The Porous Cognition-Action Interface, Language Processing, and Pluralism

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We review extensive recent research showing that action trajectories – as measured through computer-mouse trajectories during experimental tasks – can serve as informative behavioral signatures for unfolding cognition. Such results demonstrate what we term the "porous" nature of the cognition-action interface: Cognition flows into the execution dynamics of the action system. Among these extensive demonstrations, we describe recent work showing that action dynamics can sometimes appear to contain discrete shifts or changes of mind. We tie this range of findings into a broader theoretical discussion and argue that theories in psycholinguistics should seek more pluralistic and integrative approaches to complex, multi-scale language phenomena.

Introduction

This chapter has two goals. The first and primary goal is to review empirical evidence for what we will call the "porous cognition-action interface." Below we review research demonstrating that action execution, measured in the form of computer-mouse cursor movements, co-varies in interesting and systematic ways with psycholinguistic processing. We show that such tracking of computer-mouse trajectories during computer-based experimental tasks provides a dynamic signature of the *structure of change* that the cognitive system is undergoing, affording a window onto the diverse kinds of processing in the cognitive system. A secondary goal is a broader theoretical one. We argue that the processing of language may reveal diverse characteristics depending on one's level of analysis, and the kind of psycholinguistic task a cognitive agent is carrying out. The upshot is a theoretical pluralism: The "great debates" of cognitive science cannot be meliorated by choosing a single theory, but by integrating theories in a way that captures these diverse characteristics of processing. Action trajectories are described as having the potential to be an empirical context in which this diverse processing can be measured and identified -- bridging action, cognition, and language processing in a promising empirical framework.

In what follows, we first describe the interface between cognition and action as being a "porous" one: Executed action is not merely a function of endpoint decisions from cognitive processing, but execution dynamics can co-vary and "blend" with unfolding cognitive processing even before that processing is finished. Following that, we supply strong neuroscientific and basic cognitive evidence for this blend, then detail a wide variety of psycholinguistic work showing that action co-varies with language processing. At higher-levels of linguistic processing (e.g., sentence verification) interesting patterns in the action trajectories become evident. We end by summarizing the core debates that have taken place in cognitive science, and motivate the pluralistic perspective.

The Porous Cognition-Action Interface

For at least two decades, there has been a prominent movement in cognitive science to broaden the role of the body in theories of cognition (Ballard, Hayhoe, Pook, & Rao, 1997; Barsalou, 1999; Clark, 1997; Glenberg & Robertson, 2000; Lakoff & M. Johnson, 1998; Varela, Thompson, & Rosch, 1991). Of particular relevance here is the observation that the dynamics of action systems, from premotor cortex (see Kalaska, Scott, Cisek, & Sergio, 1997 for a review) into limb movements (e.g., Tipper, Lortie, & Baylis, 1992), seem to be richly intertwined with cognitive processing. For example, as reviewed below, motor programs are not simply a collapsing of decision processes onto the body's effectors, but rather continually and simultaneously track multiple possible choices and movements in the environment as decisions are taking place (Cisek & Kalaska, 2005). Also, the exact same limb movement goal may be reached under differing dynamics depending on the distractors present in the movement environment (Castiello, 1999; Spivey, Grosjean, & Knoblich, 2005; Tipper, Howard, & Jackson, 1997). This suggests that the relationship between cognition and action is not simply one of a discrete transition or collapse of the "decision function." The systems appear to have a "porous" interface, as cognition is systematically "leaking out" into the body's effectors in a way that permits dynamic tracking of attention to objects in the task environment. In the following section, we review further basic neuroscientific and behavioral evidence that strongly demonstrates the porous nature of this interface.

Neural and Basic Processing Evidence for the Porous Interface

Extensive research in neuroscience has revealed exciting details about the mammalian motor system. Early theories of limb control considered movement to be a simple and direct function of balancing muscle groups. This "equilibrium point theory" (Bizzi, Kalil, & Tagliasco, 1971) considered movements to be programmed in single and central commands, and multiple movements programmed serially, from equilibrium to equilibrium (see Jeannerod, 2006 for a brief history). This theory works well in simple reaching contexts, particularly when complex and sense-guided movement is ignored. Outside these ideal confines, recent work suggests that movements may be forwardly predicted and controlled

(Wolpert & Flanagan, 2001), they may overlap and compete with each other in covert action commands (Cisek & Kalaska, 2005), and they may be immediately modulated by changes in the sensory environment (Farné, Pavani, Meneghello, & Ladavas, 2000). Further, the organization and processing of premotor and motor regions show that the neural system leading into action is complex, integrative, partial and simultaneous. We provide some selective review here that demonstrates each of these characteristics.

