TOPICS IN COGNITIVE SCIENCE

Topics in Cognitive Science (2017) 1–12

ISSN:1756-8757 print / 1756-8765 online
DOI: 10.1111/tops.12302

This article is part of the topic "Coordination and Context in Cognitive Science," Christopher T. Kello (Topic Editor). For a full listing of topic papers, see http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1756-8765/earlyview.

Editor's Introduction and Review: Coordination and Context in Cognitive Science

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Received 5 November 2016; received in revised form 14 June 2017; accepted 4 August 2017

Abstract

The role of coordination in cognitive science has been on the rise in recent years, in terms of coordination among neurons, coordination among sensory and motor systems, and coordination among individuals. Research has shown that coordination patterns corresponding to cognitive activities depend on the various contexts in which the underlying interactions are situated. The present issue of *Topics in Cognitive Science* centers on studies of coordination that address the role of context in shaping or interpreting dynamical patterns of human behavior. This introductory article reviews some of the prior literature leading up to current and future research on coordination and context in cognitive science.

Keywords: Coordination; Cognition; Dynamics; Complex systems; Pattern formation; Context sensitivity

1. Introduction

The term "coordination" often refers to the way that body parts work together to perform physical functions like walking or swimming (Turvey, 1990). Coordination also refers to the way that people interact as teams or groups (Galantucci & Sebanz, 2009). Decades of movement research have yielded a rich landscape of theories and results on coordination dynamics among the sensory and motor systems of single individuals (Beek,

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Peper, & Stegeman, 1995), as well as the dynamics of multiple individuals interacting (Schmidt & Richardson, 2008). Dynamics at both levels are formalized in terms of oscillatory forces and couplings between them, because oscillatory movements are so common in nature. For instance, locomotive coordination like walking and swimming involves oscillations of the limbs, and turn-taking involves oscillations between two different phases of activity, like throwing and catching a ball back and forth between two individuals. Oscillatory forces and couplings can be described in terms of mathematical relations between the amplitudes, frequencies, and phases of oscillators (Kelso, 1995). Indeed, the famous Haken, Kelso, and Bunz (1985; HKB) model of coordination dynamics, which has been applied to a remarkable array of coordination phenomena (see Schöner & Nowak, 2015), is essentially a model of how two pendula affect each other via coupling.

The construct of coordination has played a lesser role in cognitive science, understandably, compared with movement science. Cognition is traditionally described in terms of information processing, where representations of percepts, concepts, and language are manipulated according to various types of computations. Computations are not theorized in terms of oscillations or coordination, although one could say that cognitive systems "coordinate" with each other when they interact to compute a decision or select an action or recall an item from memory, etc. The term typically is not used in this sense because coordination implies a dynamical description of how system components work together. Such a description often is not available in studies of cognitive systems, because the components are theorized as informational and not directly measurable. A dynamical description may not even be warranted depending on one's theoretical perspective. Computational theories tend to abstract away from physical forces and interactions (Pylyshyn, 1984), which puts these theories at a distance from making predictions about coordination dynamics. A computational approach leads one to measure the consequences of processing, such as the likelihoods of different decisions (Chater, Tenenbaum, & Yuille, 2006), rather than the physical couplings of components hypothesized to implement decision-making processes.

The traditions of information processing and computation continue to flourish in modern day cognitive science, but the role and relevance of coordination has been on the rise for many years. One of the earliest and best examples comes from Esther Thelen and Linda Smith's work on motor and cognitive development (Thelen & Smith, 1994). An important line of inquiry in developmental science has been to identify progressive stages of development and the transitions between them. The development of locomotion provides a vivid illustration in which stages correspond to distinct modes of coordination —locomotion in a horse is accomplished by specific coordination patterns like walking, trotting, cantering, and galloping, each one characterized by amplitude, frequency, and phase relations among oscillating limbs. Over the course of motor development, horses and other animals successively learn multiple modes of locomotive coordination, and become facile with transitioning among them. Thelen et al. showed how principles and models of *phase transitions* (Stanley, 1987) can shed light on the stage-like progression and measurable dynamics of motor development (Thelen, 1995a). The concept of phase transitions also has been applied toward phenomena of cognitive development (Thelen, 1995b), as well as speech (Tuller & Kelso, 1990) and conceptual development (Stephen, Dixon, & Isenhower, 2009).

