Affording cooperation: Embodied constraints, dynamics, and action-scaled invariance in joint lifting

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Understanding the physical and interpersonal constraints that afford cooperation during real-world tasks requires consideration of the fit between the environment and task-relevant dimensions of coactors and the coactors' fit with each other. In the present study, we examined how cooperation can emerge during ongoing interaction using the simple task of two actors' moving long wooden planks. The system dynamics showed hysteresis: A past-action mode persisted when both solo and joint actions were possible. Moreover, pairs whose arm spans were both short, both long, or mismatched made action-mode transitions at similar points, when scaled by a relational measure. The relational measure of plank length to arm span was dictated by the pair member with the shorter arm span, who, thus, had a greater need to cooperate during the task. The results suggest that understanding affordances for cooperation requires giving more consideration to constraints imposed by the fit between coactors' action capabilities.

Many activities require that we cooperate with other individuals to accomplish a goal or complete an action. For instance, although we might move a coffee table by ourselves, moving a sofa would oblige us to work together with another individual. Such cooperative activity, or *joint action*, is a common part of our everyday, face-to-face social behavior. It is also becoming a focus of experimental investigation: Extensive research has demonstrated that the body and the environment contribute significantly to social cognitive processes (Beer, 1995; Clark, 1997; Gibbs, 2006; Niedenthal, Barsalou, Winkielman, Krauth-Gruber, & Ric, 2005; Warren, 2006) and to joint action (Knoblich & Sebanz, 2006; Richardson, Marsh, & Baron, 2007; Sebanz, Bekkering, & Knoblich, 2006; Wilson & Knoblich, 2005).

One such recent approach to joint action, as it occurs in the real world, suggests it can be understood by adopting a synergistic and ecological perspective (Marsh, Johnston, Richardson, & Schmidt, 2009; Marsh, Richardson, Baron, & Schmidt, 2006; Marsh, Richardson, & Schmidt, 2009; Richardson, Marsh, & Schmidt, 2010). Specifically, in this approach, coactors, environment, and task are examined as a single system or *synergy*. Furthermore, this approach emphasizes that joint action, no less than individual ac-

tion, emerges in part from the perception and actualization of affordances.

An *affordance* is an opportunity for action that is scaled to the action capabilities of a perceiver (Gibson, 1979/1986). Perception of an affordance depends on detecting the environment in relational rather than absolute terms (Gibson, 1986; Michaels & Carello, 1981). For instance, an individual will perceive stairs as being climbable when the riser height of the stairs is a certain ratio of one's leg length, not when the riser is a certain metric height (Warren, 1984). Such action-scaled ratios, or *pi numbers*,[1] are formalized as the ratio of a relevant property of the environment to the task-relevant property, or *effector*, of an actor's action system. As an intrinsic or dimensionless measure of the fit between a person and their environment, they might also serve as an important constraint on joint action.

Recently, affordance research has been extended in order to examine similarities between solo and joint action (Richardson et al., 2007). Participants who were asked to move wooden planks of various sizes made action-mode transitions between one- and two-handed grasping and between two-handed solo action and cooperative action. These transitions were predicted by action-scaled ratios: the fit between the effectors of the individual or pair (hand

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span or average arm span of the pair) taken with respect to the length of the planks. Moreover, the same dynamical properties were observed at both levels of transition, indicating that action-mode transitions in environment–person and environment–person–person action systems are functionally equivalent. Overall, the action-mode experiments highlight how, in the face of systematically varied features of the environment, the action capabilities of two individuals can be extended through joint action. However, the task-relevant features of the *coactors* were not systematically varied and their potential contributions to joint action were left unaddressed.