First, when the neurons underlying premotor and motor systems are closely examined, their firing properties appear to have complex and integrative characteristics. Individual cells may have multi-response characteristics, while networks of neurons exhibit systematic response gradients (P. B. Johnson, Ferraina, Bianchi, & Caminiti, 1996). In a study of reaching to visual targets, Ferraina et al. (1997) discovered that some cells in premotor cortex have multiple roles. Some are directionally tuned to visual and manual spatial position, while many appeared to have firing characteristics influenced by the presence or absence of accompanying eye-movements to a target. This suggests that cells in this region may be actively integrating sensory information from multiple sources to guide reaching.

Second, the premotor and motor systems seem to represent both the target and the continuously evolving reach movement. There appear to be regions which specify a visual target, while others in primary motor cortex continuously track and control motor movement as it is executed (Hatsopoulos, Joshi, & O'Leary, 2004; Paninski, Fellows, Hatsopoulos, & Donoghue, 2004). This may result in the expectation that motor cortex is just involved in the actual movement parameters exhibited by motor output. Instead, Shen and Alexander (1997) found that primary motor cortex activity does not just co-vary with limb and spatial characteristics of a reaching task. In their instruction-based motor-movement task, in rhesus macaques, a substantial proportion of neurons recruited during the task were involved in accomplishing the “instructed” movement: They did not co-vary primarily with just limb movement or target location. They seemed to mediate a more complex, instructed trial that had limb movement and target location dissociated.

Finally, action representations appear to be partial and simultaneous. Premotor systems gradually accumulate information to make a decision, simultaneously representing multiple potential actions, in both manual and occulomotor contexts (Cisek & Kalaska, 2005; Gold & Shadlen, 2001). Cisek and Kalaska (2005) tracked nerve cell firing in premotor cortex in a reaching task with two possible choices in opposite directions. In trials in which monkeys were not cued in which of the two directions to reach, a collection of cells in this region maintained a level of activation for both possible reaches. When a cue was then provided to direct reaching, the appropriate directionally tuned cells then became much more active while the opposite directional cells quieted.

This selective review is from a large and still-growing literature on the neurophysiology of reaching and other action (see Caminiti, Ferraina, & Mayer, 1998 and Kalaska et al., 1997 for early reviews). These studies are encouraging in looking to action as a dynamic index of unfolding cognitive processing. Premotor and motor systems for reaching appear to be complex and integrative, and unfold continuously with simultaneous competition among possible responses.

It should come as no surprise then that an increasing amount of research on basic cognitive processing also reveals that dynamic characteristics of motor output reflect underlying cognitive processing. For example, when the cognitive system directs manual output amidst an array of graspable objects, the arm's movement does not always proceed in ballistic fashion toward a single selected object, but may reveal subtle dynamic characteristics depending on the nature of underlying processing. Both manual output and oculomotor responses demonstrate these dynamic characteristics intrinsic to the temporal extent of a response, not just the final outcome of the response.

For example, Doyle and Walker (2001) demonstrate that saccadic eye movements reflect attentional processing of visual cues in a simple fixation experiment. Saccade trajectories to the same location exhibit very subtle differential curvature depending on the position of distractor or cue stimuli (see also Sheliga, Riggio, & Rizzolatti, 1995). Similar findings show that manual motor output can reveal graded representations. The force and velocity of manual responses vary concomitantly with frequency in a lexical decision task (Abrams & Balota, 1991; Balota & Abrams, 1995), and response and stimulus probability in simple reaction-time tasks (Balota, Boland, & Shields, 1989; Mattes, Ulrich, & Miller, 2002; Osman, Kornblum, & Meyer, 1986; Ulrich, Mattes, & Miller, 1999). At higher levels of cognition, Frak, Nazir, Goyette, Cohen, and Jeannerod (2010) have shown that grip changes depending on the verb used to instruct participants, and Dale, Roche, Snyder, and McCall (2008) reveal that such cognition-motor relations emerge during acquisition of knowledge (see also Ross, Wang, Kramer, Simons, & Crowell, 2007). For a review of other recent work in vision, attention, and related domains, see Song and Nakayama (2009).