Phase transitions highlight a duality to coordination (Kelso & Engstrøm, 2006) that plays out in movement science and is especially relevant to the present article and special issue of *Topics in Cognitive Science*. On the one hand, coordination is expressed as stable, dynamical relations among system components, such as the phase and frequency relations that define a gallop and distinguish it from a trot. On the other hand, coordination is transient by nature. A gallop is stable only for so long—sooner or later, locomotion will transition to a slower mode like trotting, or movement may stop altogether. One coordination pattern will end, at least temporarily, and another pattern will take its place. A phase transition is a theoretical description of a system as it switches between different patterns of coordination.

The present importance of coordination stems from its inherent transience. The HKB model has a *metastable* regime in which dynamics intermittently switch between in-phase and anti-phase coupling relations (Kelso & Jeka, 1992)—that is, two oscillators may switch back and forth between synchronization and syncopation as two available and relatively stable modes of coordination. This property of metastability has been applied toward understanding the dynamics of neural activity (Bressler & Kelso, 2001), as a reflection of perceptual, cognitive, and motor processes. It is well-known that neural activity associated with cognitive function can be oscillatory, as reflected in alpha and gamma waves for instance (Buzsáki, 2009). However, the strengths of these oscillations vary substantially over time, over different brain areas, different timescales, and different cognitive states. These variations appear to reflect differing patterns of coordinated neural activity that correspond with changes in cognitive activity (Ward, 2003). The inherently transient nature of neural and cognitive patterns is evidence of their metastability (Kello & Van Orden, 2009).

Transient patterns of coordinated activity are commonplace in groups and teams of individuals as well. For instance, consider a conversation around the dinner table as a kind of coordination (Richardson, Dale, & Kirkham, 2007). There are various configurations that the conversation may take. One person may "hold court," whereas others listen and occasionally interject. Anecdotes may bounce around spontaneously from person to person, driven by associations and timing, with everyone involved in the dynamic. The conversation may divide into two or more groups, with people occasionally switching affiliations, or groups merging and splitting as time goes by. These commonplace scenarios suggest that, like neural activity, many patterns of coordination are possible among interlocutors, and each pattern is likely to last only so long. The inherently transient nature of conversational configurations is evidence of their metastability (Abney, Paxton, Dale, & Kello, 2014; Fusaroli, Rączaszek-Leonardi, & Tylén, 2014), and representative of other coordinated activities of groups and teams.

Transience is important for applying coordination dynamics to cognition because cognitive activity is inherently metastable. Several studies have provided evidence for technical predictions that stem from metastability (Freeman & Holmes, 2005; Haldeman & Beggs, 2005; Kello, Anderson, Holden, & Van Orden, 2008; Tognoli & Kelso, 2014), but here we focus on the question of what factors might be responsible for shifting from one coordination pattern to the next. For starters, metastability predicts that cognitive activity is susceptible to change, even in response to relatively small perturbations. If we assume that cognitive systems are stochastic and inherently noisy, then the noise itself may cause patterns to shift. Studies of such *intrinsic dynamics* have been, to date, the main source of evidence for metastability in neural and behavioral studies.

