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Synchrony in triadic jumping performance under the constraints of virtual-reality

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ABSTRACT

The development of an immersive virtual reality system, available as a work space for both sports and physical education, would be beneficial considering the current state of high-risk virus infection. In this study, we confirm this possibility by reproducing the mathematical ordered pattern of “triadic jumping” in a virtual space. Three jumpers were asked to move together in a cramped space that was insufficient to pass each other. Within this restricted space, the ordered pattern of the jumpers’ synchrony systematically transits to another state depending on the geometrical configuration of the work space. Although the temporal rigidity of the synchrony was partially lost, the ordered pattern of the “triadic jumping” synchrony that emerged in the virtual space was qualitatively equivalent to that emerging in real space. If the sensory feedback of the collision successfully improves the temporal rigidity of the joint action ordered pattern, the idea of expanding the work space for physical education to a virtual one, could turn into a reality.

Introduction

Online meetings and sharing of documents on cloud storage has enabled people across the globe to overcome communication limitations in terms of distance and availability. These communication technologies are more important in the current state of the COVID-19 pandemic. The next challenge is the creation of a virtual physical reality; for instance, construction of an online dance hall that enables synchronization of the dance moves of multiple dancers who are not present in the same physical space. To construct such an environment, the lag among the individual actions must be suppressed to several tens of milliseconds. In addition, synchronization patterns underpinned by a mathematical theory (i.e., self-organized patterns with temporal and spatial order, in which the state transition is governed by the group theory; see Table 1 in Supplementary information) need to be replicated in the space. We show that such an ordered pattern of whole-body joint action can be robustly attained in virtual space. We also discuss the potency of the virtual space as a work space for sports or physical education, which can enable the emergence of a strict ordered pattern for body synchrony.

The limb synchronization patterns of legged animals can be analyzed as a type of non-linear dynamical system, and their mechanism can be explained using the principle of non-linear coupled oscillators¹⁻³ or the theory of Hopf bifurcation (i.e., a type of bifurcation in which periodic solutions occur due to changes in the stability of the system)⁴⁻⁶. For example, when two actors are asked to coordinate their single limb or whole-body movement, their synchrony fluctuates when the frequency reaches a critical value, and thereafter, a phase transition emerges suddenly^{7,8}. The stability of the bifurcation patterns fluctuates depending on the inertial effects on the actor’s body or the gaze direction^{9,10}. These ordered patterns of dynamical systems can be applied to more complex joint movements in sports, such as dance^{11,12}, 1-on-1 match up scenes in basketball^{13,14}, or martial arts¹⁵⁻¹⁸. For example, Okumura and colleagues observed a spontaneous phase transition in the synchrony of the whole body movement of kendo players’ forward-backward step, which is equivalent to that of non-linear coupled oscillators¹⁵⁻¹⁷. Yokoyama and colleagues analyzed the synchrony in the triadic joint action of soccer players based on the group theory and revealed a symmetry in the synchrony of Hopf bifurcation in excellent players^{19,20}. Consequently, the ordered pattern of human synchrony is being unveiled based on the theory of symmetry breaking^{21,22}.

In a dyadic system, under strict spatial-temporal constraints, either of the two actors in the aforementioned example instantaneously leads another at a given moment, and this leader-follower relationship constantly alternates. For example, in martial arts, each of the two fighters compulsively go forward or backward according to the opponent’s choice if the distance between the fighters is sufficiently shortened^{15,23}. The system is highly unstable and moves towards the end of the game when both fighters simultaneously move forward. Conversely, if both go backward, the system remains stable but will halt and the

‘dynamic’ stability would be lost. The two fighters, thus, share the 1D distance that enables them to hit each other, and the continuously fluctuating forward-backward coordination dynamically stabilizes the tit-for-tat game state.

Similar synchrony would emerge in a more casual situation; for example, when the two pedestrians cross a narrow path, each of the two pedestrians deviates from their walking trajectory in the same direction to pass through. Now, suppose you walk through a 2D space crossing two other people coming from different directions. If strict spatial-temporal constraints act on this action coordination, the walkers will have to deviate from their walking trajectory in the same direction without stopping each other. In these three walkers’ synchrony, coordination of the direction between walkers *a* and *b* must be matched to those between each of these two walkers and another walker *c*. To ease this frustration, three constraints, namely, the geometry of the work space (environmental constraint), each walker’s ability (organismic constraint), and the spatio-temporal demands of the walkers (task constraint), would act effectively^{24–26}. The ordered pattern of movement coordination involving more than two elements can be reproduced by adopting an experimental system that enables the independent control of each of these 3 constraints.

It is fair to say that the physics of real-world motor coordination is being elucidated based on the principles of dynamical systems. However, there are few reports where three humans were immersed in a virtual reality space and were able to work together to recreate such an ordered pattern (see²⁷ for an example of recreating the ordered pattern of two). In fact, many researchers do not necessarily plan experiments that assume the physical structure of synchronization in real space, and the definition of the accuracy and function of ‘synchronization’ performed in virtual space is different for each researcher. Due to the disagreement among researchers considering the definition of synchrony, the views on the possibilities of virtual space are also largely divided. For example, some researchers consider synchrony to be expressed simply because the avatar mimics the participant’s behavior. Meanwhile, other researchers do not regard the movement cooperation between the two as synchrony if the delay of the avatar that follows the movement of the participant exceeds a certain range (e.g. < 0.58 s²⁸). Moreover, many reports conclude that co-operation with avatars induces prosocial emotions^{28,29}, while others conclude that such effects are only emergent when synchrony is attained unintentionally^{30,31}. That is to say, prosocial emotions, which have different views on the presence or absence of reproduction, are created by ‘unintentional motor synchrony’ with the avatar, not by-products of intention or togetherness to maintain synchrony. However, there was no example of reproducing the synchronized states of three-human dynamics which unintentionally transits to different states under physical constraints (differing from informational and psychological constraints) without being instructed by the experimenter to synchronize with the avatar in virtual space. Against the backdrop, we have reproduced on a virtual space an experimental system: triadic jumping that can induce and emerge synchrony among three parties by applying geometric constraints to the operating environment without cognitive intervention in the subject’s intention. Furthermore, we have compared the quantitative and qualitative accuracy of the ordered pattern emergent in the virtual space with the ordered pattern in the real space.

