) to maintain self-organization when perturbed [1]. Therefore, it is reasonable to suspect that social entrainment [18] relies on bidirectional symmetries to sustain coordination across spatial and temporal scales. This dualistic paradigm allows the reaction time analyses of interpersonal symmetry effects on cooperative imitation. I hypothesize that the long-term associative links that enable coordination between self and others develop through mirror-symmetric alignments that maintain self-other connectivity through automatic imitation. Automatic imitation is a stimulus-response compatibility effect "in which the speed and/or accuracy of behavioural performance is modulated by the relationship between the topographic features of task-irrelevant action stimuli and the [subjects] responses" [15]. Therefore, I hypothesize that symmetrical imitation is an automatic behaviour activated by long-term associative links between self and others. This association-induced automaticity means it must be demonstrated that observation of symmetrical (compatible) and not anti-symmetrical (incompatible) imitation facilitates responding despite its function as a task-irrelevant cue. For this, task-relevant visual (stimuli are used to assess the destabilizing effect of attention on compatible and incompatible action observation during cooperative imitation.

In summary, this experimental framework evaluates the modulatory capacities of symmetrical and anti-symmetrical action observation on behavioural performance in terms of speed and accuracy. I leverage this framework to measure response times (RTs) during task-irrelevant action observation. This was done to assess the hypothesis that symmetrical and not anti-symmetrical imitation encodes the long-term associative links between self and others. Here, incompatible (anti-symmetrical) associations impede task-performance (i.e., slowing responses), whereas compatible (symmetrical) associations play a facilitatory role (i.e., hastening responses). Finally, the RTs of subjects assigned to the role of followers serve as the baseline measure for comparing the effects of symmetrical and anti-symmetrical imitation in the absence of attentional manipulation.

3. Subjects and Methods

3.1 Subjects

Sixty-four subjects (age range 18 to 40; mean age = 20.8; 41 females, 23 males; 5 left-handed) were recruited from the Department of Psychology, University of Manitoba, and received research participation credits. All subjects were enrolled in Introduction to Psychology at the University of Manitoba. From this subject pool, thirty-two (age range 18 to 30; mean age = 20.5; 23 females, 9 males; 2 left-handed) participated in Experiment 1a and thirty-two (age range 18 to 40; mean age = 21; 18 females, 14 males; 3 left-handed) participated in Experiment 1b. All subjects had normal or corrected-to-normal vision and were unaware of the experiment's purpose (see Appendix A). The Psychology/Sociology Research Approval Board approved this study (Protocol HS19206 (P2015:153)).

3.2 Task-relevant and task-irrelevant stimuli

Stimuli and task instructions were displayed on a Dell computer monitor with a diagonal screen measurement of 60 cm. The monitor was oriented toward and positioned in the action initiator's peripheral vision (see Figure 1a). The subjects assigned to the role of initiator (i.e., leaders) were instructed to lead action selection during cooperative exchanges. The initiators' stimulus set was either a 25 x 25 cm blue or red square positioned in the computer monitor's center (see Figures 1b & c). These visual stimuli are displayed randomly and serve as the initiator's task-relevant cues, which in Experiment (1a) initiators respond to after a delay and in Experiment (1b) simultaneously. The subjects assigned to respond to the initiator's actions (i.e., followers) operate in this context as task-irrelevant stimuli that produce social cues in the initiator's direct field of vision during task execution. These stimulus-response dynamics allow the subject’s responses to perform separate relevance functions depending on the assigned role. Here, initiators generate responses that are the task-relevant sensory cues activating cooperative imitation in followers. On the other hand, followers respond to initiators by generating action stimuli that are task-irrelevant to the initiators' responses but are salient signals of cooperative intentions.

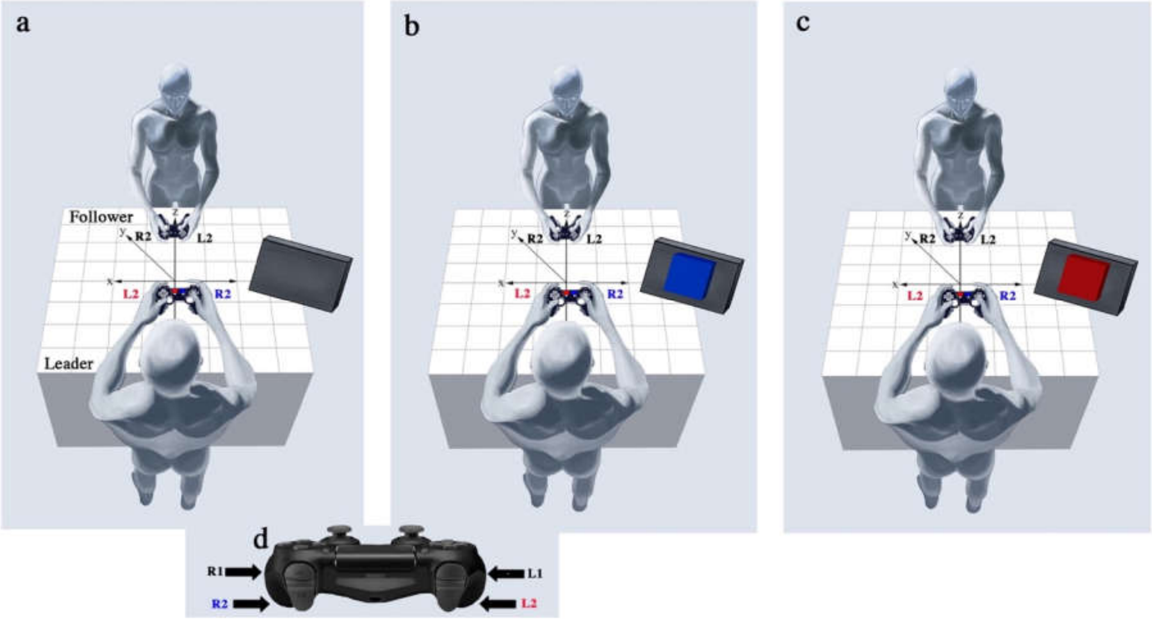


Figure 1. An illustration of the setup for Experiments 1a and b. Here, the response time differences between symmetrical (R2 leader actions → L2 follower responses or L2 leader actions → R2 follower responses) and anti-symmetrical (R2 leader actions → R2 follower responses or L2 leader actions → L2 follower responses) cooperation in the Z dimension were evaluated during divided attention manipulations. Leaders were tasked to pay attention to a blue (b) or red (c) square presented on a computer monitor and respond by selecting the corresponding (L2 or R2) trigger on the controller (d) on stimulus or after a 1-second delay. Simultaneous with this task, Leaders were required to monitor the Followers' responses to ensure cooperative actions were fulfilled. Followers were tasked to respond to Leaders by engaging the (L2 or R2) triggers on the controller (d) by imitating the Leaders symmetrically or anti-symmetrically.

Ultimately, this stimulus-response setup enables the response time analysis of cooperative action observation effects on task performance.

3.3 Data recording

PlayStation 4© controllers (SONY Corporation, Minto, Japan) were used as the interface to measure response times. E-Prime 2.0 Professional© (Psychology Software Tools, Inc, 2012) was used to record RTs in milliseconds. In Experiment 1a, completion of a 1-second stimulus presentation marked the beginning, and the initiator's response marked the end of the initiator's response time interval. In Experiment 1b, stimulus presentation marked the beginning, and the initiator's response marked the end of the initiator's response time interval. In both experiments, the initiator's response marked the beginning, and the follower's reactive response marked the end of the follower's response time interval.

3.4 Methods and analysis

Subjects were assessed in groups of two. Each group member was assigned to the role of (1) *leader* or (2) *follower.* The leader (i.e., action initiator) and follower were oriented face-to-face across a table; each was provided with a controller (see Figure 1a). The pair were instructed to hold their controller while positioning the index and middle fingers of their right and left hands on the controller's R1, L1, R2, and L2 triggers, respectively (see Figure 1d). A computer monitor was positioned to the follower's right so that the stimulus set and instructions were displayed to the leader without obstructing the leader's view of the follower's responses. At the experiment's midpoint, the subjects switched roles and positions. Experiments 1a and 1b comprise two stimulus-response conditions: (1) *symmetrical* and (2) *anti-symmetrical*. The symmetrical condition involved the imitation of action feedback within ipsilateral hemispace (e.g., right-side action observation followed by left-side responses or left-side action observation followed by right-side responses). In contrast, the anti-symmetrical condition involves imitation of action feedback within contralateral hemispace (e.g., right-side action observation followed by right-side responses or left-side action observation followed by left-side responses). The symmetrical and anti-symmetrical conditions were presented in a 20 block procedure comprising 24 trials allocated to each block. Subjects switched roles and seating positions after 10 consecutive blocks. These 10 blocks were partitioned into 5 symmetrical blocks and 5 anti-symmetrical blocks that were counterbalanced. At the beginning and end of each 5 block condition, the computer monitor displayed text instructions ("Press R2 or L2 to begin mirroring" or "Press R2 or L2 to begin matching" or "Press R2 or L2 to continue"). Leaders were required to share the terms of the cooperative conditions and await an affirmative from followers before proceeding. Note, that the "mirroring" and "matching" task instructions denote the symmetrical and anti-symmetrical conditions, respectively. In Experiment 1a, when the procedure begins, the leaders must select their controller's R2 trigger as quickly as possible after a 1-second display of a blue square or the L2 trigger after a 1-second display of a red square. In Experiment 1b, the only procedural difference was that leaders must select their controller's R2 trigger as quickly as possible immediately after the blue square or the L2 trigger immediately after the red square is detected (see Figures 1b & c). Therefore, both experiments required the leaders to pay close attention to the