The study of joint action allows a new type of constraint to be examined that cannot be examined by studying individual action: the physical, task-relevant properties of the coactor's bodies in relation to each other. Manipulating coactors' action capabilities relative to each other may have two consequences: a change in the action-scaled information used to judge joint action capabilities and a change in the action-scaled information used to specify the *emergence*—spontaneous transition from working alone to working together—of joint action itself. For instance, action-scaled information defined over an environment–person–person system was accurately used by participants to judge whether pairs comprising a large or small adult and a large or small child could simultaneously pass through apertures (Chang, Wade, & Stoffregen, 2009). Even though the action capabilities of adults and children differed from each other, it was the pair-level capabilities that perceivers correctly detected. However, in the experiment, only perceptual judgments were examined, not the spontaneous emergence of joint action during ongoing interaction.

In the present study, we used the cooperative plank-moving task of Richardson et al. (2007) to address the following question: What are the consequences for the emergence of joint action if we systematically vary features of the coactors? A key implication of an ecological, dynamical perspective is that across a wide range of acting pairs, the same invariant action-scaled ratio should specify mode transitions, and the same dynamic properties of those transitions should hold. If previous claims that coactors, environment, and task can be understood as a single synergy or system (Marsh et al., 2006; Richardson et al., 2010; Richardson, Shockley, Fajen, Riley, & Turvey, 2008) are to be taken seriously, it is important to identify an invariant action-scaled ratio that specifies mode transitions across pairs that are matched *and* mismatched by action capabilities.

We therefore used pairs matched to have short or long arm spans, as well as a mismatched group, in order to examine the influence of a discrepancy in coactors' action capabilities on action-mode transition boundaries. Mismatching participants by arm span within pairs alters the constraints imposed by the coactors' bodies and may alter the emergence or the dynamics of joint action. We anticipated that the action-scaled ratio would be dictated by the short-arm-span participant in all three groups, for two reasons: short-arm-span individuals must transition

to joint action at shorter plank lengths than long-arm-span individuals, and people have been shown to be sensitive to others' action capabilities (Ramenzoni, Riley, Shockley, & Davis, 2008; Stoffregen, Gorday, Sheng, & Flynn, 1999). The average arm span of each pair, in contrast, should not impose a defining limit, because it is a statistical construct, rather than a functional constraint. Therefore, the key prediction was that action-mode transition boundaries should differ between groups when only plank length is considered, but using the proper description of the system—an action-scaled ratio based specifically on the shorter-arm-span member of each pair—should eliminate action boundary differences between groups.

METHOD

Participants

Forty right-handed undergraduate students at the University of Connecticut, all strangers to each other, participated in the study in pairs, as partial fulfillment of a course requirement. The pairs were matched by gender. Sign up for sessions was restricted by height in order to form three groups: short-arm-span pairs, long-arm-span pairs, and pairs mismatched in arm span. The heights of women and men in the long-arm-span group were at least 68 and 74 cm, respectively, and no more than 62 and 68 cm, respectively, in the short-arm-span group. The mismatched group was composed of pairs with one long-arm-span and one short-arm-span member. Two pairs used two-handed grasping for all planks in the descending and random conditions and were therefore dropped from the analysis, although they are considered in the discussion. Thus, there were six pairs in each group. The mean arm span was 162.6 cm ($SD = 6.1$) for the short-arm-span group, 175.0 cm ($SD = 6.1$) for the mismatched-arm-span group, and 182.6 cm ($SD = 5.0$) for the long-arm-span group. The mismatched-arm-span group had a mean difference in arm span of 15.7 cm ($SD = 4.1$), relative to differences of 5.0 cm ($SD = 2.1$) and 6.5 cm ($SD = 1.8$) in the short- and long-arm-span groups, respectively.

Materials and Apparatus

Two sets of 71 wooden planks, ranging in length from 80 to 220 cm in 2-cm intervals, were painted black to mask any identifying marks or size information conveyed by grain patterns. The 2 cm at the ends of each plank was painted red to show the participants where they were allowed to grasp the planks.

