Let the Force Be With Us:
Dyads Exploit Haptic Coupling for Coordination

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People often perform actions that involve a direct physical coupling with another person, such as when moving furniture together. Here, we examined how people successfully coordinate such actions with others. We tested the hypothesis that dyads amplify their forces to create haptic information to coordinate. Participants moved a pole (resembling a pendulum) back and forth between two targets at different amplitudes and frequencies. They did so by pulling on cords attached to the base of the pole, one on each side. In the individual condition, one participant performed this task bimanually, and in the joint condition two participants each controlled one cord. We measured the moment-to-moment pulling forces on each cord and the pole kinematics to determine how well individuals and dyads performed. Results indicated that dyads produced much more overlapping forces than individuals, especially for tasks with higher coordination requirements. Thus, the results suggest that dyads amplify their forces to generate a haptic information channel. This likely reflects a general coordination principle in haptic joint action, where force amplification allows dyads to perform at the same level as individuals.

Keywords: joint action, interpersonal coordination, haptics

Much of what people do concerns coordinating their own actions with those of others, including actions such as carrying furniture, building bridges, playing sports, and dancing together (Sebanz, Bekkering, & Knoblich, 2006). These examples indicate that people can do many things together that they could not do alone. Owing to this observation, research on the mechanisms underlying joint action is a rapidly developing research domain. Here, we focus on one aspect of joint action, namely joint action coordination. We use this term to refer to situations in which two or more actors coordinate their actions under real time constraints with or without the explicit intention to do so.

Joint action coordination takes on many different forms, including rowing a boat, walking hand in hand, having a conversation with another person, or performing a wave in a stadium full of people. The diversity of these examples indicates that such coordination tasks may differ from one another in several ways. First, information available to them (e.g., when two people row a boat while one is sitting behind the other) and in relation to the possible roles coactors fulfill for coordination. For example, in some cases one actor may be the leader and another actor a follower (e.g., in dance), while in other cases different actors may have the same roles. Third, joint action coordination tasks may require continuous coordination with others (e.g., while dancing a waltz) or may require coordination at particular points in time (e.g., when taking turns in a conversation).

A complete theory of joint action coordination will ultimately require an understanding of which role different modalities as well as social factors and different time constraints play for such coordination (Galantucci & Sebanz, 2009; Schmidt, Fitzpatrick, Caron, & Mergeche, in press; Vesper, Butterfill, Knoblich, & Sebanz, in press). One issue in this regard concerns how providing different opportunities for coupling between coactors within a dyad may shape the enfolding dynamics of joint coordination. The notion of coupling refers to the extent to which the movements of two or more parts of a system (e.g., two actors in a dyad) show regularities in their relative behavior over time. Such coupling plays a key role in the Haken-Kelso-Bunz (HKB) model of coordination dynamics (Haken, Kelso, & Bunz, 1985). This coupled-oscillator model was originally developed to account for rhythmic interlimb coordination, but has since been extended to rhythmic interpersonal coordination as well. Within the model, a coupling function quantifies the extent to which the component parts (e.g., two limbs) of the moving system are linked.

Coupling may emerge from the presence of a mechanical linkage (as in interlimb coupling or in physically connected dyads) or from the presence of an informational linkage between component parts of the system. Informational coupling could rely on visual, auditory, and haptic information. Theoretically, providing more...
ways for dyads to informationally couple their individual action contributions to each other should stabilize the dynamics of joint coordination and create greater similarity between interpersonal and interlimb coordination. In this article, we focus on the role haptic (touch) information may play for achieving successful coordination in a continuous interpersonal coordination task. Before we discuss the possible role of haptic information for joint coordination, we will shortly review the insights obtained in previous research on interpersonal coordination based on visual information exchange.

Many previous studies on continuous interpersonal coordination have focused on coordination based on visual information exchange. In line with the HKB model, these studies indicated that the macroscopic dynamical principles for visually guided interpersonal coordination are very similar to those underlying intrapersonal interlimb coordination. Thus, when two individuals produce rhythmic movements while they can see each other, their movements tend to become coupled in much the same way as the coupling that emerges between two moving limbs of one individual. Such visually mediated coupling is reflected in the tendency for actors to unintentionally synchronize their actions and the tendency for in-phase movements to be more stable than antiphase movements. These tendencies appear to be quite general, because they emerge when people walk (van Ulzen, Lamoth, Daftershofer, Semin, & Beek, 2008), swing pendulums (Amazeen, Schmidt, & Turvey, 1995; Richardson, Marsh, & Schmidt, 2005; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998) or legs (Schmidt, Carello, & Turvey, 1990), or rock in rocking chairs (Richardson, Marsh, Isenhower, Goodman, & Schmidt, 2007) alongside each other. The amount of visual information available has been shown to modulate the coupling strength between the movements of two people (Richardson et al., 2007). Thus, when participants rock chairs alongside each other while they only have peripheral information about each other’s movements, their coordination is less stable than when they have full visual information. For verbal information exchange, Shockley and colleagues (Shockley, Baker, Richardson, & Fowler, 2007) similarly found that increasing speaking rate (which could be conceived of as providing a stronger coupling) unintentionally resulted in an increase in shared postural activity between two speaking partners (but not between speakers of different pairs). Thus, increasing the available information through different modalities could lead to stronger coupling between components of a system.