Examples from Psycholinguistic Research: From Phonemes to Deception

The preceding case made for a porous cognition-action interface is, we feel, a strong one. Readers familiar with Ekman's work on "leakage" in deception and emotions (e.g., Ekman & Friesen, 1974) or Rosenbaum's work on the systematicity of action under various task demands (e.g., Rosenbaum et al., 1990) will perhaps not be surprised by it (nor require any further persuasion to believe it). Yet, so much of cognitive psychology and other areas of the psychological sciences have neglected action as an important *detailed* source of information about unfolding thinking (Rosenbaum, 2005). In this section, we present the use of action trajectories, described in passing above and more in more detail here, to provide important new information about the *structure of change* of cognition during language processing. We will first explain what action trajectories are and how we collect them. Following that, we review work using this method to study various levels of linguistic complexity: speech perception, semantic categorization of words, syntactic ambiguity resolution, evaluative thinking, and false responding (i.e., experimentally idealized "deception").

Several studies in the past few years have used a simple experimental interface to track computer-mouse trajectories while participants carry out a task (first seen in Spivey et al., 2005 with spoken-word recognition). A general schematic of these experiments is shown in Fig. 1A. Here, participants initiate a trial by clicking on a bottom-center cue that reveals a stimulus (either a word above the cue, an auditory stimulus, or a sequence of words that are clicked until a response is cued). Once the stimulus is presented, participants are tasked with choosing a response that is appropriate for the task (e.g., recognizing a spoken word, for instance). This general experimental format affords a wide variety of psycholinguistic experiments, as we will detail in this section. In general, in all these experiments, the raw data that are used to extract measures about the unfolding decision are sampled x-y coordinates of the computer mouse's cursor, making up a trajectory **T**. These are bivariate data collected at a particular sampling rate, and begin at the initiation cue and continue until the final choice is made: $\mathbf{T} = (\mathbf{x},\mathbf{y})$, where $\mathbf{x} = x_{t=1}, ..., x_{t=N}$ and $\mathbf{y} = y_{t=1}, ..., y_{t=N}$. As will be described below, any trajectory **T** provides a large number of possible dynamic measures that are psychologically relevant (see Figs. 1 and 2). For example, the simplest of these is total reaction time, the time from initiation to final click, the conventional measure used in other studies. But other new measures are possible, relating to the velocity, acceleration, and jerk of the movement, the complexity of the decision as it is unfolding, and so on. These will be showcased in relevant studies discussed here. First, consider "low-level" psycholinguistic processing: basic speech perception.

Speech perception.

There has been a long history of analyzing speech perception into discrete categories (Liberman, Harris, Hoffman, & Griffith, 1957). It is clear that speech is naturally variable and discrete analysis cloaks the dynamic process that underlies perception (Pisoni & Luce, 1987). Therefore, using action trajectories, online measurement of spoken language perception may reflect a richer and more dynamic view of underlying perceptual/cognitive processes. For example, the pin/pen merger is a common phenomenon that occurs within the southern United States. The pin/pen merger refers to a speaker's inability to produce/perceive differences between /I/ and /ɛ/ (Labov, 2001). Categorization tasks evaluating /I/ and /ɛ/ show that listeners find it difficult to discriminate between the vowels. However, measuring the maximum x-axis deviation towards the incorrect, competing sound choice in mouse-cursor movements during online processing of the vowels in real time implies that the production of /I/ and /ɛ/ compete during perception (Roche, Dale, Farmer, & Zevin, 2009; see also Farmer, Liu, Mehta, & Zevin, 2009). This suggests that /I/ and /ɛ/ are not merely perceived as one discrete category, rather they are attracted to each other in perceptual space, extending out into the dynamics of the action execution itself (see Fig. 1B). In a similar study that was the first to use this mouse-movement paradigm, Spivey et al. (2005) showed the parallel competition between word referents when there is a temporary phonological ambiguity in spoken-word recognition (e.g., "can...dy" when a candy and a candle are the two available options). These results on speech-related processing coincide with other groundbreaking work on speech processing using eye-movements as the action signature, also revealing gradedness as recognition unfolds in time (e.g., McMurray, Tanenhaus, Aslin, & Spivey, 2003)