doi:10.20944/preprints202203.0316.v2

task-relevant stimuli displayed on the screen while continually monitoring the follower's task-irrelevant action stimuli. Adherence to these task instructions was enforced during procedural breaks via verbal reminders that the leader must maintain a forward-facing head position while passively observing the follower's responses throughout the task. Followers were instructed to react to the leader’s actions by selecting as quickly as possible the R2 or L2 trigger on their controllers depending on the experimental condition: (1) symmetrical action observation followed by symmetrical responses or (2) anti-symmetrical action observation followed by anti-symmetrical responses. For the event chain (i.e., stimulus-response feedback cycle) to proceed uninterrupted, subjects must engage the correct trigger. For example, in the leaders' case, a R2 trigger response must follow blue stimulus observation, and a L2 trigger response must follow red stimulus observation. Concerning followers, the experimental condition dictates the correct response. This means the correct action executed in the symmetrical condition was always symmetrical, likewise for the anti-symmetrical condition. Crucially, in all conditions, an incorrect trigger response slowed a subject's RTs; this was due to the procedural rule that the correct response must be selected to advance the cooperative exercise. Subjects were provided with training before the experimental procedure commenced. Training consisted of 20 blocks, where each block contained 12 trials. The partitioning of trials, event chain sequences, and task instructions unfolded the same way as those outlined in the Methods section above.

No trials were excluded from the analyzed dataset. However, to reduce the influence of outliers, each subject's median RT was used as a measure of central tendency [19]. To avoid violations of the sphericity assumption, I employed a two-way repeated measures analyses of variance (ANOVA) for all reported ANOVA statistics. All pairwise comparisons were performed using paired-samples t-tests in which a Bonferroni adjusted alpha of 0.0025 was employed to control for inflation of Type 1 error.

4. Results

4.1 Experiment 1a: Task-relevant delayed response manipulation

The results revealed a significant main effect for IMITATION STATE with faster responses in the symmetrical condition than in the anti-symmetrical condition, $F(1, 31) = 99.87$, $p < .001$. Furthermore, a significant main effect of ROLE was found, $F(1, 31) = 51.73$, $p < .001$. Subjects were faster in the role of the leader than in the role of follower. Consequently, a significant interaction effect between IMITATION STATE by ROLE was detected, $F(1, 31) = 7.98$, $p < .008$. To expose the nature of this interaction, a post hoc analysis was conducted. In the role of leader, response times were significantly faster when observed actions were symmetrical (207 ms) compared with anti-symmetrical (245 ms), $t(31) = 3.47$, $p < .002$, d = 0.61. This behavioural pattern was repeated in followers; here, reaction times were significantly faster in the symmetrical (323 ms) compared with the anti-symmetrical condition (397 ms), $t(31) = 7.86$, $p < .001$, d = 1.39 (see Figure 2 and Table 1). The imitation effect in the symmetrical condition indicates that subjects produce faster responses in the task-relevant dimension when observed actions are generated in the ipsilateral and not the contralateral hemispace. All but one follower produced faster baseline responses in the anti-symmetrical condition (see Appendix B1). Here, subject 15 generated marginally faster anti-symmetrical (225 ms) than symmetrical (229 ms) responses.

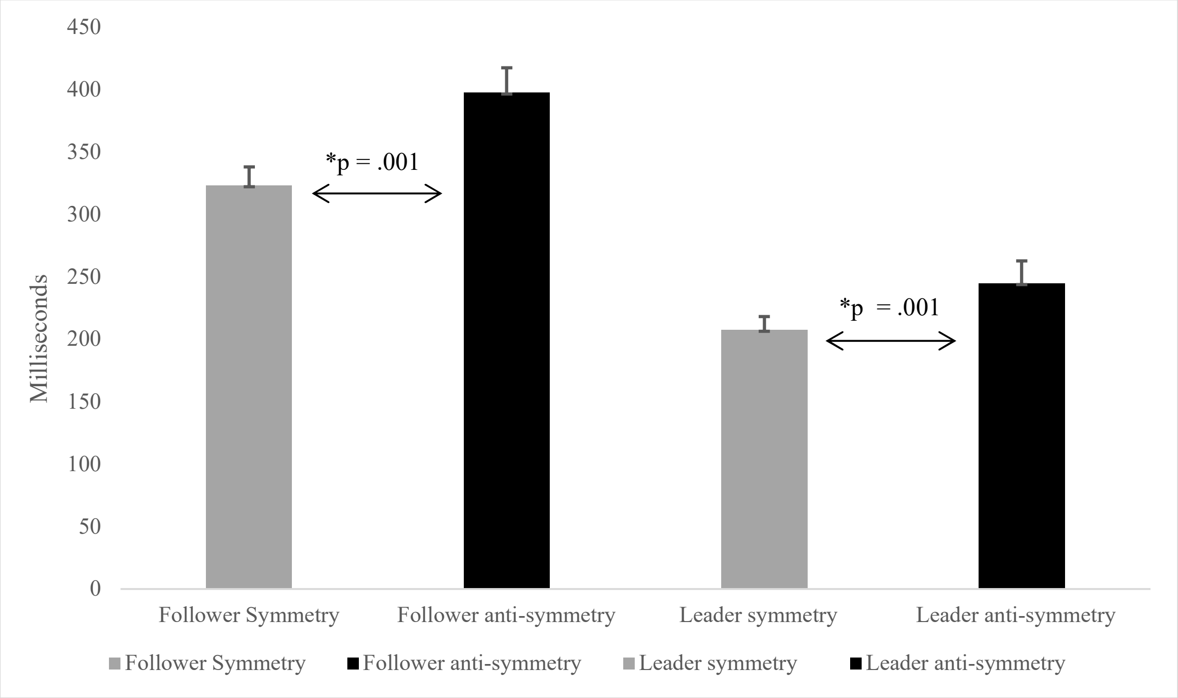


Figure 2. . Response time (mean± SEM) differences between symmetrical and anti-symmetrical cooperation are compared. *p < .0025.

Pairwise Comparison	95% Confidence interval Lower vs. Upper	t-statistic	df	P-value	Cohen's d
Leader: symmetry vs anti-symmetry	[-59.54, -15.43]	-3.47	31	.001*	.613
Follower: symmetry vs anti-symmetry	[-93.75, -55.12]	-7.86	31	.001*	1.389

Table 1. *p < .0025.

4.1 Experiment 1b: Task-relevant on-stimulus response manipulation

The results show a significant main effect for IMITATION STATE with faster responses in the symmetrical than in the anti-symmetrical condition, $F(1, 31) = 23.3$, $p < .001$. Furthermore, a significant main effect of ROLE was found, $F(1, 31) = 51.9$, $p < .001$. Subjects were faster in the role of the follower than in the role of the leader. Consequently, a significant interaction effect between IMITATION STATE by ROLE was detected, $F(1, 31) = 34.6$, $p < .001$. A post hoc analysis was conducted to evaluate this interaction. In the role of leader, response times were not significantly different when observed actions were symmetrical (422 ms) compared with anti-symmetrical (431 ms), $t(31) = -1.38$, $p < .179$, d = - .24. Followers did not repeat this behavioural pattern; instead, response times were significantly faster in the symmetrical (306 ms) compared with the anti-symmetrical condition (383 ms), $t(31) = -7.84$, $p < .001$, d = -1.389 (see Figure 3 and Table 2). In leaders, inhibition was observed when the responses to task-relevant stimuli were elicited on-stimulus instead of after a 1-second delay like in Experiment 1a. Here, the on-stimulus response manipulation abolished the response speed difference between the symmetrical and anti-symmetrical conditions. All followers produced faster baseline responses in the symmetrical condition than in the anti-symmetrical condition (see Appendix B2).

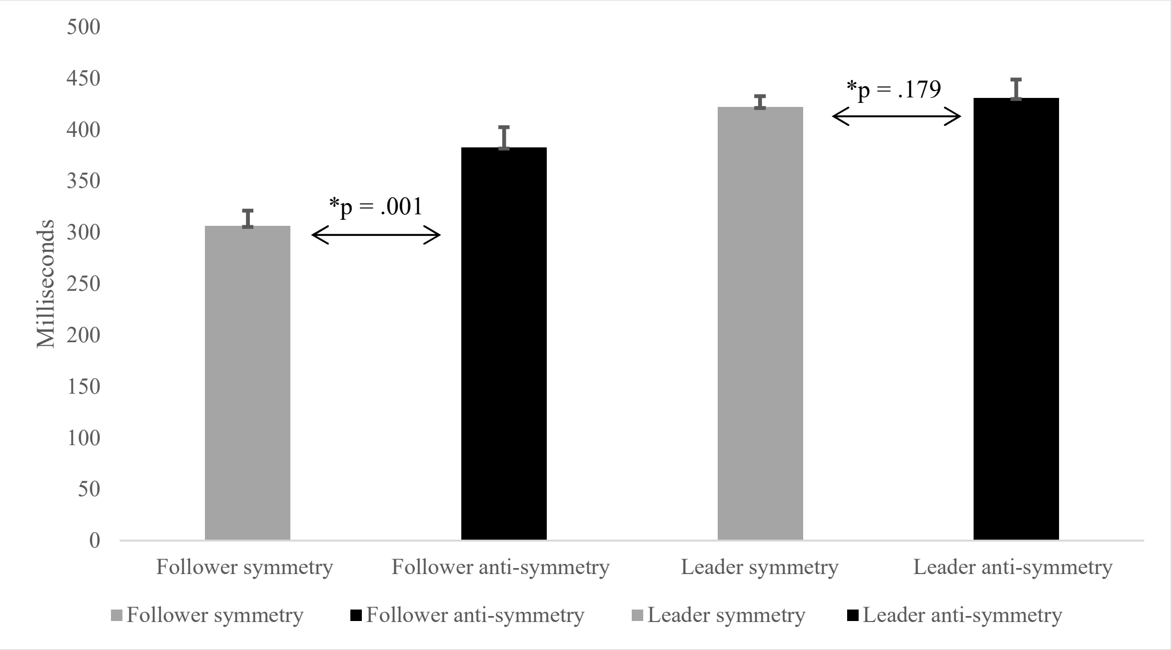


Figure 3. Response time (mean± SEM) differences between symmetrical and anti-symmetrical cooperation are compared. *p < .0025.