The research on visually mediated coupling between individuals suggests strong similarities between individual and joint continuous coordination. However, these two forms of coordination exhibit important differences as well. Interpersonal coordination based on visual information alone typically shows a weaker coupling than interlimb coordination (e.g., Richardson et al., 2007; Richardson et al., 2005; Schmidt & O’Brien, 1997), which in part could be because of the absence of a mechanical linkage between the component parts. Perhaps resulting from this weaker coupling, increased coordination difficulties have been observed for intentional joint continuous coordination based exclusively on the sharing of visual information (e.g., Bosga & Meulenbroek, 2007; Knoblich & Jordan, 2003; Newman-Norlund, Bosga, Meulenbroek, & Bekkering, 2008) (such as when carrying a couch) has rarely been examined. Most studies on joint action to date have used paradigms that did not involve a direct physical coupling between actors. Here, we focus on coordination of physically coupled joint actions, in particular the use of haptic information for this kind of coordination.

Verbal information exchange may be less useful when two actors intentionally perform continuous coordination tasks, however. Especially when people perform a joint action coordination task with a direct physical coupling between actors, adjustments need to be made quickly and continuously. For example, when two people move a couch together the movements of each actor directly influence the forces that operate on the couch as well as on the other actor. For such tasks, sharing a haptic channel may provide a quick informational coupling that may enable dyads to coordinate successfully. The role haptic information may play for continuous interpersonal coordination in the presence of visual information (such as when carrying a couch) has rarely been examined. Only a handful of studies to date have used a task in which two actors were physically coupled to one another directly. In one study, Harrison and Richardson (2009) examined whether similar gait dynamics emerge for the legs of a quadruped (e.g., horse) compared with the legs of two people whose upper bodies were either unconnected, visible for each other, or connected with a foam appendage, thus resembling the middle part of the body of a horse. The physical connection between actors provided an obligatory coupling in this experiment, which should make interpersonal coordination more similar to interlimb coordination. The authors asked pairs of participants to walk at different speeds and examined the extent to which participants adopted one of four possible patterns that quadrupeds tend to adopt at different speeds. The results indicated that participants adopted quadruped-like gait patterns, and did so most strongly while they were physically coupled. Therefore, the authors argued that interpersonal and intrapersonal coordination dynamics emerge from the same lawful principles.
participant performed this same task bimanually. The task was to control one dimension (e.g., x) with one robot arm, and to control the other dimension (e.g., y) with the other robot arm. However, both robot arms could also be used to control movement in the respective other dimension. Because of the range of target locations created through the use of a rectangular target a range of different endpoints could be used to complete the task successfully. It is important to note that the amount of movement in the irrelevant dimension for one robot arm directly affected the spring stiffness of the other robot arm. Therefore, movements in the irrelevant dimension for each robot arm could ease the movements of the other robot arm. Participants were told to achieve the task as easily as possible. The question of interest was whether individuals and dyads would adjust their endpoints in the target to ease movements of the other robot arm.

The results indicated that whereas individuals tended to adopt solutions that reduced the amount of force required for moving both robot arms by moving in both dimensions, dyads predominately moved only in the dimension that was assigned to them. This solution implied that the movements for each robot arm required more force, but also that the amount of force required for one participant of the dyad did not depend on the endpoints adopted by the other participant.

The results by Braun and colleagues raise the possibility that when people need to coordinate forces with one another, they strive for solutions that reduce the amount of interdependence. This possibility is difficult to square with the results of a third study on physically coupled joint actions, however. Reed et al. (2006) examined how pairs of participants coordinated their forces when they performed a joint target aiming task compared with when they performed the aiming task by themselves. In this task, participants manipulated a two-handled rigid crank such that they moved it from a start orientation to a target orientation. A given participant always controlled only one handle on the crank. The other handle was either left uncontrolled (in the individual condition), or moved by another participant (in the dyad condition). In the dyad condition, the movements to the targets always required the same direction and extent of rotation of the crank for the two participants. To ensure that a participant could in principle complete the task with the same amount of force in the individual and dyad conditions, the inertia of the crank was doubled in the dyad condition.