Triadic jumping task

Triadic jumping is an experimental system that enables control over the geometrical constraints of the joint action environment and eases the frustration arising due to triadic (3-actor) action coordination³². The work space of the triadic jumping is constructed by 3 or 4 hoops (each $\phi=0.65$ m) aligned on the laboratory floor, as shown in Figure 1B and C. In this study, three participants in a group were asked to stand in the assigned hoop and were asked to jump to the left or right hoop on receiving the auditory signal generated by a metronome. The signal was presented following two warning tones once per second; therefore, three jumpers had to coordinate their jump direction and synchronize their jump every 3 s (see Figure 1A). A trial ended when 20 successful jumps were recorded to avoid the effect of participants’ fatigue while ensuring the statistical reliability of the mean and the standard deviation of the timing of the jumping delay among the participants (i.e., lag_{mean} and lag_{sd} , see ‘Dependent measures and statistical analysis under the ‘Method’ section). Therefore, the participants had to jump a distance of 1.30 m at least 20 times. Although the movement is quite easy for the participants, they have to perform a preparatory postural movement. Any exchange of verbal speech, glance, or other body expressions was prohibited. The jumpers were further prohibited to favor a particular jumping direction before the trial began and were also asked to not repeat the same jumping direction. They had to predict the direction of the jump by referring to initiate the movement of others. If they failed to synchronize in terms of the jump direction, they were asked to return to the hoop assigned at the beginning of the trial.

As can be inferred from Figure 1B and C, three jumpers were made to jump in the same direction regardless of the hoop conditions (triangle or square). This was done to ensure that they could not establish any mutual understanding about the jump direction beforehand; they had to synchronize the preparatory posture to jump to the left or right, as shown in the snapshot in Figure 1B and C. Each of the three jumpers’ degrees of freedom were constrained by their position assigned by the hoop. The constraints for each jumper were symmetrical in the triangle condition and asymmetrical in the square condition. The constraint on an individual jumper was kept constant until the trial ended (i.e., the triad completed 20 successful jumps), because the jumper returned to the hoop assigned at the beginning of the trial.

Jumpers of 7 triads collided 3 to 4 times on an average until they completed 20 jumps, irrespective of the hoop alignment

conditions. The jumper who led the other 2 jumpers emerged as the lead jumper in each jump. The lag of the two followers was recorded to be much shorter (≈ 0.1 s) than the whole-body reaction time (≈ 0.3 – 0.4 s) or even shorter than the simple reaction time (≈ 0.2 s). The probability of each of the three jumpers to be the lead jumper was equal (i.e., 33.33% for all three jumpers) in the triangle geometry, whereas in the square geometry, only a jumper who stood in the hoop just before the open space (black in the left diagram of Figure 1C) in the jumping direction (i.e., the red jumper in the clockwise direction or yellow in the counterclockwise direction) would emerge as the lead jumper. The geometrical position of the lead jumper can be predicted by analyzing the geometrical hoop-jumper configuration based on the group theory. The details are stated in the Supplementary information and Table 1.

The ordered pattern of the triadic jumping emerges via the synchrony of the ‘preparatory movement’ of the jump, that is, the coordination of the backward-forward movement of the arms and the flexion-extension of the knee movement in the 2 s period before the jump as shown in the snapshot in Figure 1B and C. Each of the three jumpers synchronizes this movement and gains a sufficient ground reaction force to jump and move into the next hoop, which is approximately separated by 1.30 m. The geometrical structure of the actor-hoop configuration strictly constrains the frustration of the jumping direction emerging in the synchrony of the three jumpers. The spatio-temporal ordered pattern that emerged under such a systematic constraint is physically accurate and reproducible at a statistically significant level. Triadic jumping is the only system that enables the reproduction of such an ordered pattern of the triadic human joint action.

The present study clarifies that an ordered pattern emerges not only in a physically real space but also in an immersive virtual reality space. A virtual reality system is expected to be an experimental tool that enables the reproduction of complex daily movements while controlling the visual field of the work space^{33–36}. Movement in the virtual space is not *quantitatively* the same as that in real space (e.g., decrease in the movement’s amplitude^{36,37}, increase in the distance between two pedestrians crossing a road^{38–40}); however, the reproducibility of the *qualitative* ordered pattern of human synchrony has not been clarified, and the possibility of expanding the work space for the synchrony of human action to the virtual space remains unknown. We discuss the possibility of realizing the synchrony of perceptual-motor behavior in the virtual space. It should be emphasized that in our daily life, we maintain our physiological and mental health by spontaneously cooperating with peers who are physically close to us. Therefore, if the ordered pattern can be reproduced with the same accuracy as that in the real space, even with a person who is physically separated, it may be possible to reproduce the positive health effects caused by the coordination of movements. The system therefore could enable the creation of a virtual playfield of sports and will bring about physiological and psychological well-being considering the current state of mental and physical health risks owing to COVID-19.

Methods

Participants

Fourteen participants were recruited among the students of the Department of Physical Education at the University of Yamanashi. Seven triads were composed, with each of the seven participants involved in the two triads. Four participants were female (Age = 18.00 ± 0.00 yrs., Height = 160.50 ± 5.20 cm, Weight = 53.75 ± 6.50 kg), and ten were male (Age = 20.40 ± 1.51 yrs., Height = 171.80 ± 6.12 cm, Weight = 68.40 ± 11.75 kg). Two out of four female participants were involved in two triads, and the other two were involved in one triad. Any effects arising out of gender distribution were not observed in the results. All of the male and the female participants possessed good physiological and psychological health and had no experience of triadic jumping in both real and virtual spaces. Informed consent was obtained from all the participants using the procedure approved by the Research Ethics Committee of the Faculty of Education, University of Yamanashi.