In speech processing beyond phonemes, emotional prosody has also been used to assess a listener's ability to identify emotions in speech (de Gelder & Vroomen, 2000; Massaro, 1997). Traditionally it has been assumed that the contribution of emotional cues to language is processed post-perceptually with relatively little influence on early processing (Massaro & M. M. Cohen, 2000). Basic categorization tasks have provided information about a listener's ability to decode emotions, but the true nature of the perceptual process may be hidden. Evaluating emotional speech dynamically may show that the contribution of such emotional information adds to the perceptual and cognitive processes related to the speaker's intent. For example, a categorical perception task evaluating talker intent during the processing of emotion-like prosodic sentences (e.g., disgust, irritation, neutral, compassion, sarcasm and innuendo; Roche & Dale, in preparation) has shown that emotional information interacts much earlier in the perceptual system than previously assumed. This is evident in x-axis movements towards a target emotion response within 200ms of hearing a 2000ms statement. This suggests that emotional cues to speech perception may in fact be processed relatively early within the perceptual system. A move towards integrating dynamic measurement techniques will provide a clearer view to the domain of speech perception, and is akin to similar work showing rapid visual-linguistic interaction (e.g., Spivey, Tyler, Eberhard, & Tanenhaus, 2001; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995)

Semantic ambiguity.

Traditional semantic processing has also been explored within an action-dynamics framework, namely, the time course of processing in semantic categorization. To do so, Dale, Kehoe, and Spivey (2007) used a simple adaptation of the typicality judgment paradigms for category membership (Rosch & Mervis, 1975). They presented participants with words and pictures of an animal exemplar and asked the participants to classify them in terms of superordinate class membership (e.g., "MAMMAL"). For control conditions, a participant might see a picture of a rabbit at the bottom of their computer screen and the options MAMMAL and REPTILE in the upper left and right regions of the screen. A membership judgment is made by navigating the mouse cursor from "rabbit" to the correct mammal classification, a trivially easy task. However, when class membership is ambiguous, such as matching a butterfly to the featurally-similar BIRD or INSECT options, a participant's arm movements reveal curvature to the incorrect option. Not only is there greater attraction towards the competing membership option, the trajectory movements travel a greater distance, spend more time in motion, and exhibit greater sample entropy (or complexity; see Fig. 1C). Dale et al. (2007) interpreted these results as indicating parallel activation and continuous competition between both sets of semantic features.

Syntactic ambiguity

Farmer, Cargill, Hindy, Dale, and Spivey (2007) provide a similar explanation within the context of syntactic ambiguity resolution. A primary debate in the sentence processing literature is how the cognitive parser makes sense of structurally ambiguous sentences, such as "Put the apple on the towel in the box." Does the parser initially commit to one syntactic interpretation and then later revise if the interpretation is deemed incorrect? Or are multiple syntactic possibilities available from the onset of processing, such as the possibilities that on the towel can be interpreted as modifying the apple or be (wrongly) taken as a prepositional phrase? If the latter “multiple activation” process if correct, as Farmer et al. suspected, then mouse movement trajectories will show the telltale signs of parallel activation and response competition.

To create a context where the contrasting hypothesis could be tested, the researchers used a “visual world paradigm”, like that used by Tanenhaus et al. (1995). In a critical “one-referent” condition, an apple placed upon a towel is seen in the top-left corner of a computer screen. In the bottom-right corner is an image of an empty box. And in the top-right corner of the screen is an image of a towel. Based on this visual layout, as participants hear “Put the apple on the towel in the box,” they will move from their initial location at the apple and engage in one of several hypothesized movements. One set of movements might be characterized by going directly to the box (correct interpretation) or directly to the napkin (incorrect interpretation) before reorienting to the box. If so, then this distribution of bimodal responses across participants would support the notion that only one syntactic interpretation is activated at a time. However, if the average distribution across participants is unimodal, that is, movements on average bend towards the napkin (incorrect interpretation) while traveling towards the box (correct interpretation), then greater support is provided for the notion that both syntactic interpretations are simultaneously activated and overlapping. This unimodal pattern was indeed found by Farmer et al. (2007; see also Farmer, S. E. Anderson, & Spivey, 2007).

Evaluative thinking.

In a study on more complex evaluation of linguistic information, participants evaluated the truth of simple propositions by navigating a computer-mouse to YES or NO response options in the uppermost corners of a computer screen (McKinstry, Dale, & Spivey, 2008). Propositions that had a high level of uncertainty, such as “Is murder sometimes justifiable?,” were answered with greater moment-to-moment fluctuations than propositions with a high level of certainty of being true (e.g., “Should you brush your teeth everyday?”). These unstable arm movements suggest that greater cognitive effort is involved in evaluating ambiguously true information. Moreover, the continuous movements of the arm reveal an immediate and persistent influence of a “positive confirmation” bias throughout the response (see also Gilbert, 1991). This confirmation bias was most salient while answering no to propositions that were clearly false, such as “Is the mother younger than the daughter?”. For these propositions, there was a statistically significant tendency for the arm to gravitate relatively slowly toward a yes response (positive confirmation) during a no response movement (see Fig. 2).