Although participants were instructed to complete the target aiming movements as quickly as possible in both conditions, the results indicated that dyads performed the aiming task faster than the individual participants did. In fact, dyads performed the task faster than the faster of the two individuals in the pair performing the task alone. Of interest, this finding emerged despite the fact that individuals and dyads specialized such that one member mostly accelerated and the other member mostly decelerated, the authors argued that dyads used a haptic channel to cooperate.

The possibility that people overlap their force profiles to obtain continuous haptic information is highly interesting, because it may indicate that people construct a haptic channel in the service of coordination. Within the HKB model, creating such a channel could increase the coupling strength between actors and in turn support successful coordination performance. For individuals, it is well known that haptic information can be very effective in guiding performance. For example, the lawful increase in choice reaction time with an increase in the number of stimulus-response alternatives, known as Hick-Hyman law (Hick, 1952; Hyman, 1953), does not hold when stimuli are presented haptically (Leonard, 1959). For bimanual coordination, the strong interference that is observed when people plan to simultaneously produce different movement patterns with their two hands, for example a circle with one hand and a straight line with the other hand (Franz, Zelaznik, & McCabe, 1991), is abolished when people merely haptically track moving disks creating different patterns for the two hands (Rosenbaum, Dawson, & Challis, 2006). Thus, haptic information can be an extremely powerful source to overcome intra-individual coordination difficulties.

The study by Reed and colleagues raises the possibility that dyads may exploit the haptic channel for effective coordination of physically coupled joint actions. However, the study has an important caveat. Because the control condition involved movements of one actor on only one side of the manipulandum, force overlap could not exist in the individual case. As a result, it was not possible to know whether the large force overlap in the dyad condition arose because of the interaction with another actor, or because the device needed to be controlled on both sides.

In the current study, we tested the hypothesis that dyads show more force overlap than individuals when they coordinate physically coupled actions. Creating such overlap would generate a haptic information exchange that could, in turn, support successful coordination. To ensure that we could evaluate the amount of force overlap of dyads against a meaningful individual baseline, we developed a task that people either performed bimanually (controlling both sides, one with each hand), or together with another person (controlling one side per person). In particular, we asked participants to rotate a pole that moved around a fixed axis (i.e., a modified pendulum) back and forth between two targets. They did so by pulling on cords attached to the base of the pole, one on each side. This formed a challenging task as the timing and force of pulls on either cord influenced the displacement of the pole. Thus, the task required continuous coordination between the two sides of the apparatus. By measuring the forces on each cord, we could evaluate the proportion and strength of overlapping forces. The task also allowed us to determine how quickly and successfully individuals and dyads adopted a coordination pattern for a novel task.

Given that individuals have and dyads do not have internal information about what the other hand is doing, one may expect that individuals will learn a novel task more quickly than dyads and that dyads gradually approach bimanual performance. Such a finding would be consistent with previous literature on joint action coordination tasks that rely exclusively on visual information (e.g., Bosga & Meulenbroek, 2007; Knoblich & Jordan, 2003; Newman-Norlund et al., 2008). However, it may be that providing dyads with a haptic linkage (in addition to visual information) will allow dyads to reach the same coordination performance as would one person performing the same task bimanually from the start.

We tested the generality of the tendency to increase force overlap in dyads. In particular, we asked participants to perform the task for different target amplitudes and at different speeds. This manipulation allowed us to evaluate whether the adopted coordination pattern and the amount of force overlap changed as a...
function of the spatiotemporal task requirements, in particular, the
frequency and amplitude of the required movements. With in-
creases in the required frequency and decreases in the required
amplitudes, the two sides of the task may require different coor-
dination patterns because of the spatial and/or temporal con-
straints. Thus, different coordination patterns may emerge across
the spatiotemporal continuum, as has been observed for bimanual
coordination (e.g., Kelso, 1984). If so, these different coordination
patterns may differentially rely on force overlap. Alternatively, it
may be that generating more force overlap forms a general char-
acteristic of dyadic coordination.

Finally, besides examining whether dyads would show more
force overlap than individuals we also examined how dyads use
the haptic channel to coordinate. In particular, we examined
whether dyads use the haptic channel in an intermittent or in a
continuous way to coordinate. At one extreme, dyads may use an
intermittent coordination strategy such that they produce force
overlap at specific parts of the task. At the other extreme, dyads
may produce force overlap for the full duration of the task to
obtain haptic information continuously.

**Method**

**Participants**

Fifty-four participants took part in this experiment. Eighteen
participants performed the task individually (6 males and 12 fe-
males between the ages of 17 and 32) and 36 participants per-
formed the task in dyads (1 male dyad, 11 female dyads, and 6
mixed gender dyads, all between the ages of 17 and 38). All
participants were right-handed and none reported any neurological
deficits. Participants were compensated for their time, either mon-
etarily or though course credit. Data from three individuals were
removed from the data set because of recording error.