Pairwise Comparison	95% Confidence interval Lower vs. Upper	t-statistic	df	P-value	Cohen's d
Leader: symmetry vs anti-symmetry	[-21.79, 4.23]	-1.38	31	.179	-.24
Follower: symmetry vs anti-symmetry	[-96.25, -56.50]	-7.83	31	.001*	-1.39

Table 2. *p < 0.0025.

5. Discussion

These data confirm the hypothesis that symmetrical imitation is generated automatically during cooperation. The present design demonstrates that interpersonal expectations of symmetrical exchange enhance task performance by reducing response times and attentional resource demands. Experiments 1a and b reveal that the followers' baseline measures indicate that cooperative motor plan execution in symmetrical hemispace is faster and more accurate than execution in the anti-symmetrical hemispace. This result replicates previous research by Brass et al. [20], in which they report overlapping brain activation in the anterior medial frontal cortex (aFMC) and the temporoparietal junction (TPJ) enable neural processes that inhibit automatic imitation [15]. It is suggested that this inhibition mechanism allows the nervous system to decouple the self from others by incurring a resource cost to recruit the aFMC to counter automatic imitation. In simultaneous operation with the aFMC, the TPJ generates a separation between self and others, which underpins the shared representation [21] that enables the sociocognitive capacity to infer others' mental states (i.e., mentalization). These overlapping brain dynamics imply that cognition flows with little resistance during automatic imitation, a social behaviour that is selectively inhibited by the nervous system through attentional control. The pattern of behaviour (i.e., faster symmetrical than anti-symmetrical imitation) exhibited by the followers in both Experiments 1a and 1b is consistent with research on synchronous imitation of continuous action sequences [14]. Here, the researchers found that imitation was facilitated when the model and imitator's body were in the same (mirrored) orientation. This capacity was greatly impaired when the relative orientation between model and imitator shifted away from this preferred orientation. Moreover, the researchers suggest that these behavioural differences may arise because the nervous system overlaps the topographical information about observed actions onto its own body schema to aid in continuous action prediction. This proposition is supported by Muller et al. [22] and Mechsner et al. [23], which demonstrate that humans preferentially select and more easily perform mirror-symmetrical over anti-symmetrical actions during bimanual coordination.

Experiment 1a shows that the inhibition of symmetrical coordination slows response speeds during anti-symmetrical actions and perceptions for both leaders and followers. The results of Experiment 1b support this observation by demonstrating that the on-stimulus processing of the task-relevant dimension (i.e., visual stimuli) by the leaders abolished the response speed advantage of symmetrical coordination. The logic here is that when leaders encountered the response cue and responded after a delay, as in Experiment 1a, both the response and social cues were processed sequentially. This sequence of events enabled the leaders' behavioural patterns to recapitulate those of the followers (i.e., faster symmetrical than anti-symmetrical imitation). By contrast, in Experiment 1b, when leaders encountered the response cue and must respond on-stimulus, this task required simultaneous processing of both response and social cues, which imposed greater demands on attention, thus reducing the speed of symmetrical actions compared to the followers whose attention was not manipulated. Based on these outcomes, I suggest that anti-symmetrical coordination slows response times because the nervous system must recruit attentional resources to inhibit automatic imitation in the ipsilateral (i.e., symmetrical) hemispace. This interpretation is supported by past research that suggests imitative response slowing is due to attentional competition between motor intentions and socially triggered response tendencies [20]. In other words, anti-symmetrical action observation impedes responsivity to the short-term associations established by the task-relevant dimension. Conversely, symmetrical actions and perceptions represent long-term connections activated automatically via social controls that reduce attentional resource demands by eliminating the processing cost incurred during the inhibition of actions.

Some may reason that the elimination of the response speed difference in Experiment 1b may arise from the leader's inattention to the task-irrelevant social cues during the symmetrical and anti-symmetrical conditions. This intuition ignores the fact that the response speed of leaders is reduced in both the symmetrical (422 ms) and anti-symmetrical (431 ms) conditions, which suggests both conditions impose a resource cost as opposed to liberating resources due to inattention. Therefore, the elimination of the response speed difference between symmetrical and anti-symmetrical actions of leaders reported in Experiment 1b indicates attentional resources are available for use when cooperative exchanges arise within the symmetrical (i.e., ipsilateral) and not the anti-symmetrical (i.e., contralateral) hemispace. This conjecture is evidenced by the baseline symmetrical response speed advantage observed in unmanipulated followers and the elimination of leaders' symmetrical response speed advantage in Experiment 1b compared to 1a. These findings provide additional evidence that mirror-symmetry is the expected state of social interaction for the human brain [9, 20, 22-26]. They indicate that attentional resources are more readily available under the symmetrical and not the anti-symmetrical state of social exchange.

6. Experiment 2: Interpersonal Symmetry-Breaking and Renormalization in Humans

6.1 Introduction

I postulate that the nervous system's self-other connections are conserved across space and time by encoding shared representations based on dual interpersonal modes: (1) symmetrical and (2) anti-symmetrical. Experiment 1 demonstrates that the symmetrical mode supplies stable connections that serve as the sensorimotor template for fast and efficient coordinated movements. Conversely, the anti-symmetrical mode draws from neural resources to inhibit symmetrical imitation effects and is, therefore, a collective capacity modulated by attentional processes. These findings support those established in Coordination Dynamics (CD) literature, which encompasses a line of scientific inquiry dedicated to understanding “how the parts and processes of living things come together and break apart in space and time” [27]. From the CD perspective, a living system possesses two complementary aspects in which integration and segregation exist concurrently [5]. The integrative aspect arises from self-organizing collective variables whose dynamics emerge from automatic coordination between parts. The segregation aspect emerges from attention-driven coordination that enables novel information to be accumulated through intentions that rely on the integrative aspect to guide the whole system’s functional order across space and time. These coordination dynamics activate spatiotemporal patterns of behaviour that evolve and change based on phase transitions that result from spontaneous choice, where the whole system preferentially selects one behavioural pattern over another [10, 11, 28]. This dualism captures the dynamics of cooperative stability in terms of coexisting integrative and segregative states. The capacity to switch between these coexisting states is referred to as metastable coordination [29], evidenced by spontaneous symmetry-breaking between interacting bodies [1, 13] and within brains [27]. Symmetry-breaking in neural and multi-agent dynamics enables brains and bodies to “exhibit a far more variable, plastic and fluid form of coordination in which integration and segregation coexist” [1]. The bistability afforded these coexisting dynamics arises from in-phase and anti-phase relations that spontaneously transition from anti-phase to in-phase at critical moments [1]. Given this account of coordination, I aim to test the hypothesis that synergetic group members exhibit symmetry-breaking and renormalization within symmetrical space when attentional resources are depleted. I propose that the complementary symmetrical (i.e., in-phase) and anti-symmetrical (i.e., anti-phase) modes of synchronization represent the coexisting integration and segregation aspects of a metastable collective mind.

In the experiment that follows, I instructed dyads to engage in in-phase (symmetrical) and anti-phase (anti-symmetrical) synchrony during attentionally demanding perceptual-switching tasks. In this manipulation, subjects were required to switch between perceptions about interpersonal actions repeatedly. This means subjects were tasked to pay attention to their own movements while simultaneously tracking the changing spatial positions of their partner's movements. This cooperative dynamic overlapped intentions and demanded that subjects focus their energies on synchronizing two interpersonal transformations: (1) symmetrical cycles that involved homologous muscle groups contracting synchronously and (2) anti-symmetrical cycles that involved homologous muscle groups contracting in an alternating fashion. These spatiotemporal constraints on cooperation enabled the analysis of the interpersonal phase relation inducing perceptual stability under perturbations. In other words, restricting cooperative arm movements to the vertical plane allowed attentionally demanding perceptual-switching to be employed to identify the stable (spatiotemporal) states of self-other integration. I aim to demonstrate that coordinated action spontaneously organizes interpersonal limb movements within symmetrical and not anti-symmetrical spaces during symmetry-breaking induced by perceptual instability.

7. Subjects and Methods

7.1 Subjects

Thirty-two subjects (age range 17 to 25; mean age = 20.4 years; 20 females, 12 males) were recruited from the Department of Psychology, University of Manitoba, and received research participation credits. Subjects were enrolled in Introduction to Psychology at the University of Manitoba. Subjects had normal or corrected-to-normal vision and were unaware of the experiment's purpose (see Appendix A). The Psychology/Sociology Research Approval Board approved this study (Protocol HS19206 (P2015:153)).