False responding.

In a related study, Duran, Dale, and McNamara (2010) show the influence of another cognitive bias: a "truth-bias" that persists when people answer autobiographical questions falsely. They too found "gravitation" signatures of processing competition when participants moved their arm towards "YES" or "NO" response options on a computer screen. In their study, the words in each question were presented one at a time as participants clicked a button near the bottom of their screen. When the participants reached the final word, as in tuba with the question "Have you ever played the tuba?," they were cued to respond either falsely or truthfully. The trajectories during false responses had greater sample entropy, reached peak velocity later in the movement, and had a steeper curve towards the competing option while en route to the false response.

Summary

These studies show that action dynamics can have continual "echoes" of underlying cognitive processing even in very high-level psycholinguistic processing, such as the disavowal of a sentence's truth in a false-responding experiment. The patterns of competition reveal what cognitive competition is present during processing, and the various velocity and complexity measures further provide windows onto the nature of the response as it unfolds. For example, a truth bias in sentence evaluation produces bodily velocities that are higher in high truth-value sentences compared to sentences with low truth-value (i.e., false sentences). So the porous nature of the cognition-action interface is present even when the task in question is complex and extending over several seconds of language processing.

Always Continuous?

The primary sort of findings identified in this work are shown in Fig. 1. The curvature to a competing option, in particular, is strong as evidence for the *continuous* flow of information as a process is unfolding (Spivey, 2007). Yet, little of this work has yet been devoted to identifying tasks in which arm movements reveal *discontinuities.* These are ever-present in daily activities, even in contexts of simple reaching (Resulaj, Kiani, Wolpert, & Shadlen, 2009), to the action dynamics involved in higher-level cognition (Walsh & J. R. Anderson, 2009). In an experiment designed to show that such "discrete" changes occur in a context that would likely predict it, Dale and Duran (accepted) had participants verify sentences that were true or false which sometimes contained *negation*. Negation has been classically defined, at least in simple processes contexts, as inducing a rapid operation that reverses the truth-value of some interpretation (Wason & Johnson-Laird, 1972). If such a rapid operation took place in cognition, and the cognition-action interface is porous, then we should observe rapid shifts in the action trajectories. This is indeed what Dale and Duran (accepted) found: The presence of negation produced more "shifty" trajectories, as predicted by a classical conception of the negation operation (see Fig. 1D).

This finding suggests that the porous interface between cognition and action could also reveal sharp transitions sometimes termed "phase transitions" (Spivey, Anderson, & Dale, 2009) that may look more discrete in nature, thus resembling more traditional concepts of cognitive processing anchored to symbolic representations. This concern has even been raised for the data in which continuity is observed. van der Wel, Eder, Mitchel, Walsh, and Rosenbaum (2009) have recently critiqued the basic interpretation of the trajectory data in Spivey et al. (2005) and showed that a discrete cognitive model flowing into a continuous motor control system can produce the same basic results. In response to this, Spivey, Dale, Knoblich, and Grosjean (2010) point out that van der Wel et al. focus on the original experiment, although a wealth of evidence regarding the continuous properties of the arm movement has been identified in other studies not considered by their critique (as we have reviewed). It is unclear how their model would capture the full range of these continuous effects (see Spivey et al., 2010).

From this discussion of potential discreteness, two considerations are worth noting. First, van der Wel. et al.'s (2009) valuable critique still assumes the feature we argue for here: Their model still assumes a *continuous flow* of cognition into action, even if the cognition component itself is discrete (in the sense that cognition's discrete changes immediately impact an evolving motor command). Second, the presence of discrete, symbol-like shifts in cognitive processes may very well show up in the arm movements itself when there is this continuous flow into action (Dale & Duran, accepted; Resulaj, Kiani, Wolpert, & Shadlen, 2009; Walsh & J. R. Anderson, 2009). The porous cognition-action interface and the structure of arm trajectories could serve as a valuable empirical junction point for theoretical perspectives on the nature of underlying cognitive processes. This has broad theoretical relevance, as the data drawn from dynamic arm movements may show the very underlying cognitive dynamic guiding the movement itself. We consider these theoretical implications next.