**Apparatus and Procedure**

Figure 1 shows the experimental apparatus. In the individual
group, participants controlled the cord on the left with their left
hand and the cord on the right with their right hand. In dyads,
participants sat next to each other at a distance of approximately 30
cm. The participant on the left controlled the cord on the left with
their left hand, and the participant on the right controlled the cord
on the right with their right hand.

At the beginning of the experiment, participants were told that
on each trial they would be asked to move the pole back and forth
between two targets by pulling on each of the two cords. They
were also told to do this at a frequency that approximated a
sequences of tones played before the onset of the trial (details
follow). No indication was given about how participants should
accomplish this task. Participants were then given a chance to try
out the task for approximately one minute. Dyads were also asked
not to communicate with each other verbally.

During the experimental trials, participants started with the pole
resting on the left side, and they could start moving the pole after
hearing an isochronous sequence of tones that indicated at which
speed the movement should be performed. We used a customized
Matlab program to play a sound file that indicated the pace at
which the pole should approximately be moved back and forth
between the targets. The sounds participants heard consisted of
eight alternating 700 and 850 Hertz tones (corresponding to 4
movement cycles) at the relevant target period. Participants lis-
tened to these tones, and were told to start moving the pole at
approximately the same rate after the tones had played. Thus, the
participants did not hear any tones during pole movement.

Participants were told to continue moving the pole back and
forth until the experimenter told them to stop. The experimenter
did so after participants completed 15 back and forth movements
between the targets. None of the participants appeared to have
trouble understanding the instructions.

Participants completed a total of 9 conditions that differed with
respect to their spatiotemporal coordination requirements, such
that participants moved the pole over different amplitudes and at
different periods. Our rationale for introducing these manipula-
tions was to have a way of testing the generality of the use of
haptic information. For bimanual coordination, the spatiotemporal
requirements influence the stability of the emerging coordination
patterns (e.g., Kelso, 1984). As interpersonal coordination is also
sensitive to the spatiotemporal demands (e.g., Richardson et al.,
2007), it provided a useful vehicle for testing generalities in force
overlap. We used all combinations of 3 amplitudes (4, 10, or 16 cm

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![Figure 1. Overview of the experimental apparatus, and the task for individuals and dyads.](image-url)
between the targets) and 3 target periods (462, 546, or 667 ms periods corresponding to fast, medium, and slow, respectively). We chose the particular amplitudes and periods because they seemed to cover the range for which the task was possible yet differentially challenging (based on informal pilot testing). We counterbalanced the order of conditions for individuals and dyads. Each condition was completed as a block of 5 repetitions, thus creating 45 trials in total. The experiment lasted about 45 to 50 minutes.

The pole was made from a solid PVC pipe (length = 46.6 cm, diameter = 1.0 cm, mass = 50.7 g), and was affixed to a rotating axis positioned at its base, thus creating a pivot point. A cord was attached at 0.5 cm below the pivot point on each side of the pole. The cords were 65 cm long. Participants always held each cord in the same location, at 30 cm from the pole, between their thumb and index finger. To ensure a fixed relation between the pulling angle and the pole, we ran each cord through a small hole at the same height and 17 cm away from the pivot point of the pole. From rest, the pole required approximately 1.27 N of pulling force to start moving.

Each target region was 3 cm in width and indicated by a colored area. The target regions were drawn on a white piece of cardboard that was placed on a flat platform positioned 4.0 cm above the pivot point of the pole. Different pieces of cardboard were used for the different amplitude conditions. The target regions on both sides were always equidistant from the balance point of the pole.

A goniometer (Encoder Rotary 360 PPR, Avago Technologies) recorded the pole kinematics. We recorded the forces exerted on each cord with force sensors (Low profile universal load cell, model LC703-25) that were positioned between the axis and the cord on each side. Both the goniometer and the force sensors recorded data at 200 Hz. They were connected to a Hewlett Packard Compaq dc7900 computer through a USB connection. The force data were amplified with a strain gage amplifier (INA125P, Texas Instruments).

Data Analysis

Before calculating our dependent variables, we first filtered the pole kinematics and force data with a 20-Hz low-pass Butterworth filter to remove noise. From the pole kinematics, we then calculated the mean amplitude of the pole movements by calculating the distance between direction reversal points of the pole. We used a threshold criterion of 20 degrees of movement for the amplitude values to avoid including small corrective movements in measuring amplitudes. We calculated the times between successive direction reversals (the same ones we used for the amplitude calculations) to calculate the movement periods.