The experimenter placed the planks on a conveyor belt, presenting them one at a time to the participant pairs. When a plank reached the table at the end of the conveyor belt, the participants were required to move it from the presentation ramp to the drop-off ramp, either by themselves or together (see Figures 1A and 1B). The presentation speed of the planks was paced by the participants. As each plank was being grasped, another plank was placed on the conveyor belt.

Procedure

The participants arrived at the experiment separately. If one participant arrived before the other, he or she was told to wait outside the lab for the other participant. When both participants had arrived, they were brought into the lab at the same time. They were told that the study was investigating object lifting and that they were required to move planks of varying lengths one at a time from one ramp to another. The participants were merely instructed that they could lift the planks by themselves or with each other but could only do so while grasping them by the red ends. They were also told that they were free to talk and communicate with each other during the experiment. The experimenters then demonstrated lifting the planks by grasping the red ends both individually and together. The experimental trials were videotaped for data analysis and to ensure that the participants heeded the instruction to grasp the ends.
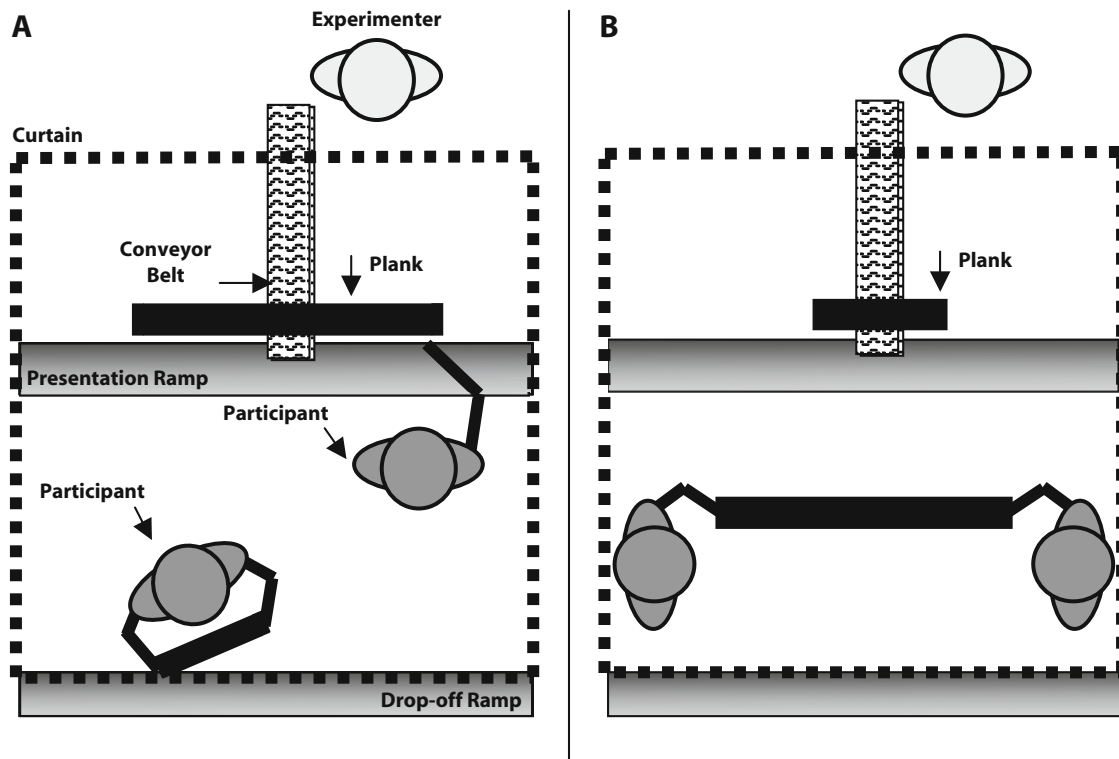
Figure 1. A plank comes toward the participants on a conveyor belt. When it reaches the presentation ramp, it is moved to the drop-off ramp behind the participants, either (A) by solo two-hand grasping or (B) by joint two-person grasping.