Broader Theoretical Relevance: Psycholinguistic Pluralism

The gradedness of action trajectories, under the porous cognition-action interface, reveals a more parallel, gradient basis for many levels of language processing. This source of data has therefore been recognized as an important empirical junction point for comparing theories (e.g., Magnuson, 2005). Action execution characteristics in this manual modality (along with associated research on eye-movement patterns) may help to meliorate ongoing theoretical debate in cognitive science. In this section we briefly review this debate. Motivated by the various findings that action execution may reveal rapid shifts (e.g., Dale & Duran, accepted; Resulaj et al., 2009; Walsh & Anderson, 2009), we argue here that the story is likely not so simple.

Many are familiar with the grand triumvirate of theories in cognitive science -- classical, connectionist, and dynamic -- and the diverse debate that transpired in the 80's and 90's about which one is "the best" (see Eliasmith, 1996, 2003). In recent years, perhaps Bayesian approaches give us a quadrumvirate, though Bayesians are often explicitly less interested in how rational solutions are implemented beyond the fact that they are implemented, depending on level of analysis of interest (Chater, Tenenbaum, & Yuille, 2006). Yet, with the headway Bayesian models have made in providing a formal basis for understanding a range of cognitive processes, this framework now stands as another major competitor among others (e.g., Tenenbaum & Griffiths, 2002).

Among several dimensions of this debate, one primary dimension has revolved around the *kind of change* that each theory predicts to occur in the cognitive system as it transitions from one state to another. This has been a primary feature of the debate between classical, connectionist, and dynamical accounts. From a so-called "classical" approach to cognition, the mind transitions discretely between "semantically transparent" (Clark, 1991) symbolic representations through a sequence of computations (e.g., Pylyshyn, 1984). Connectionist approaches sometimes permit discrete-time transitions, but predict more gradient and partial intermediate states (e.g., Christiansen & Chater, 1999). Cognition can sometimes transition between states that are not so semantically transparent – states of partial interpretation, such as halfway between one or another perceptual interpretation (as in the Necker cube and other multi-stable figures). Even further, dynamical approaches to cognition urge an absolutely gradient state and transition description (Spivey, 2007). This account anchors itself to pure continuity, analogized to the continuity present in systems of differential equations – in-principle smooth change between states (Van Gelder, 1998). So any theoretical account of a cognitive process implies a manner in which its relevant states transition, making such debates fundamentally revolving around the *kinds of state change* occurring during a cognitive system's functioning (see Dale & Spivey, 2005 for further discussion). Naturally, a devotee of any particular camp has a choice experimental paradigm in which it is shown that the predicted property is present.

Recently, many theorists have argued that this "warring camps" idea of cognitive science is unlikely to lead to broader progress (Bechtel, 1990), is overly simplistic (Edelman, 2008), and modeled too closely on a Kuhnian conception of science that is only mostly relevant to very early periods of scientific change (Dale, Dietrich, & Chemero, 2009). An outpouring of interest in complex, nonlinear dynamical systems in the physical sciences has led to more integrative ideas about dynamics and computation (e.g., Crutchfield, 1994). For example, some have argued that a theory for some domain of investigation should be motivated by its measurement space, such as scale or scope (e.g., Bar-Yam, 2004). The cognitive system, a complex system, is analyzable under multiple measurement schemes, and requires more diverse but interlinking explanatory frameworks to understand how that complex system is structured and functions. In short, a complex and multi-scale understanding of biological entities is leading to a scientific pluralism (Mitchell, 2003). If this is true, it predicts that our current meta-theoretical heuristic urging the selection of one theoretical framework, over all others, will not lead to resolution. This prediction seems to have been borne out (at least, so far).

One may counter that the three frameworks we described make mutually incompatible predictions in different contexts. Yet, it is readily observable that different empirical domains will support one framework's predictions over another, while the converse may hold in a separate domain. This is discussed in Dale (2008), where a number of examples are offered in low- vs. high-level cognition. The domains of problem-solving and high-level learning are still best captured by high-level models, such as ACT-R and other frameworks (e.g., Ritter, Anderson, Koedinger, & Corbett, 2007). However, when looking to the domain of perceptuomotor control, one finds that dynamical systems accounts have great currency (e.g., Kelso, 1995). So two frameworks' generation of incompatible predictions overall is only one part of the story, as it is clearly true that they do. From the plural perspective, the more interesting question is what to do meta-theoretically when these frameworks are supported differentially across a range of domains.