7.2 Data recording

Canon's EOS Rebel© T6i and EF-S 18-55 mm f/3.5-5.6 IS STM camera lens (Canon Incorporated, Ōta, Tokyo, Japan) were used to record the experimental sessions. The recording equipment was placed on a tripod oriented toward the subjects and positioned 5 m from where the sessions occurred. This was done to ensure the video camera captured the subject's full range of motion.

7.3 Methods and analysis

Subjects were assessed in groups of two. Group members were positioned 2-meters apart and oriented face-to-face. The pair were instructed to synchronize vertical arm movements based on four interpersonal configurations: (1) Together, (2) Apart, (3) Split Together, and (4) Split Apart. Together involved coordination in which each subject was tasked to hold their left and right arms parallel to each other during in-phase synchronization (see Figure 4a). Apart involved the same arm positioning as the Together configuration; however, subjects were tasked with coordinating anti-phase synchronization (see Figure 4b). Split Together involved in-phase synchrony where subjects decoupled their arms' so that when the right arm of one subject was at the lowest vertical position (0°), their partner's left arm was also at its lowest (0°). The same rule applied to the subject's left and right arm alignment at their highest point (180°) (see Figure 4c). Split Apart involved anti-phase synchrony where subjects decoupled their arms so that the right arm of one subject was at the highest vertical position (180°) when the left arm of their partner was at its lowest (0°) and vice versa (see Figure 4d). The experimental session comprised two cooperative conditions. Condition one involved cooperation in which subjects synchronize perceptual cycles according to the following action sequence: Together, Apart, Split Together, Apart, Together, and Split Apart. Condition two's sequence was as follows: Together, Apart, Split Apart, Apart, Together, and Split Together. These conditions were presented in a 2 block procedure comprising 2 trials allocated to each block. These trials were partitioned into CONDITION ONE and CONDITION TWO, and counterbalanced across blocks. At the onset of the first block, the subjects raised their arms to the starting position. A 2-minute timer was then activated simultaneously with a verbal prompt indicating the interpersonal configuration to be performed. Thus, the verbal prompts were presented at the beginning of the first block and at 5-second intervals until the 2-minutes elapsed. Consequently, each trial lasted 30-seconds and was presented in continuous order (e.g., CONDITION ONE → CONDITION TWO → CONDITION TWO → CONDITION ONE). Subjects were provided training before the experimental session commenced. The training involved a demonstration of the behaviours the subjects were expected to perform, followed by a practice session. Practice consisted of 2 blocks, where each block contained 2 trials. The partitioning of trials, action sequences, and task instructions unfolded the same way as those outlined in the Methods section above, except the sessions' length was 4-minutes, which means each trial lasted 60, not 30-seconds.

7.4 Coding criteria

No trials were excluded from the analyzed dataset. Data collection involved tabulating interpersonal symmetry-breaking through the evaluation of video recordings of the experimental sessions. These video recordings were analyzed at half playback speed. Symmetry-breaking was defined as an incongruence between the instructed and the executed configuration generated by the group. For example, if the task instruction prompted in-phase symmetry and anti-phase symmetry was generated, this incongruence was tabulated as a symmetry-breaking event. This same rule was applied to prompted anti-phase symmetry that resulted in the group generating in-phase coordination. Whether symmetry-breaking occurs or does not occur per session and the direction of the break (in-phase to anti-phase or anti-phase to in-phase) were the only data tabulated.

8. Results

The results reveal that coordinated movements transition automatically from anti-phase to in-phase synchrony under cognitive perturbations. Anti-phase to in-phase symmetry-breaking emerged spontaneously in 16 out of 16 sessions, whereas in-phase to anti-phase symmetry-breaking did not occur in a single session. In other words, synchronized movements spontaneously transitioned from (b) to (a) and (b) to (c) and never (a) to (b) or (c) to (b) (see Figure 4). Furthermore, synchronized movements spontaneously transitioned from (d) to (a) and (d) to (c) and never (a) to (d) or (c) to (d) (see Figure 4).

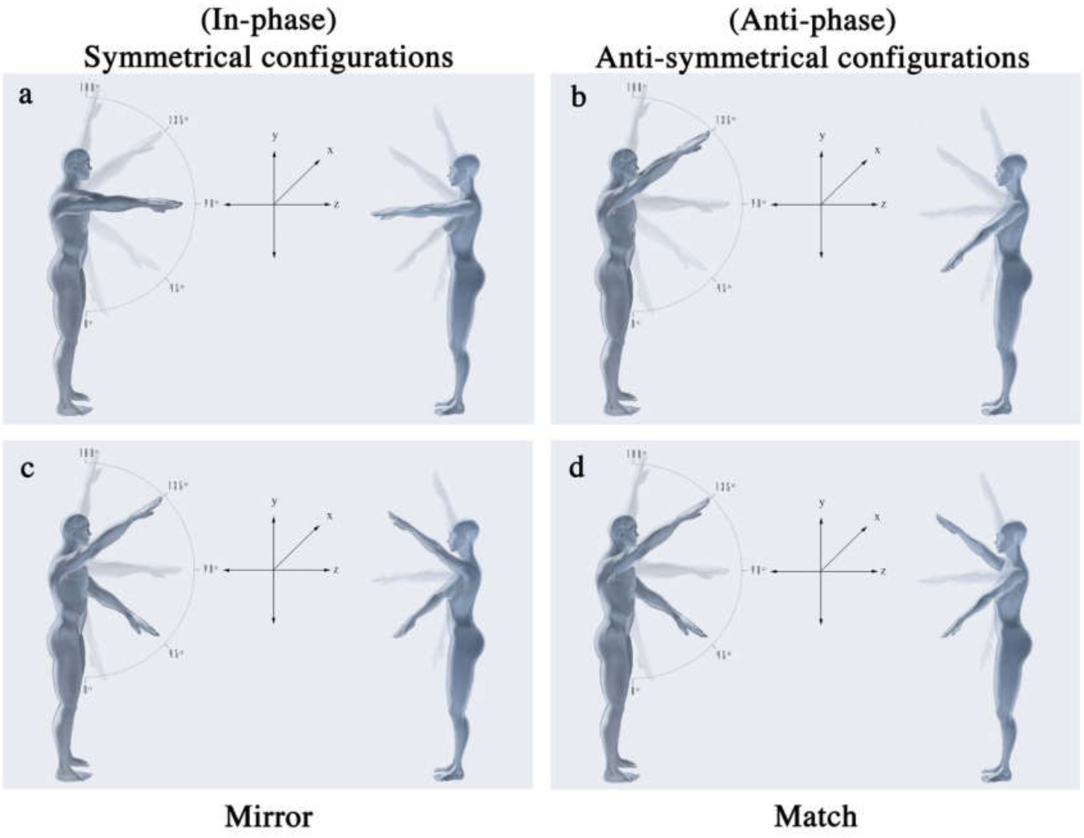


Figure 4. These illustrations depict four interpersonal configurations: (a) Together, (b) Apart, (c) Split Together, and (d) Split Apart. The subjects are tasked to switch between these configurations while synchronizing perceptions and actions in the Y-dimension.

9. Discussion

The present experiment examined spontaneous symmetry-breaking in interpersonal dynamics. The data collected here support the claim that cooperative action patterns renormalize in symmetrical space when perceptual cycles are unstable [1, 2, 9, 11, 16, 30]. I demonstrate that anti-symmetrical interactions induce symmetry-breaking and symmetrical normalization when cognitive demands are high or attention divided. The results show that in-phase to anti-phase transitions arose only when instructed and never through symmetry-breaking. In contrast, anti-phase to in-phase transitions emerged spontaneously in every session. These findings conform to research on bilateral in-phase and anti-phase movements [31], which found that anti-phase movements are controlled more independently, whereas in-phase movements are generated by a common neural mechanism. These differences support the idea that mirror-symmetry is the preferential state of perceptual coordination [22, 23] due to its stabilization function and relative ease of production [13, 31]. Taken together, these findings provide strong evidence that collective dynamics operate based on dual (symmetrical and anti-symmetrical) modes of interaction characterized by coexisting integration and segregation aspects in the framework of Coordination Dynamics [5]. I claim these dual aspects achieve stability through interpersonal symmetry-seeking evinced by spontaneous symmetry-breaking, where perceptual instability results in renormalization in symmetrical (in-phase) space. The integrative aspect connects spatiotemporal dynamics by automatically aligning observed actions mirror-symmetrically with self-perceptions when perturbed. This sociocognitive mechanism suggests that human collective's enlist self-organizing processes to minimize interpersonal prediction error through automatic imitation that induces perceptual stability and attentional resource availability. Here, symmetrical interactions support and sustain themselves across individual and group scales through automatic self-other integration. This multi-level stability enables the collective's segregation aspect to recruit attentional resources to engage anti-symmetrically.