While internal noise is one factor to consider in the transience of coordination, another factor is external conditions and perturbations. Patterns of activity in one cognitive system may shift as a function of interactions with other systems, including other brain areas, other bodily systems, and other people. Metastability is the property that allows for patterns to be stable enough to take shape, and yet sensitive enough to change shape as a result of interactions with outside influences. In other words, interconnected systems form networks in which each given system is embedded (Scheier, Pfeifer, & Kunyioshi, 1998), and the states of these networks serve to shape the space of coordination patterns that emerge within each embedded system, at each point in time. When there are changes in contexts and constraints provided by external systems and conditions, these changes may alter the coordination dynamics that give rise to embedded cognitive activity. This view of coordination dynamics—as shaped by external conditions and perturbations via metastable interactions—makes context central to theorizing cognitive activities as products of coordination.

2. Context, coordination, and cognition

This special issue of *Topics in Cognitive Science* is a collection of articles on coordination that address the role of context in shaping or interpreting dynamical patterns of human behavior. Four of the articles focus on coordination between two or more people interacting through movements or speech, and two articles are concerned with perceptual-motor coordination that occurs within individuals. In each case, coordinated patterns of cognitive activity are shown to have different characteristics, or different effects, depending on the task parameters or measurement conditions. Together, these studies illustrate how context dependence is central to understanding coordination patterns as they relate to human cognition and behavior.

There are numerous ways that coordination in cognitive activity may be contextual, and several of them are considered in this special issue. Let us start with the coupling of pendula as a theoretical basis for coordination, as introduced earlier with the HKB model. The model has two primary modes of stable coordination: Two pendula that swing with the same frequency can be perfectly in synch with each other, that is, in-phase, or perfectly out of synch, that is, anti-phase. The HKB model can be initialized in the anti-phase mode at a relatively low frequency, and then driven to shift into its in-phase mode as the frequency is increased. As noted earlier, numerous studies in movement science have shown that behaviors like bimanual finger tapping exhibit the phase transition that is predicted by the model.

In this issue, Solfo and Van Leeuwen demonstrate and discuss two similar transitions with respect to perceptual-motor coordination and *experienced agency*. Their study is based on a previously reported phenomenon whereby individuals experience a false sense of control when they pinch their fingers in time with the onsets and offsets of a visual metronome. The phenomenon is known as Spizzo's effect (Luccio & Milloni, 2004), and it demonstrates how one's sense of agency is intimately tied to the entrainment of bodily movements with the environment. In this case, participants report the experience that their finger movements are causing the visual cues to blink on and off, even though they know there is no causal relation.

The authors discuss two contextual factors that shed light on Spizzo's effect. First, when the experience is reported, the series of asynchronies between finger pinches and cue presentations becomes correlated over time, whereas these self-correlations dissipate along with the experience when the dynamical relation between fingers and visual cue is disrupted. This result shows that the sense of physical agency over one's proximal environment is associated with coordination between body and environment, expressed as measurements that are "stitched together" by self-correlations over time. Second, the nature of the effect undergoes what appears to be a phase transition as the tempo of the visual metronome goes from relatively slow to fast. Finger pinches precede cue onsets for slow to moderate tempos, and this anticipation is experienced as control over the onsets. For fast tempos, finger pinches follow cue onsets, and this lag is experienced as control over cue offsets instead. Thus, the effect of tempo demonstrates a more subtle, fine-grained effect of context on the experience of agency.

The role of context can be more blatant than the Solfo and Van Leeuwen study, and it can derive from the comparison of solo versus joint coordination conditions. Jordan, Schloesser, Bai, and Abney report the results of a joint action experiment in which they designed a simple perceptual-motor task that participants could, in theory, perform in the same way individually or jointly. The task was to use two keys to restrain a dot from drifting outside of a rectangular region on a computer screen. The task was challenging because the effect of pressing either or both keys depended on direction of motion at the time of the key press event, and drift was constant. Two different performance conditions provided two different contexts in which coordinative patterns could emerge to satisfy the goal of keeping the dot in bounds. In the solo condition, one participant controlled both keys, whereas in the dyadic condition, one participant pressed one key, and the other participant pressed the other key.

