Hand in Motion Reveals Mind in Motion

Jonathan B. Freeman[1*], Rick Dale[2], and Thomas A. Farmer[3]

[1] Department of Psychology, Tufts University, Medford, MA, USA
[2] Department of Psychology, The University of Memphis, Memphis, TN, USA
[3] Department of Brain and Cognitive Sciences, University of Rochester, Rochester, NY, USA

Recently, researchers have measured hand movements en route to choices on a screen to understand the dynamics of a broad range of psychological processes. We review this growing body of research and explain how manual action exposes the real-time unfolding of underlying cognitive processing. We describe how simple hand motions may be used to continuously index participants' tentative commitments to different choice alternatives during the evolution of a behavioral response. As such, hand-tracking can provide unusually high-fidelity, real-time motor traces of the mind. These motor traces cast novel theoretical and empirical light onto a wide range of phenomena and serve as a potential bridge between far-reaching areas of psychological science—from language, to high-level cognition and learning, to social cognitive processes.

Keywords: hand, motor, real-time, temporal dynamics, time-course

Traditional theories once viewed the mind's cognitive and motor systems as functionally independent. A motor movement, therefore, was thought to be the uninteresting end-result of cognitive processing. It is becoming increasingly clear, however, that the dynamics of action do not simply reside in the aftermath of cognition. Rather, they are part and parcel with cognition, and the cognitive and motor systems are far more coextensive than previously imagined. The implication, then, is that the rich dynamics of a simple bodily movement, such as a hand movement, can leave powerful traces of internal cognitive processes.

The existence of such motor traces of the mind would represent an important advance because researchers have too often been forced to view the "black box" of cognition through off-line, indirect observation. By and large, we use inferences from stimulus characteristics and discrete behavioral outcomes, such as reaction times and errors, to generate rich accounts of mental phenomena. Although quite valuable, a major drawback to this approach is that behavioral outcomes provide relatively little information about how cognitive processing evolves over time and how multiple processes may temporally converge to drive ultimate responses. This presents a serious quandary because competing theoretical accounts in many domains make fine-grained predictions about what ought to be taking place across the time-course of mental activity—from perception, to language and high-level cognition, to social cognitive processes.

Movements of the hand, however, offer continuous streams of output that can reveal ongoing dynamics of processing, potentially capturing the mind in motion with fine-grained temporal sensitivity. Tracking the real-time control of eye movements has long been used for this purpose (e.g., Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995), but eye-tracking and hand-tracking each have their advantages (see Magnuson, 2005). For example, hand movements offer continuous streams of motor output whereas eye movements are typically comprised of discrete saccades. Here, we explain how continuous hand movements provide a powerful—yet cheap and readily obtainable—index of underlying cognitive processing as it unfolds across time. Unlike eye movements, hand movements are also able to occupy graded locations amidst multiple response locations at the same time. These fortuitous qualities of hand movements led Magnuson (2005, p. 9996), in a commentary on the seminal article by Spivey, Grosjean, and Knoblich (2005), to portend that such movements could be able to "address...some of the biggest questions facing cognitive science."

THE LINK BETWEEN MANUAL AND MENTAL DYNAMICS

Classically, motor responses were seen as the end-result of a one-way route from perception → cognition → action; thus, they were thought to reveal little about cognitive processing (see Rosenbaum, 2005, for discussion). However, substantial behavioral evidence now indicates that cognition does not discretely collapse its processing onto movement execution; rather, movement is continually updated by cognitive processing over time (Goodale, Pelisson, & Prablanc, 1986). This is buttressed by neurophysiological evidence. Studies in humans, for example, suggest that the process of categorizing a visual stimulus immediately shares its ongoing results with the motor cortex to continuously guide a hand-movement response over time (e.g., Freeman, Ambady, Midgley, & Holcomb, 2011). Further, human reaching movements suggest that multiple motor plans are prepared in parallel, and that

these cascade over time into visually-guided action (Song & Nakayama, 2006, 2008). Monkey studies show that the hand's position and velocity are tightly yoked to ongoing changes in the firing of population codes within motor cortex (Paninski, Fellows, Hatsopoulos, & Donoghue, 2004), and when a monkey must generate a hand movement based on a perceptual decision, these motor-cortical population codes are yoked to the evolution of the decision process (Cisek & Kalaska, 2005). These findings suggest that manual dynamics are intimately coextensive with mental dynamics, and therefore, hand movements that are sampled fast enough could potentially provide real-time read-outs of internal cognitive processing.