Each participant pair completed three blocks of trials, with the planks presented in ascending, descending, and random orders. The random block of trials was always presented second. Whether the ascending or descending block occurred first was counterbalanced across participants. After the experiment, each participant's arm span was measured in centimeters.

Data Analysis and Measures

Mixed-design ANOVAs on group (short arm span, long arm span, mismatched arm span) and presentation sequence (ascending, random, descending) were conducted with presentation sequence as the within-subjects variable. There were two dependent variables: the metric plank length of action-mode transition and the action-scaled ratio, or pi number, of action-mode transition. For plank length, the transition point for each pair for each presentation sequence was established, first, by determining the length of the shortest plank lifted jointly for which all longer planks were also lifted jointly, and second, by determining the longest plank that was lifted alone by either member of the pair for which all shorter planks were also lifted alone. The average of these two plank lengths was taken to be the transition plank length (Lopresti-Goodman, Richardson, Baron, Carello, & Marsh, 2009; Richardson et al., 2007; van der Kamp, Savelsbergh, & Davis, 1998). For the random presentation sequence, the same procedure was used, except that the planks were reordered by length before determining the transition point. For each sequence and pair, a pi number was calculated by dividing the transition plank length by one of three potentially relevant effectors: the arm span of the shorter- or longer-arm-span participant or the average arm span of the pair.

RESULTS

There was notable consistency in the way joint action emerged across pairs. For all of the conditions, the pairs engaged in turn taking for shorter planks in both the as-cending condition and the descending condition. In the ascending condition, when making the transition from working alone to working together, 1 participant stood off to one side of the plank and held it with one hand and waited for the other participant to grab the other end. In the descending condition, when making a transition from working together to working alone, 1 participant would initiate solo action by reaching in and grabbing both ends of the plank. Importantly, although the participants frequently engaged in conversation during the task, the content of the conversations was mostly ancillary to the task and the transitions between action modes.

The ANOVA on plank length revealed a significant main effect of group [$F(2,15) = 6.89, p < .01, \eta_p^2 = .48$] (Figure 2A). Post hoc tests revealed that the long-arm-span group made transitions at a significantly longer plank length than both the short-arm-span group [$t(10) = 2.71, p < .05$] and the mismatched-arm-span group [$t(10) = 3.22, p < .05$]. As was predicted, when the shorter-arm-span participant of each pair was used as the effector in an action-scaled ratio, the ANOVA revealed no significant effect of group [$F(2,15) = 1.78, p = .21, \eta_p^2 = .19$] (Figure 2B).

To verify that the collapsing of group differences was specific to using the shorter-arm-based action-scaled ratio, the ratios for the average arm span of each pair and the longer-arm-span participant of each pair were also explored. As was anticipated, the ANOVA on the former ratio revealed a significant effect of group [$F(2,15) = 3.88, p < .05, \eta_p^2 = .34$], with mismatched-arm-span pairs making transitions at a significantly smaller pi number than the
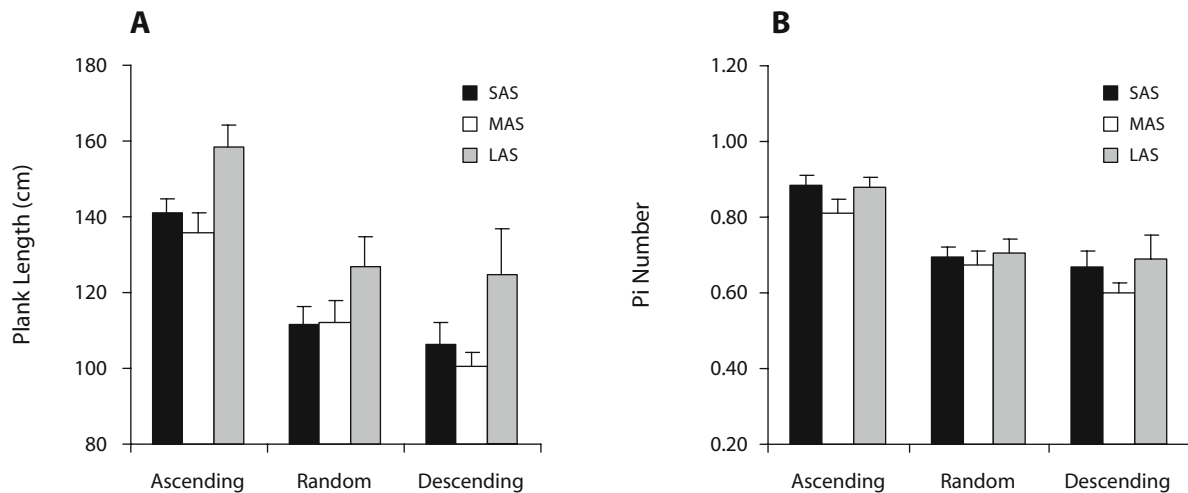
Figure 2. The (A) plank length and (B) pi number at which the participant pairs made the transition between solo and joint action as a function of presentation sequence and group. SAS, short arm span; MAS, mismatched arm span; LAS, long arm span. Error bars represent the standard errors of the means.