Multiple studies examining the link between energy and entrainment in both vertebrates and invertebrates demonstrate that multi-agent stability and resource efficiencies arise from spatial coalignment under duress. A study by Ancel et al. [32] on social thermoregulation in Emperor penguins (*Aptenodytes forsteri*) reported that aggregations of individuals fluctuated in size and density depending on air temperature, wind, and solar radiation. The key findings were that individuals' transitioned from loose aggregations to huddles when air temperature decreased, wind speed rose, or solar radiation diminished. The researchers claimed that this multi-agent behaviour enabled individuals to band together in space to conserve energy when faced with inclement weather conditions. When energy dissipation was necessary, individuals were observed breaking from huddles through spontaneous disassembly. These cooperative movements together and apart unfolded through synchronous actions [33-36] that minimized the heat loss of huddling groups and their members [37, 38]. Research involving schooling fish [39] and flocking birds [40] suggests that these coordinated behaviours serve the same resource function as huddling in Emperor penguins. Here, hydrodynamic and aerodynamic efficiencies enable schooling fish and flocking birds to reduce individual-level energy consumption during collective motion. In contrast, separation from the group produced the opposite effect. These collective behaviours coincide with those reported in ants (*Atta insularis*), where an experiment conducted by Altshuler et al. [41] found that high-panic induced herding resulted in the unidirectional use of two identical doors. In contrast, the doors were used equally as often in the low panic condition. Computer simulations by Wang et al. [42] modelling collective human escape behaviours demonstrated that spontaneous group choice is induced under perturbations. In their simulations, group choice consistently aligned the collective's trajectory such that interpersonal movements flowed unidirectionally. These examples suggest that spontaneous symmetry-breaking and renormalization are emergent properties of multi-agent interactions under duress. This energy-movement parallelism implies that coalignment together in symmetrical space performs an underlying adaptive function that automates actions and perceptions to conserve energy and form.

10. General Discussion

I hypothesized that cooperating groups of humans embody a self-integrating system capable of informational coupling and automatic response modulation when perturbed. The experimental findings I put forward confirm this hypothesis by exposing dual interpersonal modes (symmetrical and anti-symmetrical) specified by a spatiotemporal matrix. From this geometric matrix arises a collective mind bound together by imitation based on metastable symmetrical and anti-symmetrical coordination dynamics. The symmetrical form emerges automatically during coordination, whereas the anti-symmetrical form demands greater attentional resources. In this synergetic paradigm, symmetrical interactions serve as the social synchronization manifold on which anti-symmetrical interactions modify intrapersonal and interpersonal dynamics. In other words, a cooperating group and its members coexist as integrative and segregative aspects of a scale-invariant system of minds maintained by interpersonal symmetry-seeking.

The existence of an overlapping brain-generated spatiotemporal matrix is supported by research on hippocampal grid cells, i.e., cells that specify an agent's environmental location by exhibiting spatially localized firing in response to internal and external geometric associations [43, 44]. Here, each grid cell activates slightly different x, y-coordinates in the environment, which enables aggregations of grid cells to collectively organize using theta fluctuations to map the entire receptive field. These cells work in coordination with place cells, i.e., cells that detect environmental features based on their associative qualities and allocentric direction [45]. Both grid and place cells operate together to orient the nervous system within three-dimensional space specified by time [46, 47]. Functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) studies reveal that working together with place and grid cells is a mirror neuron system, which researchers claim mediates automatic imitation effects by overlapping observed and executed actions [48-52]. This mirror mechanism's integrative function suggests that automatic imitation effects underpin the coordination of self-other integration and segregation. In other words, it is plausible that the symmetrical and anti-symmetrical modes of imitation give rise to the mirror neuron system (i.e., a self-regulating neural network generating a collective model embedded in a spatiotemporal matrix).

This plausibility finds credence given hemispatial neglect, a neurological condition characterized by sensory-attention deficits to intrapersonal and extrapersonal space on the contralesional side [53, 54]. This link between behavioural and neuroanatomical features speaks to a strict bilateral partitioning of the nervous system's internal and external space. Allochiria is a phenomenon in which some patients with hemispatial neglect incorrectly perceive contralateral stimuli as occurring in ipsilateral space [55]. In the example represented in Figure 6, a patient tasked to write the numbers 1 to 12 on a clock from memory wrote all twelve digits on the clock's ipsilateral side while failing to notice the contralateral side of space. This transposition of contralateral stimuli to ipsilateral space during a task requiring attention supports the resource attenuation hypothesis of symmetrical (i.e., ipsilateral) interactions as described in this paper. This implies that the high attentional resource costs associated with anti-symmetrical (i.e., contralateral) information processing resulted in a perceptual disconnection of contralateral space. This hemispatial disconnection partitioned space bilaterally, which resulted in the content of the entire visual field outputting on the ipsilateral side of space. This neurological condition supports my claim that the nervous system constructs social reality by internally generating a spatiotemporal matrix that partitions the interpersonal world three-dimensionally. From here, inter-manual conflict, a neurological condition resulting from lesions to the frontal lobe and corpus callosum supports the dual nature of mind embedded in a matrix [56, 57]. Patients with inter-manual conflict exhibit inhibitory motor behaviours that execute without awareness. In a study by Nishikaw et al. [57] a patient reported opening a sliding door with his right hand intending on going outside, when in quick succession, his left hand closed the door, preventing his exit. The patient reported that this conflict with his own left hand repeated over and over until he eventually called his wife for help. In an experiment by Brainin et al. [56], a patient with inter-manual conflict was observed having a "tug of war between hands." In a task requiring coordination between the left and right hands, the patient maintained motor control over the left hand; however, this resulted in the right hand operating autonomously and in direct opposition to the goal. Brainin et al. [56] suggested that this behaviour can "be understood as sequences of complex inhibitory motor programs that have become isolated from normal motor planning, which usually suppresses them via the contralateral cortico-subcortical prefrontal circuits and the corpus callosum" [56].

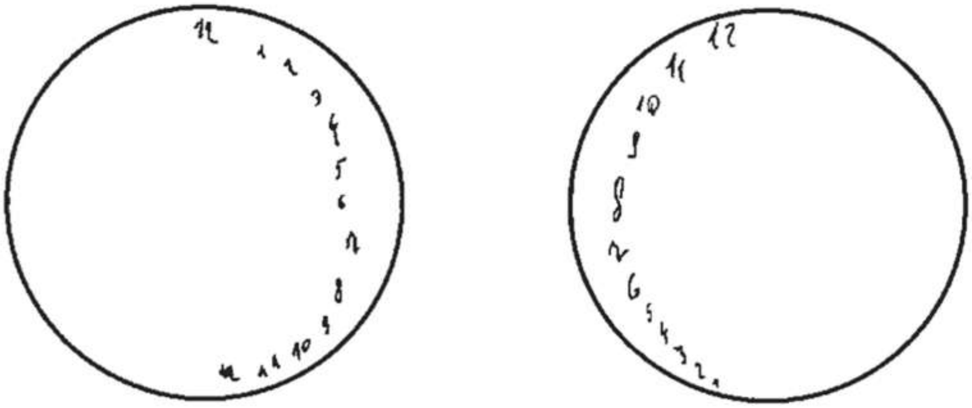


Figure 6. "In drawing a clock from memory, [patient 1] spontaneously started writing numbers clockwise and showed right allochiria (left panel), but when he was required to write numbers in an anti-clockwise direction, he located all digits in the left half of the clock (right panel)" (Grossi et al., [55]. Reproduced with permission from Grossi et al. [55].

Therefore, it is plausible that inter-manual conflict reveals the bilateral segregation of the mind and body into dual intrapersonal forms that overlaps interpersonally when in a multi-agent context. Because these patients cannot inhibit the automatic form, actions of the right hand appear to operate autonomously when attention is occupied by the left hand's use of the intentional form. In a normal functioning brain, inhibition suppresses the automatic form while the intentional form occupies attention. Thus, the oppositional behaviours observed in inter-manual conflict could be these dual intrapersonal forms operating independently. The present study demonstrates that this intrapersonal behaviour may also emerge during interpersonal coordination dynamics. Experiments 1 and 2 reveal that inhibition is required to suppress automatic (symmetrical) imitation when self-intended coactions are generated in anti-symmetrical space. The inability to inhibit the automatic form due to neurological damage as observed in inter-manual conflict or resource depletion evinced by interpersonal symmetry-breaking suggests that within brains and between bodies exists a multi-scale network bound by spatiotemporal invariance.

If correct, future neuroimaging studies using the experimental methods presented in this paper should observe neural oscillations that generate activity patterns recapitulated at multiple levels of biological organization. This means activity patterns should emerge from intrapersonal brain states that propagate to subsume interpersonal bodily states in a scale-invariant wave. In other words, spatial and temporal activity patterns should flow from intrapersonal to interpersonal and back in a recursive manner during synchronization. Further, changes in the order of magnitude should correspond with predictable changes in the level of biological organization under scrutiny. Consequently, symmetrical interactions should produce neural activity patterns that onset more synchronously than the anti-symmetrical form [57-59]. These activity patterns should emerge in intra-brain and inter-brain regions that reliably predict interpersonal symmetry-breaking as formulated in the present work. This finding would confirm that symmetrical and anti-symmetrical interactions are fundamental states of collective dynamics, as suggested by Kelso [1]. This realization would reveal the fractal architecture of social organization because it would demonstrate that interpersonal mirror-symmetry provides stability to synchronizing brains and bodies based on geometric topology.

15. Conclusion

This paper provides a methodological design that is ecologically sensitive to the nature of interpersonal coordination because of its use of real-life social interaction as the focus of analysis. Moreover, the three-dimensional (face-to-face) design enables a group and its members to be analyzed using multimodal coordination dynamics specified by spatial and temporal invariance. Consequently, this methodology solidly embeds the mind and its neural architecture in a collective matrix specified by interpersonal (spatio-temporal) symmetries. This matrix of minds links the mechanics of cooperative human dynamics to the classical behaviours of objects in motion and the statistical predictions inherent to Bayesian communication systems. Suffice to say, this research sheds light on how human brains work together to predict the external world's unknown variables while simultaneously inducing self-other stability through cooperative activity.

