Behavioral Dynamics of a Collision Avoidance Task: How Asymmetry Stabilizes Performance

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Abstract

The current project examined how changes to task constraints impacted the behavioral dynamics of an interpersonal collision avoidance task previously examined and modeled by Richardson and colleagues (2015). Overall, the results demonstrate that decreasing the cost associated with colliding influences the stability and symmetry of the movement dynamics observed between co-actors in a manner consistent with those predicted by the Richardson et al. (2015), collision avoidance model. The current study therefore provides evidence that the behavioral dynamics that shape interpersonal or joint-action behavior are not only defined by the physical and informational properties of a task, but also by the strength and importance of the shared task goal.

Keywords: interpersonal dynamics; collision-avoidance; joint action; behavioral dynamics; behavioral symmetry

Introduction

Much research has been directed towards understanding the neural and cognitive mechanisms that support joint action, or the actions that individuals perform with others every day (e.g. Graf, Schütz-Bosbach, & Prinz, 2009; Vesper, Butterfill, Knoblich, & Sebanz, 2010). However, it is equally important to understand the dynamical processes that constrain such behaviors (Schmidt, Fitzpatrick, Caron & Mergeche, 2011; van der Wel, Knoblich, & Sebanz, 2011; Vesper, van der Wel, Knoblich, & Sebanz, 2013). Indeed, there is now strong evidence that the dynamics of social motor coordination provides the embodied context by which co-actors are able to develop shared task goals and intentions (e.g. Coey, Varlet & Richardson, 2012; Marsh, Richardson & Schmidt, 2009). Furthermore, the stability of motor coordination influences rapport and social cooperation (Hove & Risen, 2009), perceived group differences (Miles, Griffiths, Richardson & Macrae, 2011), and is also related to the social cognitive deficits associated with autism (Fitzpatrick, Diorio, Richardson & Schmidt, 2013).

Given the importance of understanding the dynamics of social motor coordination, it is perhaps surprising that the majority of the existing research has only investigated the presence of these dynamic processes in tasks that involve co-actors coordinating stereotyped or non-functionally directed oscillatory limb or body movements such as finger/forearm oscillations, pendulum swinging, and rocking chairs (e.g., Richardson, Marsh, Isenhower, Goodman & Schmidt, 2007; Schmidt & O'Brien, 1997). The significance of this research is that it demonstrates that the rhythmic movements of informationally coupled individuals are constrained to inphase (a stable 0° relative phase relation) and antiphase (a stable 180° relative phase relation) patterns of behavioral synchrony, and can be understood and modeled using the same coupled oscillator dynamic known to underlie intrapersonal interlimb coordination (Schmidt & Richardson, 2008 for a review). Yet, joint actions often require that individuals take on different action roles, with the spatiotemporal patterning of co-actors' behavioral movements being less symmetric and more complementary (Sebanz & Knolich, 2009).

Motivated by a need to investigate the dynamics of more complex joint action tasks, Richardson and colleagues (2015) designed a continuous repetitive targeting task in which pairs of participants were instructed to move a computer stimulus between different sets of targets without colliding into each other (Richardson, Harrison, Kallen, Walton, Eiler, Saltzman & Schmidt, 2015). Pairs of participants stood back-to-back while each faced a 50" computer monitor and moved a small dot between target squares in the corners of the monitor (see Figure 1 top). Participants controlled their stimulus with a motion-tracking sensor, which allowed the participants to move the stimulus between the bottom-left and top-right targets, or between the bottom-right and top-left targets. The experiment was designed as a game, such that, a point was earned for each successful trial (40 seconds of movement without colliding) and the experiment ended after successfully completing 15 trials. If a pair collided, the trial simply ended.

It is important to appreciate that unlike other previously investigated social motor coordination tasks, which involve or require canonical inphase or antiphase movement synchronization, the collision avoidance task was chosen by Richardson et al., precisely because moving in a straight line between targets in an inphase or antiphase manner would result in task failure. Indeed, this led participant pairs to be faced with a conflict between the natural tendency to synchronize straight-line movement trajectories between the targets in an inphase or antiphase manner, and the fact that such synchronization would result in task failure.