Real work space setting

Procedure

The urethane foam mattresses were placed on the laboratory floor, and 3 or 4 plastic hoops (each $\phi = 0.65$ m) were aligned in a regular triangle or square shape, respectively. The position of each hoop of different colors in each of the triangular and square geometries was aligned as shown in Figure 1, that is, each of the red and yellow hoops was aligned left and right of the blue, respectively, and black was aligned diagonal to the blue hoop. Three participants in each triad were asked to remove their shoes and stand in each hoop with a color assigned beforehand. A rhythmic tone of a 3 s cycle was presented, and detailed instructions about the task were given. Subsequently, we asked them to jump once at the timing of the high tone that is cyclically presented every 3 s following two warning signals each presented by a low tone. We confirmed in advance that an interval of 3 s is sufficient for the participants to maintain their posture while preparing for each jump. A trial continued until the achievement of 20 successful jumps, and if they missed any synchronization or collided with each other, they were asked to return to the hoop assigned beforehand. Thereafter, they were asked to perform triadic jumping several times in either of the triangle or square geometry, and subsequently, began the trial under the same conditions as before. In case they missed a jump and returned to the assigned hoop, they were verbally guided to restart the jumping trial (e.g., ‘So, let’s prepare for the next signal, three, two, one ... go!’). All methods were performed in accordance with declaration of Helsinki.

Hardware setting for measuring jumping movement in real space

Before the beginning of the trial, all the three participants wore a motion capture cap on their head. Three reflective markers were attached to each participant's head. The positions of the nine markers were recorded using 15 infrared motion capture cameras (Miquis M1, Qualisys Inc., 100 Hz). The 3D positions of the three markers on the heads of each of the three participants were calculated, and the median point of the three markers was calculated as the position of the head top of each participant.

Virtual work space setting

Procedure

Each triad jumped in the same geometry constructed in the virtual space, 3 or 4 days after the trial in the real space was completed. The urethane mattress was sufficiently wide to avoid any collision among the three jumpers. The experimental system was constructed in the same room as that of the real space, and the mattress was also the same as that used in the trials in the real environment. The participants were asked to wear a head-mounted display (HTC VIVE Pro Eye, HTC Inc.) and held a controller in their hands. Both their dorsum and waist were attached to a VIVE tracker. The participants could move freely in the tracking space, which was separately set for each jumper as shown in Figure 2A, while each of them was immersed in the virtual triadic jumping space shown in Figure 1, which was shared with the other 2 jumpers using the back pack PC (VR GO 2.0, ZOTAC Inc., intel@Core i7-8700T processor NVIDIA GeForce@GTX 1070 graphic) wired to the head-mounted display. The work space of the triadic jumping was projected to each jumper via a head-mounted display, which was qualitatively the same as the real work space, and each jumper was assigned to one of the three hoops marked as red, blue, and yellow. The metronome tone, adopted to instruct the timing of the jump, was the same as that used in the real space. After all the trials under the triangle and square conditions were completed, each of the three participants separately answered the questionnaire concerning their age and physiological profiles (sex, height, weight, sports experience), experience of the virtual activity (such as playing games or watching movies) prior to the experiment, feeling of disturbance due to the equipment in contact with their body which created the virtual reality space, and the ease of the task in the real and virtual spaces. Similarly to the procedure in real setting, all methods were performed in accordance with declaration of Helsinki.

Hardware and software configuration for constructing a virtual work space

We used the Lighthouse System (HTC Inc.) to track the head-mounted display (HMD), tracker, and controller positions. We set four base stations that segregated the tracking space into three divisions, each assigned with a participant. A triadic jumping game requires three players. Each player wore a backpack PC (ZOTAC VR GO 2.0) with an HMD, two controllers (for each hand), and three trackers (for both the legs and the waist), and the backpack PC collected each device's position to keep track of the player's head, hand, leg, and waist positions. Then, the backpack PC transferred the position data to a desktop PC (Intel Core i7 7700 K 4.20 GHz), which collected the data regarding the positions of the body parts of the three players. Finally, the desktop PC constructed a virtual space for a triadic jumping game with three virtual avatars corresponding to the three players. Unity (Version 2018.2.11f1) was used to build the virtual space. We placed 3 or 4 hoops in the virtual space in exactly the same setting as that of the real space, as shown in Figure 2B (i.e., the hoop $\phi=0.65$ m and aligned as their edges touched each other). For example, Figure 2B shows the three avatars, each of which is placed in a hoop in the virtual space. We controlled the avatars in the virtual space using the inverse kinematics algorithm package, designed for Unity (Root Motion Inc.), based on the positions of the players' body parts. In addition, we used a network engine service (Photon Unity Networking 2, PUN2) to deploy a multiplayer game with three avatars. Figure 2C indicates the player's view of the replicated task space.

Dependent measures and statistical analysis

The vertical position of each jumper's head was obtained as the data in the real and virtual work spaces. To detect the timing of the jump, the time series of the three jumpers' positions were added, and the peak timing of the added time series was assigned as the timing of each jump. Figure 3A shows an example of the added time series, including twenty successful and two failed jumps. It also shows the fluctuation in position of each jumper's head, measured during the first successful jump, and is included in the time series presented in the lower panel. The timing of each of the three peaks was distributed around the timing of the peak of the added time series. The timing of the peak at which the lead jumper performed the n th successful jump is defined as $t_1(n)$, and those for the 2nd and 3rd jumpers are defined as $t_2(n)$ and $t_3(n)$, respectively. The representative of the two followers' delays in the n^{th} jump was calculated as follows:

$$L_n = \frac{\sum_{i=2}^3 (t_i(n) - t_1(n))}{2}$$

This representative value for each of the 20 successful jumps, $L_1, L_2 \dots L_{20}$, was calculated, and the mean and standard deviation for these values are defined as lag_{mean} and lag_{sd} , respectively. Moreover, the ratio of the lag of the 2nd jumper to that of the 3rd jumper was calculated for each of the 20 successful jumps, and the mean of these values was defined as the lag_{ratio} . Two-way

ANOVA, with repeated measurements consisting of the task space (2: real, virtual) and hoop condition (2: triangle, square), was applied to each of these 3 variables. The level of statistical significance was set to $p < .05$.