Funding: This research was funded by the NSERC Discovery Grant (grant number RGPIN/6423-2015).

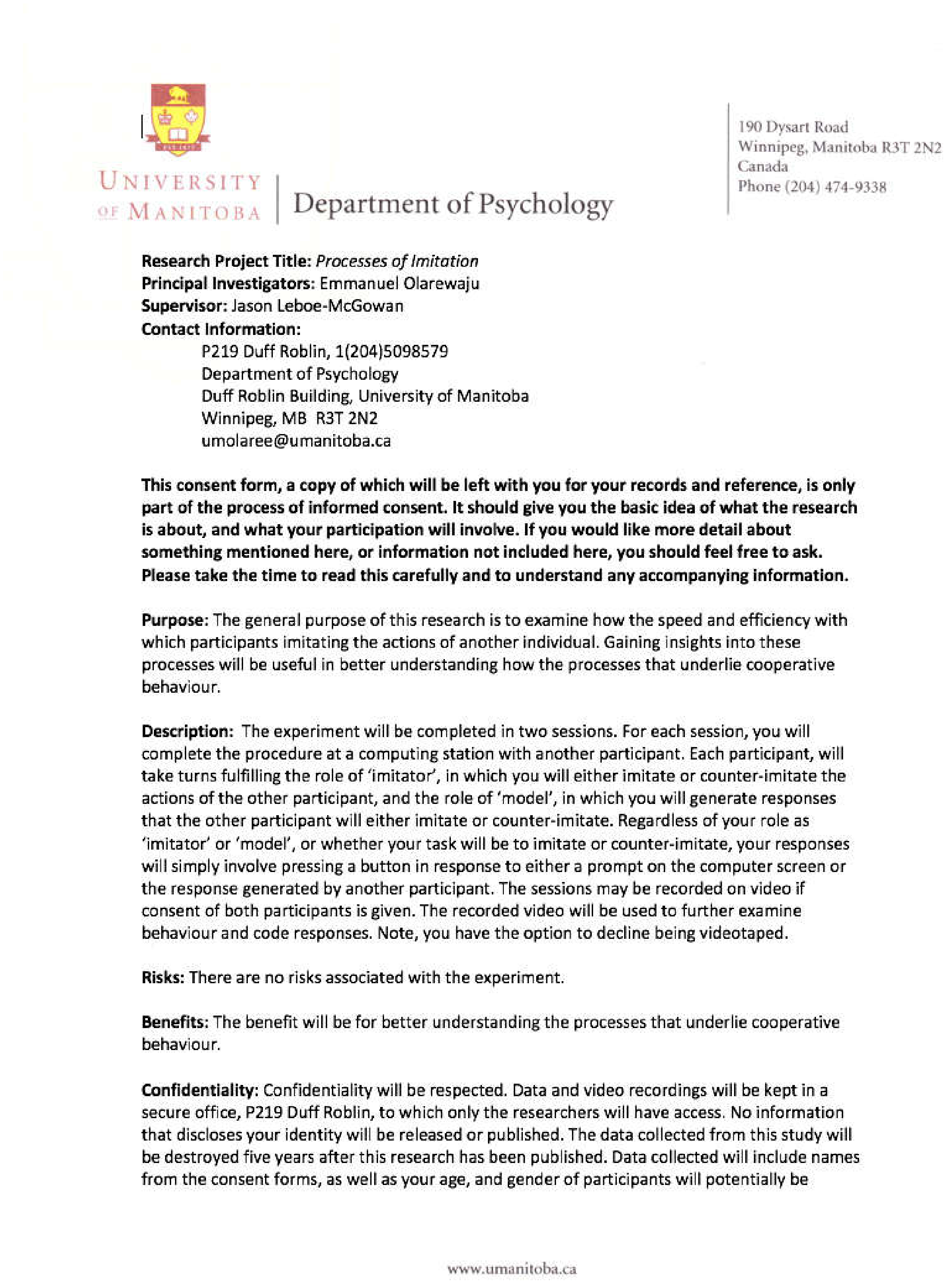
Institutional Review Board Statement: This study was conducted according to the guidelines of the Psychology/Sociology Research Approval Board (Protocol HS19206 (P2015:153)).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available in the article and upon request from the corresponding author.

Acknowledgments: I would like to thank Drs. Jason Leboe-McGowan and James F. Hare for their support and guidance.

Conflicts of Interest: The author declares no conflict of interest.



Appendix A: Consent Form

UNIVERSITY OF MANITOBA | Department of Psychology

190 Dysart Road
Winnipeg, Manitoba R3T 2N2
Canada
Phone (204) 474-9338

Research Project Title: *Processes of Imitation*
Principal Investigators: Emmanuel Olarewaju
Supervisor: Jason Leboe-McGowan
Contact Information:
P219 Duff Roblin, 1(204)5098579
Department of Psychology
Duff Roblin Building, University of Manitoba
Winnipeg, MB R3T 2N2
umolaree@umanitoba.ca

This consent form, a copy of which will be left with you for your records and reference, is only part of the process of informed consent. It should give you the basic idea of what the research is about, and what your participation will involve. If you would like more detail about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

Purpose: The general purpose of this research is to examine how the speed and efficiency with which participants imitating the actions of another individual. Gaining insights into these processes will be useful in better understanding how the processes that underlie cooperative behaviour.

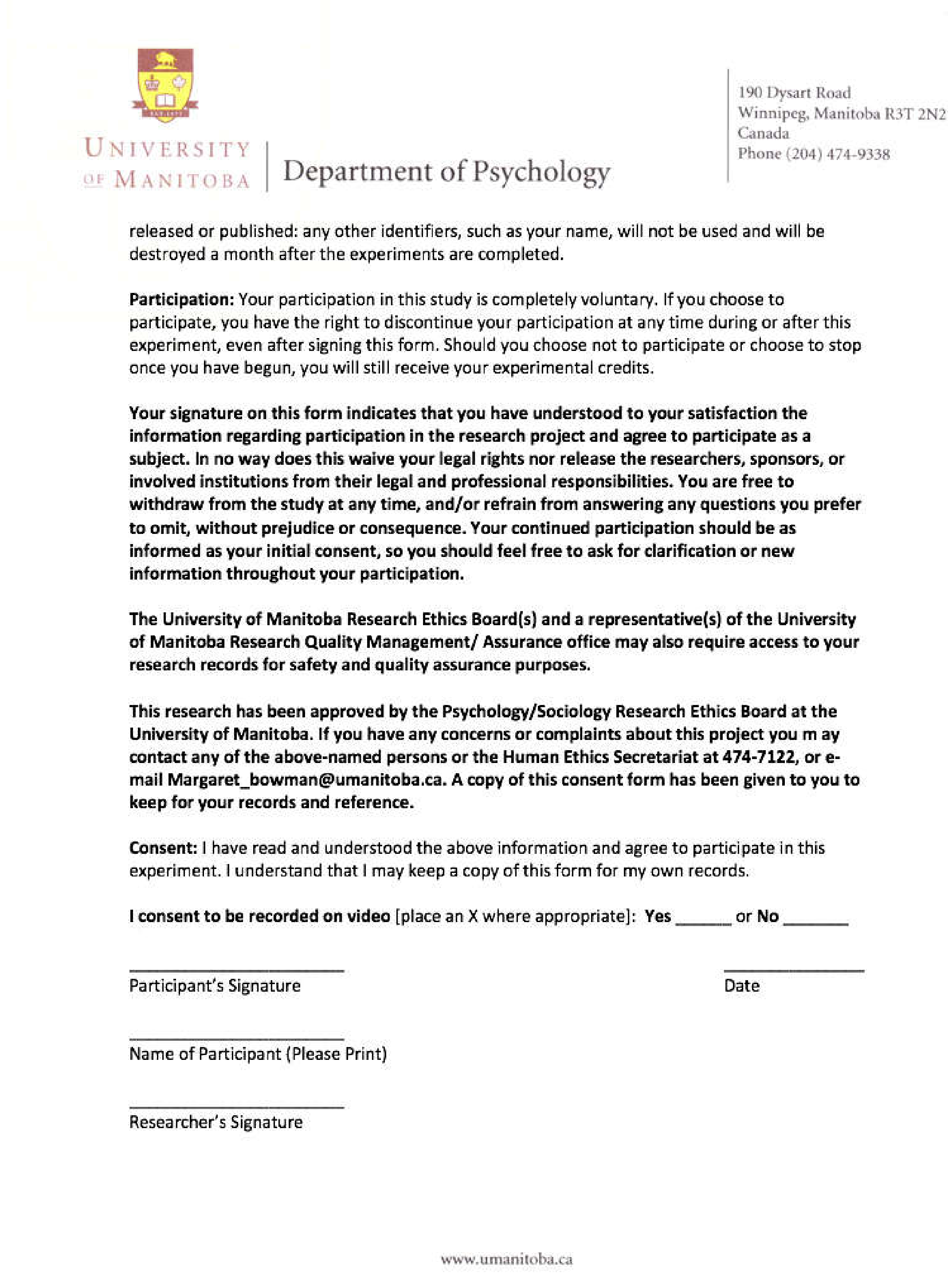
Description: The experiment will be completed in two sessions. For each session, you will complete the procedure at a computing station with another participant. Each participant, will take turns fulfilling the role of 'imitator', in which you will either imitate or counter-imitate the actions of the other participant, and the role of 'model', in which you will generate responses that the other participant will either imitate or counter-imitate. Regardless of your role as 'imitator' or 'model', or whether your task will be to imitate or counter-imitate, your responses will simply involve pressing a button in response to either a prompt on the computer screen or the response generated by another participant. The sessions may be recorded on video if consent of both participants is given. The recorded video will be used to further examine behaviour and code responses. Note, you have the option to decline being videotaped.