The results revealed that pairs quickly converged onto a solution that involved complementary task roles, with one participant adopting a more straight-line trajectory between targets and the other participant adopting a more elliptical trajectory between targets. In addition, the participant who adopted the more elliptical trajectory consistently lagged the participant who adopted the more straight-line trajectory by an average of approximately -30°. This asymmetric and complementary pattern of behavior was consistent across pairs and reflected a highly stable and robust pattern of behavior that enabled participants to synchronize their movements while simultaneously avoiding a collision.

Dynamical Modeling. Richardson and colleagues (2015) hypothesized that the complementary behavioral dynamics observed in the above described collision-avoidance task were the result of a functional symmetry break in the repulsive coupling that prevented participants from crashing into each other. To test this hypothesis, they formulated a task dynamic model of the behavioral dynamics observed using the following system of equations:

$$\ddot{x}_1 - b_1\dot{x}_1 + c_1x_1^2\dot{x}_1 + k_1x_1 = \alpha_1(\dot{x}_2 - \dot{x}_1) - \gamma_1(x_1 + y_2)e^{-|x_1+y_2|}$$
$$\ddot{y}_1 + b_2\dot{y}_1 + k_2y_1 = \gamma_1(y_1 - x_2)e^{-|y_1-x_2|}$$
$$\ddot{x}_2 - b_1\dot{x}_2 + c_2x_2^2\dot{x}_2 + k_1x_2 = \alpha_2(\dot{x}_1 - \dot{x}_2) + \gamma_2(x_2 - y_1)e^{-|x_2-y_1|}$$
$$\ddot{y}_2 + b_2\dot{y}_2 + k_2y_2 = -\gamma_2(y_2 + x_1)e^{-|y_2+x_1|}$$

Here, each participant's behavior was modeled as an oscillating point-mass (end-effector) within a two-dimensional task space (i.e., a task space plane). The two-dimensional task space projected within the body space coordinates of the behavioral goal are illustrated in the middle panels of Figure 1. In this task space, the *x*-axis corresponds to the instructed axis of oscillation with a van der Pol oscillator employed to generate a self-sustained oscillation of the point-mass along this between target axis. The *y*-axis corresponds to deviations away from the oscillatory motion axis and thus, a simple damped mass-spring equation was used for *y* to minimize deviations away from the primary motion axis. Accordingly, in the above equation x_1 and y_1, $\dot{x}_1$ and $\dot{y}_1$, $\ddot{x}_1$ and $\ddot{y}_1$ correspond to the position, velocity, and acceleration of participant 1's end effector within task space, and x_2, and y_2, $\dot{x}_2$ and $\dot{y}_2$, $\ddot{x}_2$ and $\ddot{y}_2$ correspond to the position, velocity, and acceleration of participant 2's end effector with task space. The parameters k_j and b_j are stiffness and damping coefficients, respectively, and the $c_i x_i^2 \dot{x}_i$ expressions are the van der Pol (limit cycle oscillator) escapement functions (for a much more detailed overview of this model see Richardson et al., 2015).

In terms of inter-agent coupling, $\alpha_1(\dot{x}_2 - \dot{x}_1)$ and $\alpha_2(\dot{x}_1 - \dot{x}_2)$ are dissipative coupling functions that operate to minimize the difference between each participant's primary oscillation axes (i.e., the between target axes x_1 and x_2) with a strength defined by α. Consistent with the large body of research on interpersonal rhythmic coordination, these attractor coupling functions essentially capture the natural tendency of co-acting individuals to synchronize their rhythmic movements inphase with one another (Kelso, 1995; Schmidt & Richardson, 2008).

Finally, the far right expressions in each equation are repeller functions that act to push the two participants' end-effectors away from each other, at a strength determined by an exponential function of distance and γ_i. It is these latter repeller functions and the corresponding strength parameters γ_1 and γ_2 that are most important for our current discussion, in that scaling γ_1 and γ_2 reveals how the complementary roles that contributed to the task success of pairs (i.e., asymmetry in path ellipticality and deviations from 0° relative phase) was the result of a functional inter-participant asymmetry in the strength of these repeller dynamics. This is best revealed by detailing the three ways in which scaling γ_1 and γ_2 can influence the movement trajectories produced by the above system of equations:

1). If $\gamma_1 = \gamma_2 = 0$, then no motion is created along y_1 or y_2 (i.e. $\dot{y}_1 = \dot{y}_2 = 0$). Synchronized straight-line movement trajectories are therefore produced along the primary, oscillatory axes of motion, x_1 and x_2, which is equated with unsuccessful task performance as such trajectories would result in a collision (see Figure 1. bottom left).