As shown in Figure 1B and C, the relative geometrical relationship of the three jumpers' position does not change every time they jump (Note that each jumper had to return to the initially assigned hoop when they missed to achieve synchrony). In the jumper-hoop condition of triangle geometry shown in Figure 1B, there is no difference in the degrees of freedom among the three jumpers assigned in the red, blue, and yellow hoops. Therefore, in the triangle condition, we simply calculated the probability of a participant being the lead jumper in the red, blue, and yellow hoop, which does not have an open space next to him/her. Contrarily, in the square condition, a jumper positioned in the red hoop has an open space (depicted by the black hoop in Figure 1C) in the left and the jumper in the yellow has an open space in the right, and the jumper in the blue hoop does not have any open space next to him/her. Therefore, the probability of a jumper achieving a synchrony was not simply defined with respect to the hoop color; instead, it was calculated based on the position of a hoop relative to the open space, which was dependent on the direction of each jump.

- A_o : A jumper assigned to one hoop *ahead* of the open hoop (i.e., yellow for clockwise or red for counterclockwise depicted in two upper-right icons in Figure 5B)
- D_o : A jumper assigned to the hoop *diagonal* to the open hoop (blue for both directions depicted in the upper-middle icon in Figure 5B)
- B_o : A jumper assigned to one hoop *before* the open hoop (i.e., red for clockwise or yellow for counterclockwise depicted in the two upper-left icons in Figure 5B)

The probability of being a lead jumper was calculated for each jumper in each of the three positions; the statistical significance of the task space (2: real, virtual) and hoop position (3: red, blue and yellow for the triangle condition; 3: A_o , D_o and B_o for the square condition), and their relationship, on the probability of a jumper being the lead jumper was tested using a two-way ANOVA with repeated measurements. The multiple comparison for the (simple) main effect of the hoop position was tested using the Bonferroni method. The level of statistical significance was set to $p < .05$.

Results

Jump timing lag between the leader and followers

The lag between the lead jumper and the followers was calculated based on the vertical head position of the jumpers and a mean of the representative value of the leader-follower lag (for details of the calculation procedure, see Figure 3) was also calculated. This leader-follower lag was calculated for each of the 20 successful jumps and averaged as the lag_{mean} . The significance of the task space condition (2: real or virtual) and hoop alignment condition (2: triangle or square), and their interaction on the value of lag_{mean} was tested using the two-way ANOVA. The main effect of the task space was statistically significant ($F(1, 6)=19.675$, $p=0.004$, $\eta^2=0.766$), whereas the main effect of the hoop alignment ($F(1, 6)=0.427$, $p=0.537$, $\eta^2=0.066$) and the interactive effect of both the factors ($F(1, 6)=3.09$, $p=0.129$, $\eta^2=0.34$) were not significant. The mean of the lag_{mean} averaged over the seven triads was significantly shorter in the real space (0.076 s) than in the virtual space (0.176 s). The value observed in the real space was extremely short compared to the response time of the whole-body coordination. The lag_{mean} measured in the virtual space was far longer; however, the value was far shorter than the whole-body reaction time (≈ 0.3 s; the interval between the trigger signal to jump to the moment of the foot's take off) measured in the same age group⁴¹; moreover, it was even shorter than the simple reaction time (0.2s). In addition, as shown in Figure 3, all three jumpers' actions, including the preparation to takeoff, continuously fluctuated in the isomorphic (Mexican hat) shape, and the two followers would not *react* to the leader's jump direction, but instead, all of the three jumpers synchronized their preparatory action and *mutually interacted* to extrude jumpers who led others towards the jumping direction.

Furthermore, we calculated the standard deviation of the leader-follower lag of 20 successful jumps (lag_{sd} , Figure 4B) for each trial. Two-way within-group ANOVA revealed a significant task space effect ($F(1, 6)=6.95$, $p=0.038$, $\eta^2=0.537$) on the lag value, whereas the main effect of hoop alignment ($F(1, 6)=0.697$, $p=0.435$, $\eta^2=0.104$) and the interaction of task space and hoop alignment ($F(1, 6)=1.846$, $p=0.223$, $\eta^2=0.235$) were not significant. As shown in Figure 4B, the mean of the lag_{sd} averaged over seven groups measured in the real space (0.047 s) was smaller than that measured in the virtual space. In addition, as shown in Figure 4B, the between-triad deviation was also smaller for the real-space condition. The results suggest that synchronized patterns of the triadic jumpers are uniquely determined in real space; conversely in the virtual space, the occurrence of patterns will fluctuate in a stochastic manner. Additionally, we calculated the ratio of the 2nd jumper's lag to the third jumper's lag (lag_{ratio} ; Figure 4C) and found that the main effects of task space and hoop alignment and their interaction were not significant (task space: $F(1, 6)=0.055$, $p=0.823$, $\eta^2=0.009$; hoop alignment: $F(1, 6)=0$, $p=0.983$, $\eta^2=0.000$; interaction: $F(1, 6)=1.603$, $p=0.252$, $\eta^2=0.211$). The value distributed around 0.5 indicates that the lag between the 1st and

2nd jumper and that between the 2nd and 3rd jumpers were equivalent, and this trend was also observed for the trials in the virtual space.

Geometrical position of the lead jumper

All jumpers participated in this experiment with the same student in the same department of physical education and all possessed equally sufficient body action skills to perform triadic jumping. In the triangle condition, the degrees of freedom for the three jumpers were symmetrical (or equivalent), as none of them had space to move. We calculated the probabilities of each of the three jumpers, assigned to red, blue, and yellow hoops, to lead others. The equivalence in the probability of being a leader can be predicted from the symmetrical configuration of the hoop-actor geometrical alignment. The equivalence in the triangle condition indicates that the geometry constructed in the virtual space also constrains the ordered pattern of synchrony among the three jumpers in real space.