From the force data, we calculated two dependent variables to test the hypothesis that dyads display more force overlap than individual participants. First, we calculated the mean proportion of instances of force overlap. We classified all data samples for which the pulling force exerted on each separate cord exceeded a threshold of 0.5 N as instances of force overlap. We chose this threshold based on the rationale that at this force level coordination based on haptic information is possible (e.g., Rosenbaum et al., 2006). For the instances of force overlap, we also calculated the mean amount of force overlap to evaluate possible differences in the amount of force exerted on both cords. To evaluate whether individuals and dyads used haptic information intermittently or continuously, we considered how the instances of force overlap were distributed across different parts of the movements by dividing each movement trajectory into quadrants.

Results

The results are reported in two sections. In the first section, we report on the pole kinematics to evaluate how closely individuals and dyads matched the required amplitudes and target periods. In the second section, we provide the analyses on the force data to evaluate force overlap for individuals and dyads in each of the conditions. For both types of analyses (pole kinematics and force data), we examined the effects of our experimental manipulations on performance. For the pole kinematics, we also tested for learning effects by examining the effect of the number of completed trials on performance. To do so, we considered trials 1 to 15 as Phase 1, trials 16 to 30 as Phase 2, and trials 31 to 45 as Phase 3 of the Experiment. For the force data, we performed a similar analysis to determine whether force overlap changed as participants learned the task. We applied a Greenhouse-Geisser correction to the degrees of freedom when the assumption of sphericity was violated.

Pole Kinematics

We calculated the mean absolute difference of the pole location (in degrees) relative to the alternating target locations to evaluate how closely individuals and dyads matched the required amplitudes. We also used this mean absolute endpoint error to evaluate the rate of learning in individuals and dyads. We used the durations between pole reversal points to estimate the mean movement period in each trial.

Movement Amplitudes

To evaluate the effect of target amplitude and target period on performance in individuals and dyads, we calculated the mean absolute endpoint error for the five trial repetitions within a condition. Thus, we reduced the data for each individual and dyad to one value per condition. We then performed a 2 (individual vs. dyad) × 3 (target amplitude; small, medium, or large) × 3 (target period; slow, medium, or fast) repeated-measures analysis of variance (ANOVA) on the resulting values.

Figure 2 shows the results. The results indicated a main effect of target amplitude, $F(2, 62) = 3.181, p < .05$, partial $\eta^2 = .093$, such that the mean absolute endpoint error significantly increased for the large amplitude ($M = 4.22, SE = .41$) compared with the medium ($M = 3.28, SE = .30$) and small ($M = 3.33, SE = .38$) amplitude conditions. The results showed no other significant main effects or interactions, $p > .10$. Importantly, mean absolute endpoint error did not differ for individuals ($M = 3.61, SE = .40$) and dyads ($M = 3.61, SE = .37$).

Movement Periods

We analyzed the movement periods in terms of their absolute values rather than in terms of their deviation from the prescribed target periods. The rationale for this approach was that participants did not hear the metronome while they performed the task. As a
result, the timing criterion was imposed much less strictly than the amplitude criterion. Our main question for the movement period analysis was whether the achieved periods approached those prescribed by the metronome, and whether they did so to the same extent for individuals and dyads. Thus, the aim of the analysis was simply to check that participants adjusted their speed of performance to the target period.

Figure 3 shows the mean movement period for each target amplitude and metronome rate. We performed a 2 (individual vs. dyad) × 3 (target period) × 3 (target amplitude) repeated-measures ANOVA on the movement periods. The results indicated a main effect of target period, \( F(2, 62) = 100.67, \ p < .01, \) partial \( \eta^2 = .765, \) such that the mean movement period increased with increasing target period (\( M = 665 \) ms, \( SE = 20, \) for the slow rate; \( M = 568 \) ms, \( SE = 17, \) for the medium rate; and \( M = 521 \) ms, \( SE = 21, \) for the high rate). The results also indicated a main effect for target amplitude, \( F(1.69, 52.40) = 13.75, \ p < .01, \) partial \( \eta^2 = .307, \) such that movement period increased with increasing target amplitudes (\( M = 570 \) ms, \( SE = 18, \) for the small amplitude; \( M = 588 \) ms, \( SE = 18, \) for the medium amplitude; and \( M = 598 \) ms, \( SE = 21, \) for the large amplitude conditions). The results revealed no other significant main effects or interactions. Again, individuals and dyads did not significantly differ, \( p > .10. \)

Learning

Figure 4 shows the mean absolute endpoint error for a trial as a function of the number of trials participants completed. To exami-
ine how well individuals and dyads learned to control the apparatus, we performed a 2 (individual vs. dyad) × 3 (Experiment Phase; trials 1–15, trials 16–30, and trials 31–45) repeated-measures ANOVA. For this analysis, we calculated the mean absolute endpoint error for each set of 15 trials for individuals and dyads. The results of this analysis indicated a main effect of Experiment Phase, $F(1.64, 50.76) = 18.66, p < .01$, partial $\eta^2 = .376$, such that mean absolute endpoint error decreased with each phase ($M = 5.03 \text{deg}, SE = 0.46$ for Phase 1; $M = 3.32 \text{deg}, SE = 0.36$ for Phase 2; and $M = 2.42 \text{deg}, SE = 0.26$ for Phase 3). This learning effect did not differ for individuals and dyads, $p > .10$.