In our view, the upshot of a more ecumenical meta-theoretical heuristic is that theories of cognitive processing are deeply contextual entities, both in the sense of the task context of the cognitive agent under study, and also in the sense of the context of inquiry itself, as in the kind of measurements used, the explanatory goals being sought, and so on. Thus our complex, nonlinear cognitive system gives way to *diverse emergent species* of processing. We use the term "species" only in a loose sense, as the biological metaphor would indeed break down readily. But we do mean it in two of its strongest senses. First, cognitive processing may appear *qualitatively different* under different task contexts for the cognitive agent, and investigative contexts for the cognitive scientist. Second, like all biological species, species of cognitive processes are rooted in *common origins of self-organizing patterns*. The cognitive system, coupled to its environment, is undergirded by countless subsystems nested inside subsystems that coordinate at multiple time scales that can give way to qualitative shifts in types of processing.

In this section, we have so far argued that cognitive science should pursue diverse theoretical descriptions of cognitive processing because the cognitive system will exhibit diverse species of processing depending on various contextual factors. Admittedly, this discussion is so far vague, and only captures the potential theoretical landscape coarsely. In order to argue rigorously and concretely for this need for diversity, and thus challenge the standard approach to cognitive science's theoretical debate, a detailed coverage of specific examples, theoretical and empirical, are needed. Along with several others (e.g., Abrahamsen & Bechtel, 2006; Chemero & Silberstein, 2007; Smolensky & Legendre, 2005; Weiskopf, 2009), we have done this kind of thing elsewhere (Dale, 2008). Here, we sought concreteness in an even more specific way. We reviewed a particular empirical context in which the diverse species of processing may very well become evident. The purpose of this chapter was not to make a wholesale case for this emergent, dynamic pluralism of process, but instead to introduce an experimental paradigm in which the characteristics of processing can be identified. Action dynamics is especially relevant to language processing, revealing the structure of cognitive processing as it unfolds. Language is a complex behavior organized at multiple scales, perhaps archetypal as an example of cognitive complexity (Elman, 1999), making future experiments using such dynamic measures crucial for identifying the diverse properties of processing under different contexts or tasks.

Conclusion: Identifying Discrete and Continuous Processing

If, as seen in processing sentences with negation, cognition can sometimes appear more discrete in its action-trajectory signatures, then it is possible that other systematic predictions may be made for this relative discreteness. Such predictions depend upon a few important factors. For one, the linguistic elements in question may theoretically predict discreteness, such as in the case of negation. Second, the task context may need to be carefully designed to tap into the discontinuity if it is present. For example, if participants wait too long to respond, then the "shift" or discrete cognitive transition may have taken place "in the cranium" before leaking into the porous action channel. Third, careful analysis has to be conducted to test whether shifts are "natural" rather than, say, random or haphazard. Participants who move the computer mouse whimsically while mulling over a decision should show early movements that are not systematically decision-related: The directionality would be random. Any such test of discreteness should ensure that the shifts themselves are systematic in nature (as in Walsh & J. R. Anderson, 2009).

We must admit however that much of the work on action trajectories so far reveals a high amount of parallelism and gradiency in output trajectories. This at least suggests that there is much more granularity in language processing than many fairly brittle, symbolic theories predict. Nevertheless, the potential for "changes of mind" or "shifts in processing" present in action trajectories recommends looking for them (Dale & Duran, accepted; Resulaj et al., 2009; Walsh & Anderson, 2009). Some have indeed argued these shifts may be the basis for some aggregate differences in arm movement patterns (e.g., van der Wel et al., 2009). Further research is needed to delineate the boundaries of these properties of language processing. The approach we have presented here makes use of a porous connectivity between cognition and action subsystems, which could contribute substantially to characterizing the microstructure of cognitive change across a range of processes.