In contrast to the triangle hoop condition, there exists a 'unique' open space in the square hoop condition and the degree of freedom of the three jumpers is asymmetrical (or non-equivalent) depending on the relative position to the open space that constrains each jumper's degree of freedom until the completion of a trial. In the sense that both have open spaces on either sides, the degrees of freedom for the red and yellow jumpers are symmetrical. In contrast, the degree of freedom for the blue jumper is not symmetrical to the other two, because both sides of the blue jumper were occupied by red and yellow jumpers. In addition to the triangle hoop condition, we predicted that such asymmetry in the geometrical configuration constrains the leader-follower asymmetry. To confirm this hypothesis, we compared the probability between the jumper's position relative to the 'unique' open space that introduces geometrical asymmetry into the system.

Two-way ANOVA with repeated measurements revealed that the main effects of the task space were not significant ($F(1,6)=0.151$, $p=0.710$, $\eta^2=0.016$), while the main effect of the hoop position ($F(2,12)=21.696$, $p=0.000$, $\eta^2=0.783$) was significant. The result of the post-hoc test using the Bonferroni method indicated that the probability for the B_o jumper was significantly higher than that for the other two jumpers (B_o vs. $A_o=0.000$, B_o vs. $D_o=0.000$, A_o vs. $D_o=0.128$). The effect of interaction between the factors was also significant ($F(2,12)=4.146$, $p=0.042$, $\eta^2=0.409$). The analysis of the interaction revealed that the simple main effect of the task space was significant at A_o , and the probability in virtual space was significantly higher for A_o ($F(1,6)=13.444$, $p=0.026$, $\eta^2=0.771$). The probability of B_o tended to be lower in the virtual space ($F(1,6)=5.629$, $p=0.055$, $\eta^2=0.484$), although this tendency was not statistically significant. The simple main effect of the hoop position in both task spaces was significant (real: $F(2,12)=57.867$, $p=0.000$, $\eta^2=0.905$; virtual: $F(2,12)=4.171$, $p=0.042$, $\eta^2=0.410$). However, the result of the post-hoc test using Bonferroni revealed that the difference between the hoop position was significant only in real space, indicating that the probability of the B_o jumper was higher than that of the other two jumpers ($p=0.000$ for B_o vs. A_o and B_o vs. D_o , $p=0.128$ for A_o vs. D_o). There was no significant difference between the hoop positions in the virtual space. The result suggests that the asymmetrical role of the jumpers' position robustly reflects itself in the synchrony of the triadic jump, as predicted by the geometry of the hoop-jumper configuration. Conversely, in the virtual space, although the result of the post-hoc test was not statistically significant, the simple main effect that represents an overall deviation among the three hoop positions was statistically significant. Furthermore, the statistically significant effect of the hoop position on the data combined with those measured in the real and virtual space were equivalent to the simple effect only in real space. Thus, we could partially reproduce the asymmetrical ordered pattern of the triadic jumping in the square geometry in the virtual task space with a finite level of probability.

In addition, according to the answer to the questionnaire conducted after the experiment, seven participants had a better experience in real space, and unexpectedly, the other 5 had a better experience in the virtual space (the remaining two reported no significant difference in the ease between the two spaces). Two participants experienced severe disturbance due to the equipment attached to their body (e.g., head mount display or backpack PC, etc.).

Discussion

The ordered pattern of the triadic jumping emerges under the constraint of the geometrical parameters of the environment, task demand, and ability of the participant to perform the task. An extremely short lag between the jumpers was newly confirmed in the real space of the current experiment. As shown in Figure 3B, the movement profiles of the three jumpers were identical and continuously progressed from the preparation phase (i.e., the first negative peak) to the takeoff (positive peak) phase. In addition, in real space, they synchronized with a small phase lag ($lag_{mean} < 0.1$ s), as shown in Figure 4A. Moreover, the extremely short, lag_{sd} , indicates that the extremely short phase lag pattern was reproduced for every 20 successful triadic jumps. In the square hoop condition, the constraint of the geometrical symmetry inherent in the triadic jumping system compelled the jumper in one hoop before the open space to lead the other two jumpers, resulting in the spatio-temporal ordered pattern shown in Figure 5B. Generally, in a system of cooperative action, the ordered pattern with the highest symmetry emerges among the patterns inherent in the system. This rule of cooperation has been repeatedly confirmed in many laboratory experiments^{7,9} and in the field of sports^{15,19,23}. The ordered pattern of triadic jumping that we have discovered is not a product of intentional

cooperation through language, but emerged spontaneously and unintentionally under the geometric constraints of the system. An emphasis should be placed on the fact that the ordered pattern of triadic jumping is endowed with mathematical rigor and reproducibility; the novelty of our finding is assured by the fact that the intentional coordination in motion used in virtual space research so far does not have an ordered pattern with such mathematical rigor and reproducibility. A further interesting observation can be noted that, in the triadic jumping system, a change in the hoop-jumper geometry prompted a bifurcation to states with different symmetry without the intention of the participants (D_3 for a triangular arrangement, and D_1 for that of a square arrangement; see Figure 1 and Table 1).

The most important result of the present study is that the qualitative and quantitative robustness of the ordered pattern that emerges spontaneously can be reproduced in virtual space. Certainly, in case of the virtual space, the lag and its standard deviation were large compared to the data obtained in real space, suggesting that the exactness of the ordered pattern was perturbed. This large perturbation was observed not only for such a time constant of inter-jumping synchronization but also observed in the asymmetrical ordered pattern of leader-follower interaction that was constrained by the asymmetrical jumper-hoop configuration in the square geometry. The lack of significance in the result of the post-hoc analysis of the virtual space data indicates that the A_o jumper (one hoop ahead of the open space) led others more frequently and the B_o jumper (one hoop before the open space) led others less frequently, each compared to the probability in real space. In previous studies on inter-personal coordination, visual information of actions among the participants mediated their synchrony^{7,9,42}. Of course, even in virtual space, one can visually capture the action of the mates; however, according to the answer to the questionnaire, 6 jumpers out of 14 felt it was more difficult to see the other jumpers' actions in the virtual space than in the real space. From such subjective reports, it cannot be denied that the perturbation on the sight that may result from the limited view of the head mounted display and may have caused disturbances in the ordered pattern. The refresh rate of the HTC VIVE Pro Eye is 60 Hz (≈ 16.7 ms/frame) and the interval between holding the key of the hand-held controller down to reflecting the result on the display was up to only 15 ms⁴³. Even when the delay due to rendering the scene on the display accumulated, the total temporal delay from the jumpers' action to the moment at which the result of the action visually reflected on the HMD was several tens of milliseconds. If the delay in feedback, sufficient to skew the sense of tendency or body ownership, is postulated to be approximately 150-200 ms⁴⁴⁻⁴⁷, it would not be reasonable to deduce that the mechanical temporal delay due to the virtual reality devices would cause difficulty to the six jumpers' motion (perceptual-motor).