To further investigate possible learning differences between individuals and dyads in the initial trials, we also performed a 2 (coordination mode: individual vs. dyad) × 5 (trial) repeated-measures ANOVA. We performed this analysis on the mean endpoint errors for the first five trials because this corresponded to the first condition (i.e., amplitude/frequency combination) participants completed (different for different individuals and dyads, with identical counterbalancing for the two groups). The analysis revealed a significant main effect of trial, $F(1.92, 55.74) = 12.82, p < .01$, partial $\eta^2 = .307$, such that performance increased rapidly over the first five trials. However, coordination mode did not have a significant effect on performance, $p = .66$. The interaction between coordination mode and trial also did not reach significance, $p > .10$.

To evaluate whether participants changed the speed of their performance as they learned to control the pole, we performed a 2 (individual vs. dyad) × 3 (Experiment Phase) repeated-measures ANOVA. For this analysis, we calculated the mean movement period (the time between consecutive pole reversals) for each set of 15 trials for individuals and dyads. The results of this analysis indicated a main effect of Experiment Phase, $F(2, 62) = 10.50$, $p < .01$; partial $\eta^2 = .253$, such that the mean movement period became shorter over time ($M = 623 \text{ms}, SE = 19$, for Phase 1; $M = 578 \text{ms}, SE = 23$, for Phase 2; and $M = 554 \text{ms}, SE = 21$ for Phase 3). Again, this effect did not differ between individuals and dyads, $p > .10$. Despite the fact that the timing criterion was not imposed in a strict sense, the results indicated that individuals and dyads approximated the target periods more closely over time (the mean target period across conditions was 558 ms).

**Forces**

The similarity in the performance measures for individuals and dyads raises the question if individuals and dyads used the same underlying coordination pattern to perform the task. In particular, we tested the hypothesis that dyads showed more force overlap than individuals did. We investigated how often individuals and dyads generated forces simultaneously, as well as how much force they generated in these instances. We report the results of these two measures in turn.

**Instances of Force Overlap**

To evaluate how often individuals and dyads generated overlapping forces, we calculated the instances of force overlap relative to the total trial duration. Thus, the resulting measure reflected the proportion of instances of force overlap. We then performed a 2 (coordination mode: individual vs. dyad) × 3 (target period) × 3 (target amplitude) repeated-measures ANOVA on the resulting proportions.

Figure 5 shows the results. The results revealed a main effect for coordination mode $F(1, 31) = 16.10, p < .01$, partial $\eta^2 = .342$, such that dyads ($M = .143, SE = .10$) produced overlapping forces almost twice as often as individuals ($M = .084, SE = .11$). The results also showed a main effect for target amplitude, $F(1.42, 44.16) = 6.06, p < .05$, partial $\eta^2 = .164$. This result was qualified by a three-way interaction between coordination mode, target period, and target amplitude, $F(4, 124) = 2.90, p < .05$, partial $\eta^2 = .086$. Dyads produced overlapping forces more often at the short target period with decreases in target amplitude (between conditions). In addition, for the small and medium target amplitudes dyads overlapped their forces more often for shorter target periods. For individuals, differences in the proportion of instances of force overlap did not systematically depend on the experimental manipulations. These results indicate that dyads recruited the haptic channel more when they needed to interact within a more constrained space at a higher pace. This finding may suggest that haptic information is particularly relied on when fast and precise coordination is required between people.

To determine how individuals and dyads used the haptic channel for coordination during different parts of the movements, we divided each pole movement between the targets into quadrants. The first and fourth quadrant contained data points that fell near the (left and right) target regions, whereas the second and third quadrant contained data points from the middle portion of the pole trajectory. We then calculated the proportion of instances of force overlap for each quadrant by dividing the number of overlap instance by the total number of data points within a quadrant. We applied this method because it allowed us to determine whether...
dyads used the haptic channel intermittently (i.e., at particular points in the trajectory) or continuously (i.e., evenly distributed across the trajectory).

Figure 6 shows the results for each period/amplitude combination. We performed a 2 (coordination mode: individual vs. dyad) × 3 (target period) × 3 (target amplitude) × 4 (quartile) repeated-measures ANOVA to determine the effect of quartile on force overlap for each of the period/amplitude combinations for individuals and dyads. We only report significant results concerning the factor quartile for this analysis (the results of the other factors have been described above). The results indicated a main effect for quartile $F(1.55, 41.97) = 74.72, p < .01$, partial $\eta^2 = .180$, which was qualified by two interactions. First, the results showed a significant interactive effect of quartile and coordination mode.