long-arm-span pairs [$t(10) = 2.51, p < .05$]. The ANOVA of the longer-arm-span ratio similarly demonstrated its inadequacy in capturing similitude across groups [$F(2,15) = 5.81, p < .05, \eta_p^2 = .44$]. The mismatched-arm-span group made transitions at a significantly smaller pi number than either the long-arm-span group [$t(10) = 2.88, p < .05$] or the short-arm-span group [$t(10) = 3.41, p < .05$]. Because the analyses confirmed the shorter-arm-based ratio to be the most appropriate pi number to use, other ratio measures were not considered further.

Consistent with previous research (Lopresti-Goodman et al., 2009; Richardson et al., 2007; van der Kamp et al., 1998), the analyses revealed a significant main effect of presentation sequence for both plank length [$F(2,30) = 27.84, p < .01, \eta_p^2 = .65$] and pi number [$F(2,30) = 30.39, p < .01, \eta_p^2 = .67$]. The absence of an interaction between presentation sequence and group for both plank length and pi number ($Fs < 1$) supports the prediction that all of the groups would display similar dynamical processes. The participants made action-mode transitions at larger pi numbers in the ascending condition than in either the random condition [$t(17) = 6.03, p < .01$] or the descending condition [$t(17) = 6.43, p < .01$]; however, the random and descending conditions did not differ [$t(17) = 1.75, p = .10$]. The participant pairs exhibited hysteresis: a past-action mode persisted in the ascending and descending conditions when either solo or joint action was possible (see Figures 2A and 2B). Hysteretic regions were found for 17 of the 18 pairs. One pair exhibited enhanced contrast: Instead of the past-action mode persisting, the pair showed early, prospectively focused transitions, switching at a larger plank length and pi number for the descending than the ascending sequence.

DISCUSSION

The present study is unique in that we examined differences in coactors' action capabilities on the location

of action-mode transition boundaries from solo action to joint action and vice versa. The same invariant action-scaled ratio was found to determine the point of mode transition, regardless of whether pair members had arm spans that were both short, both long, or mismatched. This action-scaled ratio was *only* invariant across groups when the arm span of the pair member who had the greater need to cooperate on the task was used as the relevant effector. This finding, taken together with the findings of Chang et al. (2009) on gap passability, warrants future examination of various joint-action constraints imposed by the mismatch between coactors' action capabilities.