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Figure 1

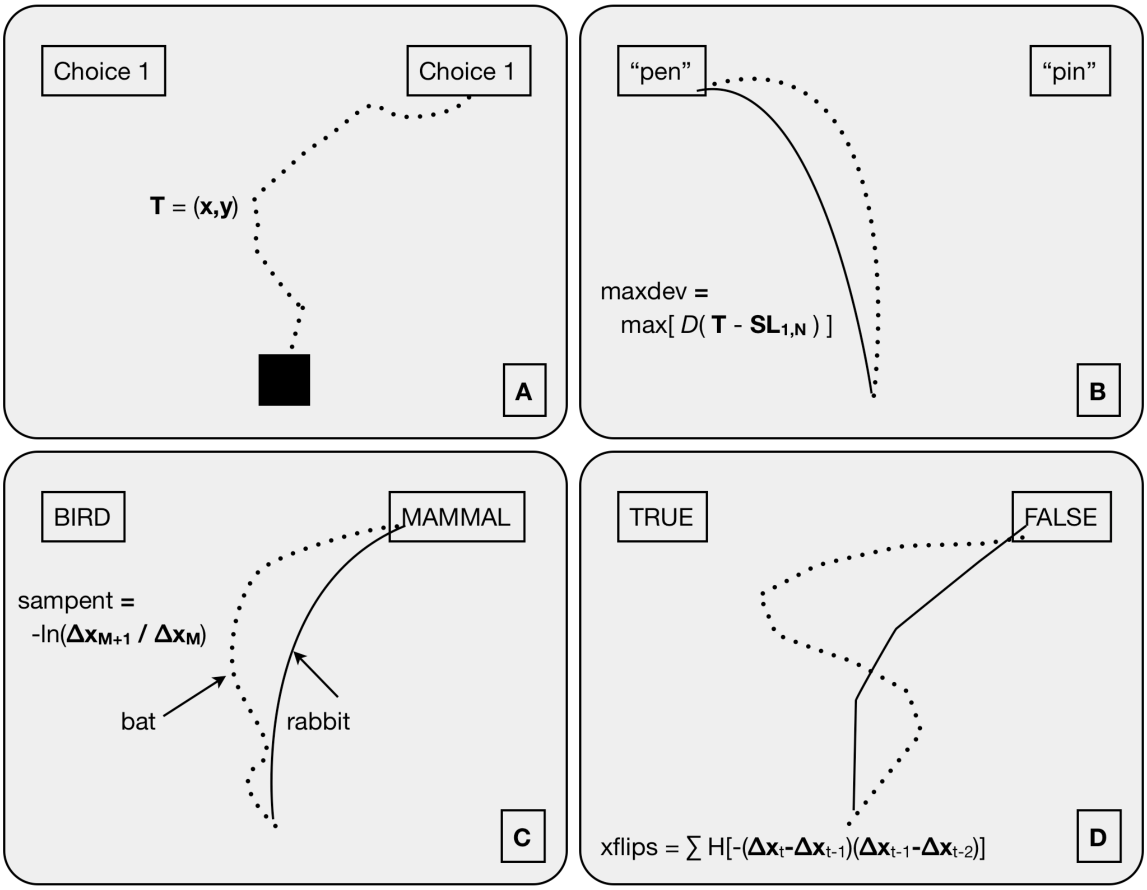

Figure 1: (A) The general setup of mouse-tracking experiments. (B) A hypothetical pair of trials with greater maximum deviation towards a competing option (e.g., "pin") when the participant has /I/ & /ɛ/ merger (see text). Maximum deviation is the maximum perpendicular distance of **T** from an assumed straight line. (C) A hypothetical trial with an atypical exemplar trial with a more complex trajectory. Sample entropy can reflect trajectory complexity. $\mathbf{\Delta x_M}$ is the number of x-coordinate changes that stay within some threshold. This score reflects the relative disorder of the change along the axis of decision. (D) x-flips is another measure reflecting competition. It is measured by taking the sum of the Heaviside function (H) over 3-time-point windows where the trajectory has changed direction.

Figure 2

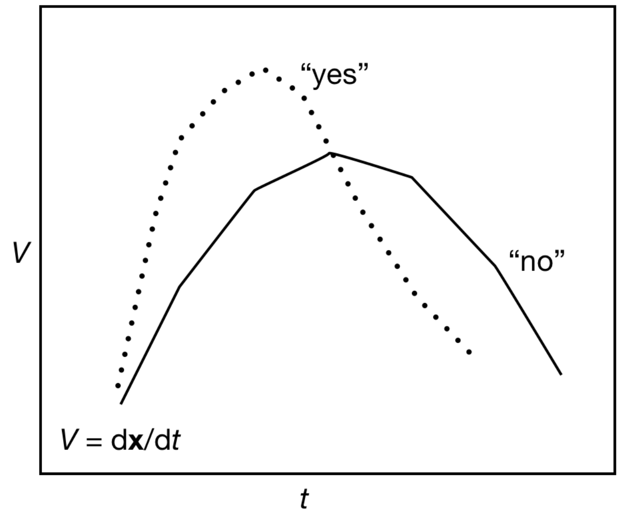

Figure 2: Hypothetical velocity profiles demonstrating a highly confident response present in the velocity of computer-mouse movement in "yes" trials vs. slower velocity (lower amplitude, higher latency to peak) in the "no" trials. See text for details and McKinstry et al. (2008) for real data.