![Figure 5](image1.png)

**Figure 5.** Proportion of instances of force overlap for individuals (solid lines) and dyads (dashed lines) at each target period and target amplitude.

![Figure 6](image2.png)

**Figure 6.** Proportional force overlap per movement quartile for individuals (solid lines) and dyads (dashed lines) at each target period and target amplitude.
mode on force overlap, \( F(1.55, 41.97) = 17.73, p < .01, \) partial \( \eta^2 = .244 \), such that dyads especially overlapped their forces for the middle portion of the pole movements (the second and third quartile) compared with individuals. The results also indicated a significant interaction between quartile and amplitude, \( F(1.87, 50.54) = 3.44, p < .05, \) partial \( \eta^2 = .307 \), such that the tendency to overlap forces more often for the middle part of the trajectory (quartiles 2 and 3) was strongest for the largest amplitude.

To determine whether individuals and dyads changed the extent to which they overlapped their forces as they learned the task, we analyzed the proportion of instances of force overlap as a function of Experiment Phase (Figure 7, left panel). The 2 (coordination mode: individual vs. dyad) \( \times 3 \) (Experiment Phase) repeated-measures ANOVA revealed a main effect for coordination mode but no main effect or interaction for Experiment Phase, \( p > .10 \). Thus, individuals and dyads did not change their tendency for force overlap over time.

**Amount of Force Overlap**

Besides examining how often individuals and dyads generated overlapping forces, we also calculated the mean amount of overlapping force for these instances. To do so, we calculated the mean of the force exerted on the left and on the right side for instances of force overlap. We then performed a 2 (coordination mode: individual vs. dyad) \( \times 3 \) (target period) \( \times 3 \) (target amplitude) repeated-measures ANOVA on the force overlap values.

Figure 8 shows the results. The analysis revealed a main effect for coordination mode, \( F(1, 31) = 16.43, p < .01, \) partial \( \eta^2 = .346 \), such that dyads (\( M = 1.20, SE = .087 \)) showed larger overlapping forces than individuals (\( M = 0.68, SE = .095 \)). The results also indicated a significant three-way interaction between coordination mode, target period, and target amplitude, \( F(2.86, 88.69) = 3.04, p < .05, \) partial \( \eta^2 = .089 \). Similar to the instances of force overlap, dyads produced stronger overlapping forces with decreasing target amplitudes at the short target period. Dyads also showed stronger overlapping forces with decreasing target periods for the small and medium target amplitudes. Individuals did not modulate the strength of overlapping forces based on the experimental manipulations.

We performed a 2 (coordination mode: individual vs. dyad) \( \times 3 \) (Experiment Phase) repeated-measures ANOVA to determine whether the strength of overlapping forces changed over time for individuals and dyads. The results (see Figure 8, right panel) revealed a main effect for coordination mode but no main effect or interaction for Experiment Phase, \( p > .10 \). Thus, individuals and dyads did not change the strength of their pulling forces for instances of force overlap over time.

**Discussion**

We tested the hypothesis that dyads (with each individual controlling half of the task) would show more overlapping forces than individuals would when they performed the same task bimanually. The rationale behind this hypothesis was that overlapping forces could provide dyads with haptic information about a coactor. Such information may support achieving successful coordination. We also asked whether increased force overlap is a general phenomenon of dyadic coordination of physically coupled actions, or whether the extent of it depended on the spatiotemporal task requirements. Finally, we examined whether dyads exploited haptic information at specific parts of the task, or whether they used it continuously.

In line with the main hypothesis tested here, the results indicated that the proportion of time for which dyads simultaneously applied forces (i.e., shared haptic information) was twice as large as when individuals performed the same task bimanually. These overlapping forces tended to be stronger as well. The overall finding that the increased force overlap for dyads did not depend on the spatiotemporal task requirement suggests that it is a general characteristic of dyadic coordination.
The observation that dyads increased force overlap compared with individuals need not imply that such overlap contributed to successful coordination. In fact, as the moving pole and the other actor were visible during performance there is a possibility that coordination emerged from sharing visual information. Sharing such information tends to induce (unintentional) coupling between actors for rhythmic coordination tasks when each actor moves a separate object (Amazeen et al., 1995; Richardson et al., 2007; Richardson et al., 2005; Schmidt, Bienvenu, Fitzpatrick, & Amazeen, 1998; Schmidt, Carello, & Turvey, 1990; van Ulzen et al., 2008). Previous studies in which dyads together controlled the movements of one object (i.e., each controlling half of the task) while sharing only visual information indicated a coordination disadvantage for dyads compared with individuals (Bosga & Meulenbroek, 2007; Knoblich & Jordan, 2003; Newman-Norlund et al., 2008). The finding that individuals and dyads showed overlapping learning curves in our task is therefore surprising. A key difference between these previous tasks and the current experiment was the availability of visual as well as haptic information. Our results suggest that enabling haptic information exchange on top of sharing visual information may help dyads overcome coordination difficulties they tend to experience for intentional continuous coordination tasks based exclusively on the sharing of visual information.