Risks: There are no risks associated with the experiment.

Benefits: The benefit will be for better understanding the processes that underlie cooperative behaviour.

Confidentiality: Confidentiality will be respected. Data and video recordings will be kept in a secure office, P219 Duff Roblin, to which only the researchers will have access. No information that discloses your identity will be released or published. The data collected from this study will be destroyed five years after this research has been published. Data collected will include names from the consent forms, as well as your age, and gender of participants will potentially be

www.umanitoba.ca



UNIVERSITY OF MANITOBA | Department of Psychology

190 Dysart Road
Winnipeg, Manitoba R3T 2N2
Canada
Phone (204) 474-9338

released or published: any other identifiers, such as your name, will not be used and will be destroyed a month after the experiments are completed.

Participation: Your participation in this study is completely voluntary. If you choose to participate, you have the right to discontinue your participation at any time during or after this experiment, even after signing this form. Should you choose not to participate or choose to stop once you have begun, you will still receive your experimental credits.

Your signature on this form indicates that you have understood to your satisfaction the information regarding participation in the research project and agree to participate as a subject. In no way does this waive your legal rights nor release the researchers, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from the study at any time, and/or refrain from answering any questions you prefer to omit, without prejudice or consequence. Your continued participation should be as informed as your initial consent, so you should feel free to ask for clarification or new information throughout your participation.

The University of Manitoba Research Ethics Board(s) and a representative(s) of the University of Manitoba Research Quality Management/ Assurance office may also require access to your research records for safety and quality assurance purposes.

This research has been approved by the Psychology/Sociology Research Ethics Board at the University of Manitoba. If you have any concerns or complaints about this project you m ay contact any of the above-named persons or the Human Ethics Secretariat at 474-7122, or e-mail Margaret_bowman@umanitoba.ca. A copy of this consent form has been given to you to keep for your records and reference.

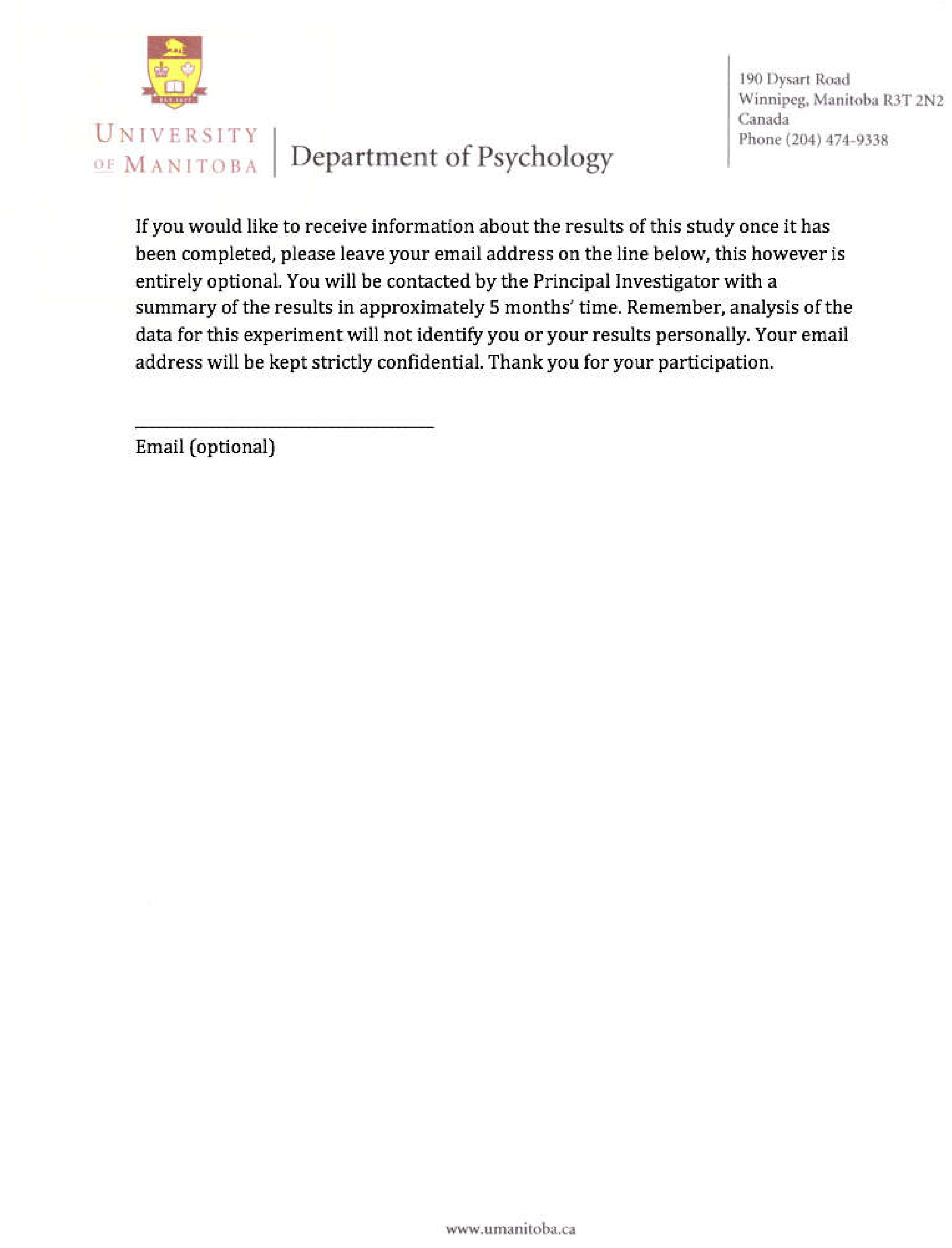
Consent: I have read and understood the above information and agree to participate in this experiment. I understand that I may keep a copy of this form for my own records.

I consent to be recorded on video [place an X where appropriate]: **Yes** ______ or **No** _______

________________________ ________________
Participant's Signature Date

____
Name of Participant (Please Print)

____
Researcher's Signature



UNIVERSITY OF MANITOBA | Department of Psychology

190 Dysart Road
Winnipeg, Manitoba R3T 2N2
Canada
Phone (204) 474-9338

If you would like to receive information about the results of this study once it has been completed, please leave your email address on the line below, this however is entirely optional. You will be contacted by the Principal Investigator with a summary of the results in approximately 5 months' time. Remember, analysis of the data for this experiment will not identify you or your results personally. Your email address will be kept strictly confidential. Thank you for your participation.

____
Email (optional)

www.umanitoba.ca

Appendix B1: Experiment 1a – Individual Response Measures

Subject	Leader Symmetry (ms)	Leader Anti-Symmetry (ms)	Follower Symmetry (ms)	Follower Anti-symmetry (ms)
1	134	127	181	228
2	191	225	248	319
3	92	176	276	377
4	202	228	241	320
5	244	252	337	388
6	174	194	239	334
7	106	134	220	281
8	188	192	268	359
9	204	250	188	315
10	205	514	437	571
11	169	174	238	341
12	276	287	296	369
13	204	194	278	333
14	309	257	283	363
15	196	209	229	225
16	302	410	418	435
17	195	216	199	290
18	227	228	382	412
19	207	229	318	380
20	222	261	407	434
21	101	106	297	310
22	174	175	362	386
23	181	196	359	415
24	199	224	291	411
25	194	260	431	468
26	238	295	343	412
27	247	239	338	401
28	293	332	593	688
29	139	198	281	325
30	190	322	575	592
31	328	370	320	588
32	312	368	470	653
Mean (milliseconds)	207	245	323	397

Appendix B2: Experiment 1b – Individual Response Measures

Subject	Leader Symmetry (ms)	Leader Anti-Symmetry (ms)	Follower Symmetry (ms)	Follower Anti-Symmetry (ms)
1	467	421	193	295
2	390	404	287	332
3	381	392	206	285
4	308	330	223	314
5	363	444	287	294
6	346	366	303	363
7	446	442	232	357
8	445	473	228	295
9	461	503	334	401
10	446	459	275	430
11	496	518	379	496
12	475	483	298	424
13	528	524	222	347
14	454	407	320	334
15	397	379	280	295
16	387	406	367	375
17	437	462	315	561
18	440	425	309	406
19	431	514	253	312
20	397	350	437	513
21	377	415	272	398
22	454	429	391	403
23	488	480	236	327
24	411	397	377	561
25	444	459	322	351
26	397	407	502	522
27	407	501	351	408
28	483	433	397	416
29	348	392	343	425
30	395	375	294	348
31	493	473	172	214
32	325	335	406	453
Mean (milliseconds)	422	431	306	383