The main reason behind the disturbance of the quantitative and qualitative ordered pattern is the absence of the risk of a physical collision, and not the mechanical delay in the devices. In a natural (real) environment, each of the triadic jumpers swung back their arms and squatted downward in the preparation phase of the jump to gain a sufficient ground reaction force to jump into the left or right hoop. In this preparatory phase, the jumper must control their posture preparing not only for a safe landing but also to avoid the impact of a collision with the other jumpers. The 'resultant' jumping direction would be decided via a synchrony in the action in this preparation phase, and no needs to prepare for a collision may make the ordered pattern of action coordination 'loose,' not only quantitatively (as indicated by lag_{mean} and lag_{sd} in Figure 4A and B, respectively), but also qualitatively (as indicated by the probability to be a lead jumper shown in Figure 5). The theoretical investigation of the emergence of the extremely short lag synchrony is attracting attention in behavioral science, and the effect of the risk of collision on the ordered pattern of the leader-follower role can be tested by introducing the force feedback function to the current system.

A series of results suggest that the bifurcation pattern of the triadic jumping based on the group theory (see, Table 1 in Supplementary information) can be reproduced in the virtual reality. Certainly, the lag between the jumpers was longer and more variable in each virtual space jump than that in real space. However, the absolute time of the lag was significantly shorter than the simple reaction time, and the jumping movement synchronized continuously, as can be seen in Figure 3. Furthermore, the main effect of the hoop geometry on the emergence of the lead jumper was significant and even limited to the data in virtual space; although the probability did not reach a significant level, the jumper assigned to one hoop before the open space tended to lead another jumper (i.e., B_o jumper, see Figure 5B). The results suggest that the ordered pattern equivalent to that of the real space also emerges in the virtual space. Although the ordered pattern was partially compromised because of the absence of the physical risk of collision, the ordered pattern is far more rigid than that investigated in the previous studies of virtual reality. Moreover, the dynamical structure of the ordered pattern can be reproduced by controlling the geometrical structure of the work space, therefore, the patterns of the synchrony would systematically be controlled. Such work space of whole-body synchrony would create a virtual playground for physical education or sports that would produce not only physiological but also positive prosocial effects as one can be predicted from the previous research about the psychological effect of movement synchrony with a virtual agent. The COVID-19 pandemic has reiterated the need to develop such technologies to exploit their full potential.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

References

1. Haken, H., Kelso, J. S. & Bunz, H. A theoretical model of phase transitions in human hand movements. *Biol. Cybern.* **51**, 347–356 (1985).
2. Kelso, J. Phase transitions and critical behavior in human bimanual coordination. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* **246**, R1000–R1004 (1984).
3. Kelso, J. S. & Tuller, B. A dynamical basis for action systems. In *Handbook of cognitive neuroscience*, 321–356 (Springer, 1984).
4. Golubitsky, M. Patterns in physical and biological systems. In *Models, Simulations, and the Reduction of Complexity*, 29–42 (De Gruyter, 2013).
5. Golubitsky, M., Luss, D. & Strogatz, S. H. *Pattern formation in continuous and coupled systems* (Springer, 1999).
6. Golubitsky, M. & Stewart, I. Symmetry and pattern formation in coupled cell networks. In *Pattern formation in continuous and coupled systems*, 65–82 (Springer, 1999).
7. Schmidt, R. C., Carello, C. & Turvey, M. T. Phase transitions and critical fluctuations in the visual coordination of rhythmic movements between people. *J. Exp. Psychol.: Hum. Percept. Perform.* **16**, 227 (1990).
8. Schmidt, R. C. & Fitzpatrick, P. The origin of the ideas of interpersonal synchrony and synergies. In *Interpersonal coordination and performance in social systems*, 35–49 (Routledge, 2016).
9. Richardson, M. J., Marsh, K. L., Isenhower, R. W., Goodman, J. R. & Schmidt, R. C. Rocking together: Dynamics of intentional and unintentional interpersonal coordination. *Hum. Mov. Sci.* **26**, 867–891 (2007).
10. Tolston, M. T., Shockley, K., Riley, M. A. & Richardson, M. J. Movement constraints on interpersonal coordination and communication. *J. Exp. Psychol. Hum. Percept. Perform.* **40**, 1891 (2014).
11. Miura, T. *et al.* Qualitative evaluation of quantitative dance motion data. In *ACM SIGGRAPH ASIA 2009 Posters*, 1–1 (2009).
12. Miura, A., Fujii, S., Yamamoto, Y. & Kudo, K. Motor control of rhythmic dance from a dynamical systems perspective: a review. *J. Dance Medicine & Sci.* **19**, 11–21 (2015).
13. Fujii, K., Yamashita, D., Yoshioka, S., Isaka, T. & Kouzaki, M. Strategies for defending a dribbler: categorisation of three defensive patterns in 1-on-1 basketball. *Sports Biomech.* **13**, 204–214 (2014).
14. Fujii, K., Yoshioka, S., Isaka, T. & Kouzaki, M. The preparatory state of ground reaction forces in defending against a dribbler in a basketball 1-on-1 dribble subphase. *Sports Biomech.* **14**, 28–44 (2015).
15. Okumura, M. *et al.* A critical interpersonal distance switches between two coordination modes in kendo matches. *Plos One* **7**, e51877 (2012).
16. Okumura, M., Kijima, A. & Yamamoto, Y. Perception of affordances for striking regulates interpersonal distance maneuvers of intermediate and expert players in kendo matches. *Ecol. Psychol.* **29**, 1–22 (2017).
17. Yamamoto, Y. *et al.* Joint action syntax in japanese martial arts. *Plos One* **8**, e72436 (2013).
18. Krabben, K., Orth, D. & van der Kamp, J. Combat as an interpersonal synergy: An ecological dynamics approach to combat sports. *Sports Med.* **49**, 1825–1836 (2019).
19. Yokoyama, K. & Yamamoto, Y. Three people can synchronize as coupled oscillators during sports activities. *PLoS Comput. Biol.* **7**, e1002181 (2011).
20. Yokoyama, K., Shima, H., Fujii, K., Tabuchi, N. & Yamamoto, Y. Social forces for team coordination in ball possession game. *Phys. Rev. E* **97**, 022410 (2018).
21. Richardson, M. J. & Washburn, A. Symmetry and the dynamics of interpersonal coordination. In *Interpersonal coordination and performance in social systems*, 83–100 (Routledge, 2016).
22. Richardson, M. J. & Kallen, R. W. Symmetry-breaking and the contextual emergence of human multiagent coordination and social activity. In *Contextuality from quantum physics to psychology*, 229–286 (World Scientific, 2016).
23. Kijima, A. *et al.* Switching dynamics in an interpersonal competition brings about “deadlock” synchronization of players. *Plos One* **7**, e47911 (2012).
24. Newell, K., Van Emmerik, R. & McDonald, P. Biomechanical constraints and action theory. *Hum. Mov. Sci.* **8**, 403–409 (1989).