Besides the general increase in force overlap dyads also showed modulation of force overlap depending on the spatiotemporal task requirements. That is, the short target period and small target amplitude condition resulted in the highest proportional force overlap in dyads. Individuals did not show this pattern. If one considers performing faster and at smaller amplitudes to be more difficult, this finding may suggest that dyads particularly overlap their forces to overcome increased coordination requirements. The observation that the mean endpoint errors were quite similar for each of the conditions makes it difficult to evaluate this possibility based on the present results, however. Future research could test the relation between force overlap and coordination requirements more directly by manipulating task difficulty in a more stringent way.

How did dyads use haptic information for coordination? One possibility is that dyads would continuously generate overlapping forces to have haptic information available throughout the task. Alternatively, dyads could overlap their forces only at very specific parts of the task, such that they would rely on an intermittent coordination strategy. Our analysis of the distribution of force overlap across the movement trajectories revealed that dyads used a combination of these possibilities. On the one hand, force overlap was more prevalent for dyads than for individual participants across the range of the movement trajectories. On the other hand, dyads tended to overlap their forces especially for the middle portion of the pole trajectory. For our particular task, the middle region of the movements included moving over the tipping point of the pole (when the pole was positioned upright), where the relation between pulling on a cord and the direction of pole movement changed. In the case of dyads, this change in coordination seems to have relied on an increase in haptic information exchange.

Previously, it has been proposed that intra- and interpersonal coordination follow the same dynamical principles. Both forms of coordination indeed comply with the HKB model (Haken et al., 1985). One reason for such compliance could be that these two forms of coordination may rely on similar perceptual information. Thus, perceptual information may drive interpersonal coordination just as much as it drives interlimb coordination (e.g., Bingham, Hughes, & Mon-Williams, 2008; Mechsner, Kerzel, Knoblich, & Prinz, 2001). Despite the role such perceptual information may play, interpersonal coordination has been found to display weaker attractor dynamics than interlimb coordination when only visual information is shared however (e.g., Richardson, Lopresti-Goodman, Mancini, Kay, & Schmidt, 2008; Schmidt et al., 1998). These differences in attractor dynamics likely result at least in part from the weaker coupling between the component parts of the dyad (i.e., the limbs of two actors) compared to the two limbs of one individual, as a mechanical linkage is missing for dyads. As stated earlier, coupling strength is not just a function of mechanical linkages however, but also results from informational linkages. Thus, sharing information through different modalities to a greater or lesser extent influences the coordination dynamics as well.
Additional access to haptic information may shift the attractor dynamics for interpersonal coordination towards greater similarity with interlimb coordination. Our finding that individuals and dyads performed our task equally well and improved their performance at approximately the same rate is in line with this proposal. A complete understanding of how people perform joint actions will require explication of how and when different modalities are used to support performance. The present experiment indicates that haptic information is very powerful for guiding joint coordination tasks such as lifting and moving a couch together. In general, it would be useful to know when dyads profit from having shared access to different information sources, and how such sources interact to guide performance. Thus, parametric manipulations concerning the access to different modalities available for planning and real-time coordination across dyads could reveal how different modalities are used and how their information is integrated for joint actions. For instance, using the present experimental paradigm, one could manipulate the presence and quality of information available through different modalities to determine how information exchange through each modality influences performance, and how different modalities interact in this regard. This could help to answer the question of whether optimal interpersonal coupling is achieved in particular modalities, whether redundancies between information in different modalities boosts coupling, and how the usefulness of information from different modalities interacts with task demands. In terms of the HKB model, taking this route could result in a quantification of how informational coupling through different modalities influences the coupling function in the model.

Another issue that requires further investigation is whether the increased force overlap in dyadic interaction provides a functional mechanism to enhance haptic information, or whether it emerges as a by-product of lacking the internal information that is available to individuals in bimanual coordination. It is tempting to speculate that force amplification serves a communicative purpose (Reed et al., 2006), whereby instrumental actions are modulated in order to serve as coordination signals.

From an implementation perspective, understanding how people coordinate physically coupled actions is of central importance for the development of interactive robots (e.g., Feth, Groten, Peer, Hirsche, & Buss, 2009). The development of robots that smoothly interact with people requires an understanding of the use of different information channels for interpersonal action planning and coordination. Our findings provide a modest but important step towards understanding how people may exploit the haptic channel to achieve such smooth interpersonal coordination.

References


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