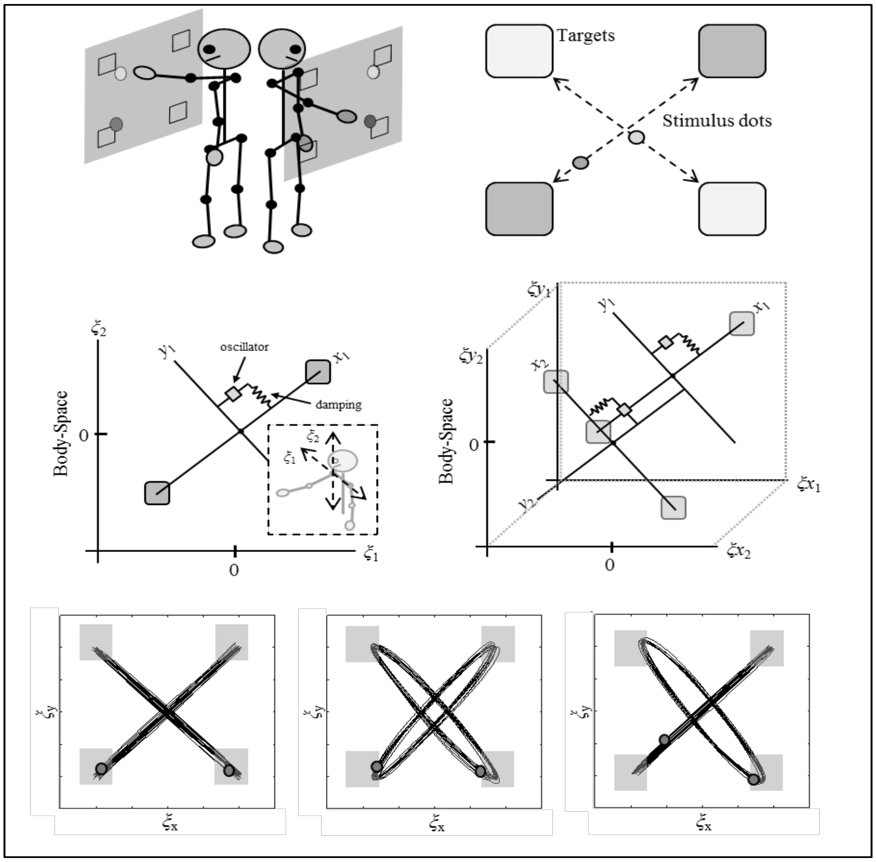


Figure 1. (*top*) Representations of the experimental setup and task display. (left *middle*) Abstract representation of the 2-dimensional task space embedded at a 45° angle within a shoulder-centered, body-space coordinate system. (*right middle*) Abstract representation of the joint-action task system, in which x_i corresponds to the between target axis of oscillation for a participant, defined by a limit cycle oscillator. y_i corresponds to orthogonal deviations away from a principal between target movement axis and is defined by a simple damped mass-spring. ξ_{xi} and ξ_{yi} correspond to the horizontal (frontal) and vertical (sagittal) dimensions of the task movements with respect to shoulder-centered body-space. (*bottom*) Examples of how modulating the strength of the repulsive coupling parameters γ_1 and γ_2 can produce different movement trajectories. The simulated time series were generated using the parameter settings $b_1 = 1$, $b_2 = 2$, $k_1 = k_2 = 2\pi$, $c_1 = c_2 = .5$ and $\alpha_1 = \alpha_2 = .5$. (*bottom left*), $\gamma_1 = \gamma_2 = 0$. (*bottom middle*) $\gamma_1 = \gamma_2 =15$. (*bottom* right) and $\gamma_1 =20$, $\gamma_{y2} = 2$. A small amount of Gaussian noise was also added at each time-step (taken from a normal distribution with a mean of 0 and an SD of 5). Solid lines denote movement trajectories; grey dots denote relative movement positions (i.e., relative phase) at an exemplar time step.