25. Hu, X. & Newell, K. M. Modeling constraints to redundancy in bimanual force coordination. *J. Neurophysiol.* **105**, 2169–2180 (2011).
26. Newell, K. M. & Liu, Y.-T. Collective variables and task constraints in movement coordination, control and skill. *J. Mot. Behav.* **53**, 770–796 (2021).
27. Nalepka, P. *et al.* Human social motor solutions for human–machine interaction in dynamical task contexts. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 1437–1446 (2019).
28. Tarr, B., Slater, M. & Cohen, E. Synchrony and social connection in immersive virtual reality. *Sci. Rep.* **8**, 1–8 (2018).
29. Raffard, S. *et al.* Using mimicry of body movements by a virtual agent to increase synchronization behavior and rapport in individuals with schizophrenia. *Sci. Rep.* **8**, 1–10 (2018).
30. Bailenson, J. N., Yee, N., Patel, K. & Beall, A. C. Detecting digital chameleons. *Comput. Hum. Behav.* **24**, 66–87 (2008).
31. Kulesza, W., Dolinski, D. & Wicher, P. Knowing that you mimic me: the link between mimicry, awareness and liking. *Soc. Infl.* **11**, 68–74 (2016).
32. Kijima, A., Shima, H., Okumura, M., Yamamoto, Y. & Richardson, M. J. Effects of agent-environment symmetry on the coordination dynamics of triadic jumping. *Front. Psychol.* **8**, 3, DOI: [10.3389/fpsyg.2017.00003](https://doi.org/10.3389/fpsyg.2017.00003) (2017).
33. Kinader, M., Wirth, T. D. & Warren, W. H. Crowd dynamics in virtual reality. In *Crowd Dynamics, Volume 1*, 15–36 (Springer, 2018).
34. Pan, X. & Hamilton, A. F. d. C. Why and how to use virtual reality to study human social interaction: The challenges of exploring a new research landscape. *Br. J. Psychol.* **109**, 395–417 (2018).
35. Levac, D. E., Huber, M. E. & Sternad, D. Learning and transfer of complex motor skills in virtual reality: a perspective review. *J. Neuroeng. Rehabil.* **16**, 1–15 (2019).
36. Haar, S., Sundar, G. & Faisal, A. A. Embodied virtual reality for the study of real-world motor learning. *Plos One* **16**, e0245717 (2021).
37. Itaguchi, Y. Size perception bias and reach-to-grasp kinematics: An exploratory study on the virtual hand with a consumer immersive virtual-reality device. *Front. Virtual Real.* **2**, 712378 (2021).
38. Fink, P. W., Foo, P. S. & Warren, W. H. Obstacle avoidance during walking in real and virtual environments. *ACM Trans. Appl. Percept.* **4**, 2–es (2007).
39. Olivier, A.-H., Marin, A., Crétual, A. & Pettré, J. Minimal predicted distance: A common metric for collision avoidance during pairwise interactions between walkers. *Gait & Posture* **36**, 399–404 (2012).
40. Olivier, A.-H., Marin, A., Crétual, A., Berthoz, A. & Pettré, J. Collision avoidance between two walkers: Role-dependent strategies. *Gait & Posture* **38**, 751–756 (2013).
41. Kai, S. *et al.* Relationships between whole body reaction time and the motion-silent period and the action period in jump. *J. Phys. Ther. Sci.* **24**, 227–229 (2012).
42. Schmidt, R. C. & Richardson, M. J. Dynamics of interpersonal coordination. In *Coordination: Neural, behavioral and social dynamics*, 281–308 (Springer, 2008).
43. Chénéchal, M. L. & Goldman, J. C. HTC Vive Pro time performance benchmark for scientific research. In Bruder, G., Yoshimoto, S. & Cobb, S. (eds.) *ICAT-EGVE 2018 - International Conference on Artificial Reality and Telexistence and Eurographics Symposium on Virtual Environments* (The Eurographics Association, 2018).
44. Ismail, M. A. F. & Shimada, S. ‘Robot’ hand illusion under delayed visual feedback: Relationship between the senses of ownership and agency. *Plos One* **11**, e0159619 (2016).
45. Shimada, S., Hiraki, K. & Oda, I. The parietal role in the sense of self-ownership with temporal discrepancy between visual and proprioceptive feedbacks. *Neuroimage* **24**, 1225–1232 (2005).
46. Franck, N. *et al.* Defective recognition of one’s own actions in patients with schizophrenia. *Am. J. Psychiatry* **158**, 454–459 (2001).
47. Blakemore, S.-J., Frith, C. D. & Wolpert, D. M. Spatio-temporal prediction modulates the perception of self-produced stimuli. *J. Cogn. Neurosci.* **11**, 551–559 (1999).
48. Richardson, M. J. *et al.* Self-organized complementary joint action: Behavioral dynamics of an interpersonal collision-avoidance task. *J. Exp. Psychol. Hum. Percept. Perform.* **41**, 665 (2015).