An important parallel can be drawn between the present study and a developmental cross-sectional study of the climbability of stairs. Although climbability for young adults is fully specified by an invariant action-scaled ratio of riser height to leg length (Warren, 1984), an additional parameter—stopping distance—is required for invariantly specifying climbability across a wider range of ages (children to older adults; Cesari, Formenti, & Olivato, 2003). A lesson in common with the present study is that discovering embodied constraints that specify a property (e.g., stair climbability or transition to/from joint action) requires careful consideration of *all* relevant environment–person and person–person regularities. For joint-action systems, in particular, many important regularities are likely to be normative or cultural constraints that are more elusive in such behavior settings and yet are certainly no less real than physical constraints.

The dynamics of the environment–person–person action system were consistent across all three groups. Hysteresis occurred for all pairs, apart from one pair that showed enhanced contrast—future-looking shifts in action. Hysteresis indicates that the system has a key feature of dynamical systems—namely, *multistability* (Kelso, 1995; Strogatz, 1994). That is, for some ranges of plank length, either action mode—solo or joint—is possible, and relatively stable, because it persists once the pair is

in that mode. Whether the participants started off cooperating, as in the descending trials, or started off in solo action, as in the ascending trials, determines when the individual will make the transition. The pull to stay in a current action mode persists until changing constraints make that mode inefficient or uncomfortable. Although it is not novel to document dynamic properties of perception (cf. Fitzpatrick, Carello, Schmidt, & Corey, 1994; Tuller, Case, Ding, & Kelso, 1994), the presence of hysteresis in the present study is notable. Documenting the dynamical properties of a system composed of persons, a task, and an environment provides evidence that such a system can be understood as a single synergy (Marsh et al., 2006; Richardson et al., 2010; Richardson et al., 2008). Furthermore, behavioral dynamics involves integrating an informational understanding of perception with a dynamical systems understanding of action (Warren, 2006). We, likewise, demonstrated that the perceptual information used by participants is consistent with an action-scaled ratio and that action modes have the dynamical properties of hysteresis and multistability.

Of course, a more cognitive interpretation of these particular findings is possible. Participants could categorize their own arm span as being longer or shorter than their coactor's arm span and infer the need to cooperate. However, note that embodied and cognitive approaches are not mutually exclusive. The advantage of the present approach resides in the demand that the dynamical characterization be coherent across settings. For example, past research has shown that action-mode transitions for individuals, from one hand to two hands, have *attractors*—stable states that the system is drawn to—of comparable strength (see Frank, Richardson, Lopresti-Goodman, & Turvey, 2009, for a dynamical model). However, the present study suggests that this is not always the case. A successful dynamical model would therefore have to be modifiable to reflect the facts of the present experiment. Namely, the attractors of solo and joint action may be of unequal strength, given that action-mode transitions in the random condition were comparable to descending trial behavior, rather than ascending trial behavior. When the stimuli were presented randomly, the pairs worked together more often for shorter plank lengths. Additionally, two pairs, excluded from the preceding analysis, showed exaggerated hysteresis: They cooperated on every trial in the descending condition *and* on every trial in the random condition. In other words, these pairs cooperated even when it was inefficient to do so and despite the fact that on many trials, both solo and joint action modes were possible. These findings suggest that for a joint perception–action system, the social pull to act in concert is somewhat stronger than the pull to act autonomously (see Richardson et al., 2007). A closer examination of social embedding in the future, in which more overt social-psychological variables that might modulate joint action are exploited, may provide an avenue to explore the ways in which situational and social constraints (e.g., individual motives or established norms for a situation) operate to further constrain the system. The promise of future research is that such influences will be subsumed under parameterizations of the same dynamical model.

Overall, the present research suggests that constraints relating to the physical and dynamical properties of coactors' bodies should be closely considered when studying the emergence of joint action. Although the fit between person and environment has typically been examined as a fixed geometric ratio of environmental properties to bodily properties, action-scaled ratios likely flow from bodily constraints in a more dynamic fashion. Simultaneous consideration of the constraints of actors' bodies, of the environment, and of social relations promises a more complete understanding of joint action as it occurs in the real world.

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NOTE

1. Pi numbers are named after the dimensionless ratio of a circle's circumference to its diameter.