2). If $\gamma_1 = \gamma_2 > 0$, then equivalent motion patterns are created along y_1 and y_2 resulting in elliptical trajectories that are symmetric and synchronized with zero phase lag (see Figure 1. bottom middle). Note that this situation actually results in a stable collision avoidance solution, especially for $\gamma_{x1} >> 0$. The solution is symmetric, though, both in terms of the movement trajectories produced and state topology—the solution is invariant to the permutation of (x_1, y_1) and (x_2, y_2)—and does not include a phase lag. In others words, this solution does not entail the functional asymmetry (complementary roles).

3). However, if $\gamma_1 \neq \gamma_2$, an asymmetry in the movement trajectory emerges, as well as a phase lag between the more-elliptical and the more-straight-line trajectory (see Figure 1. bottom right). This asymmetry and phase lag is qualitatively similar to that observed by Richardson et al., (2015). In fact, by modulating the differential magnitudes of γ_1 and γ_2 one can generate a range of movement trajectory patterns that match the range of coordinated movement patterns exhibited by participants in Richardson et al., (2015).

Current Project. The current project was designed to further explore the behavioral dynamics of the Richardson et al., (2015) joint-action collision avoidance task. More specifically, the current study was designed to test whether individuals would converge on the symmetric task solution predicted by the model described above (i.e., when $\gamma 1 = \gamma_2 > 0$, as in [2] above), such that each individual in a pair would produce more symmetric elliptical movement trajectories with little or no phase lag. Two modifications to the original task procedure were employed to facilitate this possibility. First, in contrast to the relatively high cost of collision in the original study (i.e. a collision ended a trial and participants were forced to perform additional trials until they reached a score of 15), a collision in the current study simply resulted in an auditory alarm (loud beep sound) and higher score, but did not end the trial. Second, although participants were instructed to avoid colliding into each other and attempt to get the lowest score possible (i.e., lowest number of collisions), they were only required to complete 4 two-minute trials independent of the number of collisions. Note that in addition to the expectation that the lower relative cost of colliding would reduce the degree of movement asymmetry between co-acting individuals, it was also expected that the magnitude of movement ellipticity would also be reduced. In other words, pairs would produce similar and straighter movement trajectories.

Method

Participants

Sixteen right-handed subject pairs (N = 32) participated for partial course credit at the University of Cincinnati.

Procedure

The procedure utilized a modified paradigm from Richardson et al. (2015). Participant pairs were instructed to perform the same repetitive targeting task in which they each moved a small (5 cm diameter) red dot between two square targets (20 cm) positioned in each of the four corners of a 50 inch computer monitor. Participants stood back-to-back each facing their own monitor. (See Figure 1 top). Each participant moved their stimulus dot such that one participant moved their stimulus between the bottom-left and top-right target while the other participant moved their stimulus between the bottom-right and top-left target. A Polhemus FASTRACK magnetic motion tracking system was used record the movement of each participant's right hand and to control participant stimuli in real time.

Upon arrival participants were informed that they would be participating in an experiment investigating joint action and would be playing a game in which they were required to move a dot back and forth between two targets. The exact instructions of the game were: "*the goal of this task is to move your stimulus back and forth between your target locations continuously and at a comfortable speed so that your stimuli do not collide, hit, or bump into each other*". They were informed that they would complete four, two-minute trials, and the goal of the game was to score as few hits as possible. Participants were also informed that if they did hit or collide into each other that an audible alarm beep would be played.

Results

All participant pairs were able to complete the experiment. Two trials were excluded, one trial from two different pairs, due to equipment malfunction. Prior to analysis, position time series were low-pass filtered using a 10 Hz Butterworth filter. Three data analysis techniques were used to characterize the movement and coordination that emerged during the collision avoidance task. First, we used principal components analysis (PCA) to quantify the degree to which participants adopted elliptical trajectories. Second, we calculated the distribution of relative phase angles (DRP) that occurred between the two participant's principal *x/y*-axis of movement across eighteen 20◦ regions of relative phase between -180◦ and +180◦ using the Hilbert transform to determine if an asymmetry existed in the movement trajectories. In-phase coordination is indicated by a concentration of relative phase angles around 0◦. Finally, we calculated the normalized circular variance of the relative phase that occurred between the principal *x/y*-movements of co-participants. This measure quantifies the stability of the coordination on a scale from 0 = no coordination to 1 = strong or perfect coordination, and was used to test if a relationship existed between the coordination strength and the number of collisions (hits).