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Author contributions statement

A.N., K.G. and A.K. conceived the experiment(s), A.N. and A.K. conducted the experiment(s), A.N., H.S. and A.K. analyzed the results. All authors reviewed the manuscript.

Supplementary information

Analysis of the jumper-hoop configuration and the asymmetry in the jumpers' role based on group theory

The shape of the regular triangle hoop alignment shown in Figure 1 is unchanged even when it is turned over around either of the 3 axes colored red, blue, and yellow. Moreover, it remains unchanged even when it is rotated over 3 angles: 0° (360°), 120°, or 240°. Therefore, the symmetry of the shape is defined as a dihedral symmetry D_3 , based on group theory. Contrarily, the jumping ability of the jumpers can be considered to be equivalent and this functional symmetry can be defined as S_3 . The isotropic subgroup of the hoop geometrical symmetry and the jumpers' functional symmetry are shown in Table 1, where the maximum ordered pattern subgroup is D_3 (or S_3), which means that all 3 elements commute with one another; in other words, the elements are symmetrical and correspond to the phenomenon in which all three jumpers become leaders with the same probability.

Table 1. Isotropic subgroups of the jumper-hoop configurations.

Geometry	Hoop symmetry	Jumper symmetry	Jumper-hoop symmetry (isotropy subgroup)
Triangle	D_3	S_3	D_3 (or S_3), Z_3 , D_1 (or Z_2), I
Square	D_4	S_3	D_1 (or Z_2), I

On the other hand, the square shape of the hoop shown in Figure 1 is invariant to the reflection around the 4 axes (3 dashed axes and a blue axes) and is invariant to the rotation over 4 angles, such as 0° (or 360°), 45°, 90°, and 135°; thus, the symmetry of the square hoop alignment is defined as S_4 . The functions of the three jumpers are the same as those in the triangle condition; therefore, the symmetry can be defined as S_3 . Hence, the highest-ordered pattern of the isotropic subgroup of the hoop-actor symmetry can be defined as D_1 (or Z_2), which corresponds to the result of a jumper, in the hoop before the open space with respect to the jumping direction, who can be a lead jumper; only 2 out of 3 jumpers can be permuted. Subsequently, the symmetry of the jumpers' role can be predicted using the symmetry based on group theory, and the symmetry of their role is congruent with the highest ordered pattern of the isotropic subgroup hoop geometrical symmetry and the jumpers' functional symmetry, that is, the hoop-jumper symmetry. For a more detailed explanation, see^{32,48}.

Competing interests

The authors declare no competing interests.

Figure 1. Triadic jumping task performed in real space. (A) The time schedule of the jumping cue. The timing was cued at every 3 s by a high-pitched metronome tone following 2 low tones, as shown in the pulse diagram. (B) Triadic jumping task in the triangle condition. Initial hoop-jumper configuration is shown in the left diagram. Regular triangle configuration (upper left) is retained even if the configuration is rotated by 0 (360)°, 120° or 240°, and if the configuration is reversed about any of the 3 axes (colored in red, blue and yellow). The examples of the failed and successful jumps are shown in the sequence of the photograph. The diagram in the right is a hoop-jumper configuration that emerged as the consequence of a successful jump for each hoop condition. (C) Triadic jumping task in the square condition. Initial hoop-jumper configuration (left) such that it can only be rotated by 0 (360)° and possesses only one reversing axis (colored in blue) to retain the initial hoop-jumper configuration.

Figure 2. Work space of triadic jumping constructed in the virtual space. Left: Three jumpers in the laboratory immersing into the virtual triadic jumping space. Each of them was assigned a separate place so that they never collided with each other. Center: Bird's eye view of triadic jumpers used by an experimenter to check collision among the jumpers. Collision may occur only in the virtual space and cannot be confirmed in the real laboratory space. Right: Sight of a jumper (blue in the example) through head mounted display seeing the center of square configuration of the 4-hoop alignment.

Figure 3. Vertical movement of the three jumpers and definition of the lag. (A) A typical example of the time series of the vertical position of the jumper's head summed up for three jumpers. Each timing of 20 successful jumps were detected as peaks marked by a red circle. Timings of the peaks without a marker are approximated to the timing of a coordination error (collapsed trial). (B) Each of the three jumpers' vertical position was clipped from 100 ms before to 100 ms after the peak. The pattern of vertical movement around each jump was identical between and within each jumper. In the early phase, the center of mass of their head and that of the whole-body went downward with their knees flexed and the arms swung backward. The body then lifted itself up with an arm swinging downward and forward, quickly, and the knees extended quickly as well. In the last touchdown phase, the body went downward again and recovered to prepare for the next jump.

Figure 4. Mean and standard error of timing lag between the leader and followers. (A) lag_{mean} , (B) lag_{sd} , (C) lag_{ratio} . Broken line with open circle: real space, solid with filled: virtual space. Significant effect of task space with $p < .01$ and $p < .05$ was found in the analysis of lag_{mean} (left) and lag_{sd} (center), respectively.

Figure 5. Frequency to be a lead jumper (in percentage) relative to 20 successful jumps. Mean and standard error of 7 triads. (A) Triangle geometry consisting of red, blue, and yellow hoops, as represented in the upper left drawings in Figure 1. (B) Square geometry consisting of open space, one hoop ahead from open (A_o : Red for counterclockwise and yellow for clockwise), diagonal to open (D_o : Blue for both directions), and one hoop before open (B_o : Red for clockwise or yellow for counterclockwise) with respect to the direction of the jump. Broken line with open circle: real space, solid filled: virtual space. ** indicates significant difference with $p < .01$ in the post-hoc test using the Bonferroni method.