Jordan et al. observed two clearly distinct coordinative patterns to accomplish the same task, depending on whether performance was solo or dyadic. Individuals alternated key presses at relatively long, regular intervals, in a loosely oscillatory manner, and they rarely pressed both or neither keys at the same time. This coordination pattern avoided the complex, contingent consequences of pressing both or neither keys, and it was energetically efficient and accessible because one person can precisely time each left key press relative to each right key press. This pattern was not as accessible to dyads because they were in separate rooms and could not see or hear each other—at long intervals, each key switch is like an independent event for dyads, one that requires precise timing. The dyadic context gave rise to a more effortful strategy whereby each participant tapped his or her key repeatedly in rapid succession. Each key press thereby became part of an event sequence that could be sped up or slowed down or shifted in time. Participants more easily coordinated their sequences in this case, as opposed to individual switch events, because the consequences of adjusting sequences were better communicated between members of a dyad through movements of the dot. In sum, these results demonstrate the cognitive sophistication of perceptual-motor coordination in terms of the contextual appropriateness of patterns that emerge in solo versus dyadic conditions.

The perceptual-motor task employed by Jordan et al. required relatively precise, consistent timing relations between key presses, in both solo and dyadic contexts. Other tasks may not require this kind of coordination, in which case one can ask the degree to which consistent timing relations emerge, and their relevance to task performance. Coco, Dale, and Keller report a dyadic visual search experiment in which coordination between members of the dyads was relatively open-ended. Each member of a dyad viewed a picture separate from the other member, and they verbally communicated with each other to determine whether there were or were not differences between the two pictures. Cross-recurrence quantification analysis (CRQA; Webber & Zbilut, 2005) was used to measure the degree to which consistent spatiotemporal relations emerged in eye movement trajectories as dyads searched the pictures for differences. In theory, participants could perform the task without timing their eye movements, but prior studies using similar tasks showed that trajectories do tend to align, at least to some degree (Shockley, Richardson, & Dale, 2009).

Coco et al. found that the accuracy with which dyads detected differences in pictures was *negatively* related to spatiotemporal alignment in eye movement trajectories, especially when verbal interaction was limited. It appears that limited interaction created a context in which it was more beneficial for coordination to *diversify* eye movements and thereby cover complementary regions of the picture to increase the probability of finding differences if they exist. The study did not investigate more specifically how eye movement trajectories were diversified, but one possibility is through transient, metastable coordination. The two pairs of eyes may have transitioned through numerous different spatial and temporal relations as participants searched a given picture. The result would be a complex pattern of joint eye movements that appears as a lack of alignment in terms of total amount of cross-recurrence. However, the coordination pattern would reflect sophisticated cognitive activity that enhances the detection of differences.

CRQA yields a matrix of cross-recurrence values from which a total amount of cross-recurrence can be computed, as used by Coco et al. Various other quantities can be computed from the matrix as well, and von Zimmermann, Vicary, Sperling, Orgs, and Richardson use one such quantity to measure the diversity in timing of coordination patterns produced by groups of individuals going through dance exercises together. The quantity is percent determinism, which captures how often temporary alignments in trajectories form and dissipate for a given stretch of time. The authors used percent determinism to test whether the diversity in movement timing relations is correlated with the experience of the dance exercise. Groups of 5–12 participants were led through a series of movement exercises and percent determinism was computed for all pairings of individuals in a group. After the exercises were over, participants rated their experience in terms of group affiliation, group conformity, and how much they liked their group members.

Von Zimmermann et al. found that mean pairwise percent determinism was positively correlated with ratings of group affiliation, conformity, and liking. Therefore, analogous to how Solfo and Van Leeuwen found that patterns of perceptual-motor coordination can affect individual experiences of agency, Zimmermann et al. found that patterns of interpersonal coordination can affect group experiences of cohesion. The difference is that Spizzo's effect is related to a single, stable pattern of synchronization between oscillations of the fingers and a visual metronome, whereas group cohesion is related to a diversity of patterns distributed over time. This juxtaposition demonstrates how multiple kinds of dynamical patterns are relevant to cognitive activity, including simple synchronization and more complex, diversified patterns of coordination.