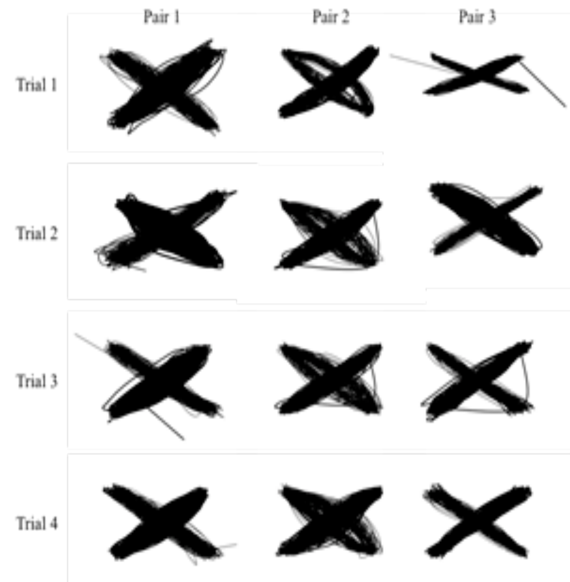
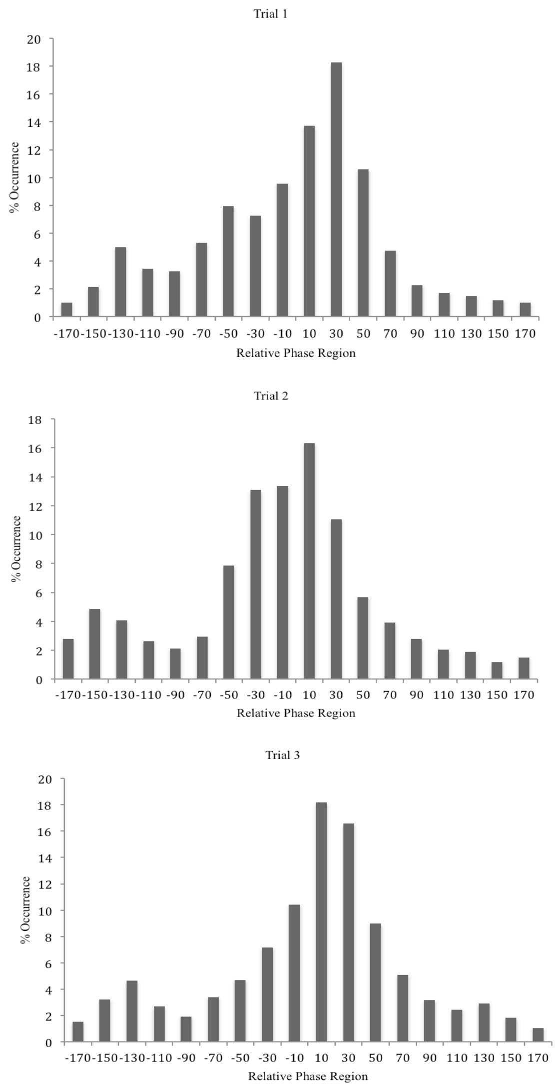


Figure 2. Representative movement trajectories.

Principal Components Analysis (PCA)

PCA was used to quantify the normalized width (δ) of each participant's motion about the primary axis of movement. δ is equal to the ratio of eigenvalues (λ) obtained from the covariance matrix between a participant's x (frontal) and y (sagittal) movement data. Thus, δ is a measure of spread relative to the angular motion direction that is established by a ratio of deviations orthogonal to the principal axis of motion. For the current data, a greater value of δ indicates a larger divergence from a straight-line trajectory—a more circular movement.

As can be seen from an inspection of Figure 2, which includes a representative sample of the movement time-series trajectories observed as a function of trial, one or both of the participants tended to adopt a more elliptical trajectory across trials. A one-way repeated measures ANOVA comparing the average δ exhibited by pairs across trials 1 through 4 was significant, $F(3,27) = 3.077$, $p = .03$, confirming this observation. Planned within subjects contrasts confirmed that differences between the first and last trial were driving this effect, $F(1, 27) = 3.89$, $p = .059$. Although this result is consistent with the findings of Richardson et al. (2015), it is important to note that the overall degree of elipticality was much less pronounced in the current study. It should be noted that although some participant pairs did still adopt complementary roles, the overall degree of this asymmetry was much less pronounced than that observed by Richardson et al.