References

1. Kelso, J.A.S., *On the coordination dynamics of (animate) moving bodies.* Journal of Physics: Complexity, 2022. **3**(3): p. 031001.
2. Haken, H., *Synergetics: An introduction. Non-equilibrium phase transition and self organization in physics, chemistry and biology.* 1983: Springer Verlag.
3. Ashby, W.R., *Principle of the self-organizing dynamic system.* The Journals of General Psychology, 1947. **2**(37): p. 125-128.
4. Heyes, C., *Cognitive Gadgets: The Cultural Evolution of Thinking (Illustrated ed.).* . 2018: Belknap Press: An Imprint of Harvard University Press.
5. Kelso, J.A., *Coordination Dynamics, in Encyclopedia of Complexity and Systems Science*. 2009: R. A. Meyers. ed. Springer. Heidelberg.
6. Tschacher, W. and H. Haken, *Intentionality in non-equilibrium systems? The functional aspects of self-organized pattern formation.* New Ideas in Psychology, 2007. **1**(25): p. 1-15.
7. Hesse, J. and T. Gross, *Self-organized criticality as a fundamental property of neural systems.* Front Syst Neurosci, 2014. **8**: p. 166.
8. Bak, P., C. Tang, and K. Wiesenfeld, *Self-organized criticality.* Physical review. A, General physics 1988(38): p. 364-374.
9. Bak, P., C. Tang, and K. Wiesenfeld, *Self-organized criticality: An explanation of the 1/fnoise.* Physical Review Letters, 1987. **4**(59): p. 381-384.
10. Haken, H., J.A. Kelso, and H. Bunz, *A theoretical model of phase transitions in human hand movements.* Biol Cybern, 1985. **51**(5): p. 347-56.
11. Kelso, J.A., *Phase transitions and critical behavior in human bimanual coordination.* Am J Physiol, 1984. **246**(6 Pt 2): p. R1000-4.
12. Ovchinnikov, I., *Introduction to Supersymmetric theory of stochastics*. Entropy, 2016. **4**(18): p. 108.
13. Richardson, M.J. and R.W. Kallen. *Symmetry-Breaking and the Contextual Emergence of Human Multiagent Coordination and Social Activity*. 2016.
14. Ramenzoni, V.C., N. Sebanz, and G. Knoblich, *Synchronous imitation of continuous action sequences: The role of spatial and topological mapping.* J Exp Psychol Hum Percept Perform, 2015. **41**(5): p. 1209-22.
15. Heyes, C., *Automatic imitation*. Psychol Bull, 2011. **137**(3): p. 463-83.
16. Schwabl, F., *Phase transitions, Scale invariance, Renormalization Group Theory, and Percolation.* Statistical Mechanics, 2002: p. 331-408.
17. Kornblum, S., T. Hasbroucq, and A. Osman, *Dimensional overlap: cognitive basis for stimulus-response compatibility--a model and taxonomy.* Psychol Rev, 1990. **97**(2): p. 253-70.
18. Phillips-Silver, J., C.A. Aktipis, and G.A. Bryant, *The ecology of entrainment: Foundations of coordinated rhythmic movement.* Music Percept, 2010. **28**(1): p. 3-14.
19. Ratcliff, R., *Methods for dealing with reaction time outliers.* Psychol Bull, 1993. **114**(3): p. 510-32.
20. Brass, M., P. Ruby, and S. Spengler, *Inhibition of imitative behaviour and social cognition.* Philosophical Transactions of the Royal Society B: Biological Sciences, 2009. **1528**(364): p. 2359-2367.
21. Brass, M. and C. Heyes, *Imitation: is cognitive neuroscience solving the correspondence problem?* Trends Cogn Sci, 2005. **9**(10): p. 489-95.
22. Müller, K., et al., *Perceptual influence on bimanual coordination: an fMRI study.* Eur J Neurosci, 2009. **30**(1): p. 116-24.
23. Mechsner, F., et al., *Perceptual basis of bimanual coordination.* Nature, 2001. **414**(6859): p. 69-73.
24. Friston, K., *The free-energy principle: a rough guide to the brain?* Trends Cogn Sci, 2009. **13**(7): p. 293-301.
25. Hove, M.J. and J.L. Risen, *It's all in the timing: Interpersonal synchrony increases affiliation.* Social Cognition, 2009. **6**(27): p. 949-960.
26. Knill, D.C. and A. Pouget, *The Bayesian brain: the role of uncertainty in neural coding and computation.* Trends Neurosci, 2004. **27**(12): p. 712-9.

27. Kelso, J.A., *The Dynamic Brain in Action: Coordinative Structures, Criticality, and Coordination Dynamics.* Criticality in Neural Systems, 2014: p. 67-104.
28. Kelso, J.A., *"Principles of dynamic pattern formation and change for a science of human behavior"*, in *Developmental Science and the Holistic Approach: Proceedings of a conference at Wiks Castle and the Nobel Institute*, L. Bergman, et al., Editors. 2000a: Stockholm; Mahwah, NJ: Erlbaum. p. 63-83.
29. Kelso, J.A., *Metastable Coordination Dynamics of Brain and Behavior.* The Brain & Neural Networks, 2001. **4**(8): p. 125-130.
30. Friston, K., M. Breakspear, and G. Deco, *Perception and self-organized instability.* Front Comput Neurosci, 2012. **6**: p. 44.
31. Shih, P.-C., et al., *Kinematic profiles suggest differential control processes involved in bilateral in-phase and anti-phase movements.* Scientific Reports, 2019. **9**(1): p. 3273.
32. Ancel, A., et al., *New insights into the huddling dynamics of emperor penguins.* Animal Behaviour, 2015(110): p. 91-98.
33. Akbar, U. and T. Ashizawa, *Ataxia.* Neurologic Clinics, 2015. **1**(33): p. 225-248.
34. Gerum, R.C., et al., *The origin of traveling waves in an emperor penguin huddle.* New Journal of Physics, 2013. **12**(15): p. 125022.
35. Waters, A., F. Blanchette, and A.D. Kim, *Modeling huddling penguins.* PLoS One, 2012. **7**(11): p. e50277.
36. Zitterbart, D.P., et al., *Coordinated movements prevent jamming in an Emperor penguin huddle.* PLoS One, 2011. **6**(6): p. e20260.
37. Ancel, A., H. Visser, and Y. Handrich, *Energy saving in huddling penguins.* Nature, 2005(385): p. 304-305.
38. Gilbert, C., et al., *Energy saving processes in huddling emperor penguins: from experiments to theory.* J Exp Biol, 2008. **211**(Pt 1): p. 1-8.
39. Hemelrijk, C., et al., *The increased efficiency of fish swimming in a school.* . Fish and Fisheries, 2014. **3**(16): p. 511-521.
40. Corcoran, A.J. and T.L. Hedrick, *Compound-V formations in shorebird flocks.* Elife, 2019. **8**.
41. Altshuler, E., et al., *Symmetry Breaking in Escaping Ants.* The American Naturalist, 2005. **6**(116): p. 643-649.
42. Helbing, D., I. Farkas, and T. Vicsek, *Simulating dynamical features of escape panic.* Nature, 2000. **407**(6803): p. 487-90.
43. O'Keefe, J. and J. Dostrovsky, *The hippocampus as a spatial map. Preliminary evidence from unit activity in the freely-moving rat.* Brain Res, 1971. **34**(1): p. 171-5.
44. O'Keefe, J. and L. Nadel, *The hippocampus as a cognitive map*. 1978, USA: Oxford University Press.
45. O'Keefe, J., *An allocentric spatial model for the hippocampal cognitive map.* Hippocampus, 1991. **1**(3): p. 230-5.
46. O'Keefe, J. and N. Burgess, *Geometric determinants of the place fields of hippocampal neurons.* Nature, 1996. **381**(6581): p. 425-8.
47. Stensola, T. and E.I. Moser, *Grid cells and spatial maps in Entorhinal cortex and hippocampus.* Research and Perspectives in Neurosciences, 2016: p. 59-80.
48. Aziz-Zadeh, L., et al., *Lateralization of the human mirror neuron system.* Journal of Neuroscience, 2006(26): p. 2964-2970.
49. Dinstein, I., et al., *Brain areas selective for both observed and executed movements.* J Neurophysiol, 2007. **98**(3): p. 1415-27.
50. Gazzola, V., L. Aziz-Zadeh, and C. Keysers, *Empathy and the somatotopic auditory mirror system in humans.* Curr Biol, 2006. **16**(18): p. 1824-9.
51. Gazzola, V., et al., *The anthropomorphic brain: the mirror neuron system responds to human and robotic actions.* Neuroimage, 2007. **35**(4): p. 1674-84.
52. Kilner, J.M., et al., *Evidence of mirror neurons in human inferior frontal gyrus.* J Neurosci, 2009. **29**(32): p. 10153-9.
53. Bisiach, E., C. Luzzatti, and D. Perani, *Unilateral neglect, representational schema and consciousness.* Brain, 1979. **3**(102): p. 609-618.
54. Buxbaum, L.J., et al., *Hemispatial neglect: Subtypes, neuroanatomy, and disability.* Neurology, 2004. **62**(5): p. 749-56.
55. Grossi, D., G. Di Cesare, and L. Trojano, *Left on the right or viceversa: a case of "alternating" constructional allochiria.* Cortex, 2004. **40**(3): p. 511-8.
56. Brainin, M., A. Seiser, and K. Matz, *The mirror world of motor inhibition: The alien hand syndrome in chronic stroke.* Journal of Neurology, Neurosurgery & Psychiatry, 2008. **3**(79): p. 246-252.

57. Nishikawa, T., et al., *Conflict of intentions due to callosal disconnection.* J Neurol Neurosurg Psychiatry, 2001. **71**(4): p. 462-71.
58. Novembre, G., et al., *Interpersonal synchrony enhanced through 20 Hz phase-coupled dual brain stimulation.* Social Cognitive and Affective Neuroscience, 2017. **12**(4): p. 662-670.
59. Kawasaki, M., K. Kitajo, and Y. Yamaguchi, *Sensory-motor synchronization in the brain corresponds to behavioral synchronization between individuals.* Neuropsychologia, 2018. **119**: p. 59-67.