The contexts in which coordination patterns are diversified, and the effect of pattern diversification on experience, are also addressed in the article by Walton, Washburn, Langland-Hassan, Chemero, Kloos, and Richardson. Like dance, musical performances evoke coordinated movements among musicians that involve complex sensorimotor, perceptual, and cognitive processes. Walton et al. report a study designed to evoke coordination patterns between two musicians that reflect their improvisation together. The authors analyzed the movements of musicians as they improvised based on two different backing tracks designed to provide stronger versus weaker constraints on performance. The more constraining track was a rhythm and chord progression from a standard swing song, which guides improvisation to follow the underlying song structure. The less constraining track was just a constant drone of two notes that only suggested a musical key to play in.

As in the study by von Zimmerman et al., Walton et al. used CRQA to measure the degree of alignment in the sequences of notes played by each musician in the improvised duets. The authors found that coordination patterns were more diversified between the two musicians when the backing track was *more* constraining. Furthermore, listeners experienced improvisations with more diversified coordination as more enjoyable and harmonious. It appears that the less constraining context led musicians to constrain each other by aligning their musical note progressions, whereas musicians broke away from each other more often when the more constraining context could act as a "home base" of sorts. Listeners preferred to hear musicians diversify their improvisations and presumably complement each other, as opposed to copy each other. This result is consistent with the positive experience of diversified timing relations in group dance exercises reported by von Zimmerman et al.

The articles reviewed thus far cover a range of different task contexts, from entrained finger pinching to movement stabilization to visual difference detection, along with the more natural activities of dancing and playing music. The last article reviewed here focuses on a peculiar type of *measurement context* that researchers have employed in dozens of studies of neural and behavioral activity. The context is suited for measuring the intrinsic dynamics of a system (Kello, Beltz, Holden, & Van Orden, 2007; Van Orden, Holden, & Turvey, 2003). It is created when a measurement is taken repeatedly, with no external variation in measurement conditions, and no forced contingencies between repeated measurements. To illustrate, one could measure the series of response times to a visual cue presented repeatedly (Gilden, 1997), or the series of acoustic durations for a word spoken repeatedly (Kello et al., 2008). At the level of dyadic activity, one could measure the asynchrony between a drummer and bassist as they play a beat repeatedly, for instance, or the time intervals between each catch as two people throw a ball back and forth to each other. At level of neural activity, one could measure power in the alpha band repeatedly, at regular intervals, in the restful waking state (Linkenkaer-Hansen, Nikouline, Palva, & Ilmoniemi, 2001).

All the contexts just listed elicit measurements that gauge how system activity fluctuates over time *without* external perturbations or contingencies. These fluctuations are hypothesized to reflect the ever-present, ongoing coordination of system components with each other, whatever the system being measured. Thus, the statistical structure of these fluctuations is a coordination pattern that reflects the system's intrinsic dynamics. Many studies in recent years have shown that the measurement context of intrinsic dynamics consistently yields *long-range correlations* in measurement series that resemble 1/f noise (Kello et al., 2010). Long-range correlation means that a measurement taken at time t is influenced by the history of the system being measured, going back dozens and even hundreds of measurements occurring at times $t-\tau n$, where τ is the mean interval between measurements, and n is the number of measurements back. Long-range correlations show how ongoing coordination is expressed as measurements that are stitched together over relatively long periods of time.

The phrase "stitched together" was used earlier to refer to self-correlations in series of finger pinches that gave rise to Spizzo's effect by virtue of entrainment to a visual metronome. In fact, the measurement context created by Solfo and Van Leeuwen was well suited to intrinsic dynamics—fingers were pinched repeatedly with minimal external perturbations or contingencies, barring the constant contingency imposed by the metronome. The authors found self-correlations in series of asynchronies going back dozens and even hundreds of measurements for slow to moderate tempos. Correlations went back less far for the faster tempos, suggesting that contingencies imposed by the tempo were amplified by the difficulty of keeping pace with a fast metronome. The amplification of external contingencies weakened the intrinsic coordination pattern of $1/f$ noise.