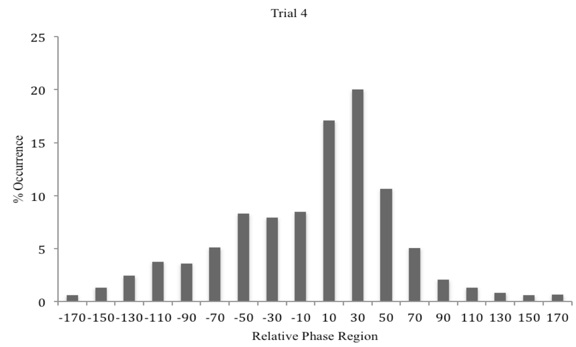


Figure 3. Distribution of Relative Phase.

Relative Phase Analysis

The mean DRP averaged across pairs is shown in Figure 3 as a function of trial number. Recall, that canonical inphase coordination is depicted by a peak around 0^0. As expected, participants did appear to coordinate in an in-phase manner, with the majority of phase angles occurring in the -30º to +30º range, with an overall average relative phase angle of -4.91°. Note that in the Richardson et al. study, there was a significant phase-lag between participants in each pair, with the overall average relative phase angle equally approximately -30º. This suggests that in the current study the strength of the repulsive coupling between participants in a pair was not only more equal, but was also weaker due to the reduced costs of collision.

Table 1: Synchronization Index and Collisions

	Trial 1		Trial 2		Trial 3		Trial 4	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
ρ	0.63	0.34	0.68	0.26	0.67	0.35	0.71	0.31
Hits	2.56	3.97	1.81	2.26	0.75	1.48	0.57	0.85

Circular Variance and Collisions

The number of collisions that occurred between pairs ranged from zero to fifteen and the normalized circular variance ranged from 0.02 to 0.97. Descriptive statistics for both of these measures are summarized Table 1 above. As can be seen from an inspection of Figure 4, there was a moderately negative association between number of collisions and the strength of the coordination observed, $r = -.302$, $p = .017$, such that the number of collisions increased as the stability of the coordination decreased. This indicates that more stable coordination resulted in better task success (i.e., fewer collisions)

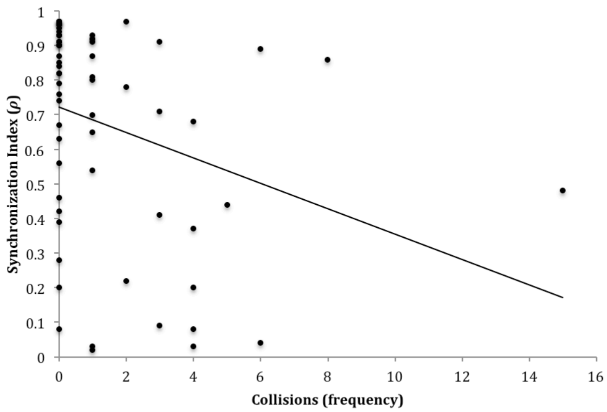


Figure 4: Relationship between collisions and ρ

Conclusion

The aim of the current project was to further explore the behavioral dynamics of the joint-action collision avoidance task previous investigated and modeled by Richardson et al., (2015). In particular, we tested whether decreasing the cost of failure would weaken the repulsive coupling between participants and that this weakening would impact the movement and coordination patterns observed, such that pairs would produce a more symmetrical pattern of elliptical inphase coordination. Consistent with this expectation and model prediction 2 above, both participants in a pair tended to exhibit less elliptical and less asymmetric movement trajectories than observed by Richardson et al., (2015). Moreover, participants produced more canonical inphase coordination in comparison to participants in the Richardson et al. study. The results of the current study therefore further validate the collision-avoidance model proposed by Richardson et al. (2015) and provides evidence that the behavioral dynamics that shape interpersonal or joint-action behavior are not only defined by the physical and information properties of the task, but also by the strength and importance of the shared task goal.

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