Balasubramaniam, Hove, and Médé report an experiment in which the measurement protocol was similar to the one examined by Solfo and Van Leeuwen. Participants pinched their fingers repeatedly, at regular intervals initialized by a metronome that was then removed after the first few pinches. The force of each pinch was measured and displayed to participants as a vertical bar meter. The meter showed a set point where participants were instructed to match the peak force of each pinch. Participants repeatedly pinched their fingers and the authors analyzed two different measures of each pinch corresponding to the two task goals of (a) constant inter-response intervals and (b) constant peak pinch forces. Series of inter-response intervals and peak forces both exhibited long-range correlations in the form of $1/f$ noise. Once again, long-range correlations appear to be the universal pattern of coordination that manifests in the measurement context of intrinsic dynamics.

Balasubramaniam et al. replicated and expanded on previous studies (Coey, Hassebrock, Kloos, & Richardson, 2015; Holden, Choi, Amazeen, & Van Orden, 2011; Rigoli, Holman, Spivey, & Kello, 2014) by testing whether long-range correlations in inter-response intervals were related to those in peak forces. Both time series reflect the measurement context of intrinsic dynamics, but they also reflect distinct sensorimotor processes. The authors asked whether each measure might express its own intrinsic dynamic because of differences in sensorimotor processes. Results provided evidence for distinct patterns of long-range correlation in inter-response intervals versus peak forces, as a product of having two subtly distinct measurement contexts. These results demonstrate a pervasive quality to 1/f noise that bolsters its interpretation as general to the ever-present, ongoing coordination between components of perception, action, and cognition.

3. Conclusions

In closing, two main themes emerge from this special issue of *Topics in Cognitive Science*. One is that coordination in human behavior can take on numerous guises depending on the context. Coupled pendula and other oscillators are useful models for some types of repetitive coordination like tapping to a beat, but coordination in cognitive activity is often more complex than synchronization or other stable phase relations. Specifically, cognitive activities are often associated with transient, metastable patterns that express a diversity of relations among brain areas, bodily activities, and behaviors coordinated among individuals. This diversity appears to reflect complementary activities among individuals, and systems within individuals, that work together toward task goals.

The other main theme is that patterns of coordination both reflect and affect human experience and performance. One's sense of sensorimotor agency and control is related to the degree of entrainment between self and environment. One's sense of affiliation with a newly formed group is related to the diversity of timing relations in individual movements, and one's sense of musical esthetics is related to the complementarity of coordination among musicians. These trends in experience have parallels in performance as well —joint visual detection is more accurate when the coordination of eye movements is complementary, which fits with other recent studies on the performance benefits of complementarity in interpersonal coordination (Fusaroli et al., 2014; Mills, 2014).

Finally, the articles in this special issue point the way toward future investigations into the roles of context and coordination in cognitive science. The importance of pattern diversity and complementarity in cognitive activity suggests further advances in methods for measuring these aspects of coordination, some of which may be based on CRQA or complexity matching (Abney et al., 2014), whereas others may be based on information theoretic measures (Fusaroli & Tylén, 2016). Theoretical advances may come from computational models of coordination and interaction that emphasize transience and complementarity (e.g., Dale, Fusaroli, Tylén, Raczaszek-Leonardi, & Christiansen, 2016; Rodny, Shea, & Kello, 2017). Lastly, future studies may further elucidate the ways that coordination patterns in cognitive science are inextricably situated in their neural, bodily, environmental, and social contexts (Van Orden, Kello, & Holden, 2010).

Acknowledgments

This special issue stemmed from the 2015 meeting of the society for complex systems in cognitive science, held jointly with the meeting of the cognitive science society in Pasadena, CA.

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