The recent tracking of hand movement en route to choices on a screen has opened up new avenues of investigation into a wide range of psychological phenomena. Hand trajectories recorded by a computer mouse, or sometimes a wireless-remote or position sensor, have proven able to sensitively track participants' tentative commitments to various choice alternatives over hundreds of milliseconds. As such, the emergence of a behavioral response can be sampled anywhere from 40–120 times per second. This permits insights into fine-grained temporal dynamics, providing unusually high-fidelity, real-time motor traces of the mind. Its sensitivity to these dynamics can reveal "hidden" cognitive states that are otherwise not availed by traditional measures (Song & Nakayama, 2006, 2008, 2009). More broadly, these real-time dynamics may be used to assess how multiple processes temporally interact and how multiple information sources weigh in on processing across hundreds of milliseconds, thereby resolving critical empirical questions and theoretical impasses across psychology (e.g., see Spivey, 2007).

DOING PSYCHOLOGY BY HAND

LANGUAGE

In language research, debate continues as to whether the language system is a discrete-symbolic architecture or whether it integrates multiple sources of information in parallel to continually constrain its operation. Considerable evidence for the parallel, integrative approach came from eye movements, but still some researchers argued that the discontinuity of eye-movement patterns could be accommodated by discrete-symbolic accounts. The link between manual and mental dynamics has recently served as compelling evidence that language processing is indeed, at multiple levels, gradient and parallel.

Spivey et al. (2005) asked participants to move the computer mouse from the bottom-center of the screen to the top-left or top-right corners. For instance, a picture of a candle appeared in the top-left and a picture of a candy appeared in the top-right while a spoken phrase was heard (e.g., "click the candle"). When the distractor object corresponded to a word whose initial set of phonemes overlapped with the spoken word (e.g., a picture of *candy*, for the spoken word, *candle*), hand movements showed a continuous attraction toward the distractor before settling into the correct alternative. Thus, the ongoing accrual of the spoken word partially activated multiple lexical representations (e.g., both *candle* and *candy*), causing movements to partially gravitate towards *candy* before settling into *candle*. This showed that the language system continually integrates the acoustic-phonetic input of a spoken word, triggering parallel competing representations that resolve over

time. This permitted a discrimination among theoretical models previously not possible.

In some cases, however, comprehending spoken language is more difficult and would benefit from help of the visual system. Consider the following syntactically ambiguous sentence:

Put the apple on the towel in the box.

Typically, listeners resolve such ambiguities by incorporating available visual cues (e.g., is there an apple on a towel or an apple by itself?). In a series of studies, participants were given several objects on a screen while they heard a sentence instructing them to move one object to another. For example, hearing the above sentence, participants would use a computer mouse to click on an image displaying an apple on a towel, and to then drag it onto an image of a box. Before reaching the box, however, participants' hand movements exhibited a continuous attraction toward the object associated with the incorrect syntactic parse (in this case, an empty towel). Consistent with analogous eye-tracking studies (e.g., Tanenhaus et al., 1995), the attraction effect was not seen when a second relevant object was present (e.g., an apple on a napkin). This provided strong support for constraint-based accounts of language processing by demonstrating partially-active syntactic alternatives competing over time with a weighing-in of visual, contextual, and linguistic factors (Farmer, Anderson, & Spivey, 2007; Farmer, Cargill, Hindy, Dale, & Spivey, 2007). Importantly, hand movements were able to reveal competition on a trial-by-trial basis, thereby evading longstanding concerns with analogous eye-movement results that were limited by discrete oculomotor output.

In some contexts, however, sentence processing may not flow so smoothly. For instance, Dale and Duran (2011) had participants verify simple statements by clicking on a "true" or "false" response. Statements involving a negation (e.g., "cats are not dogs") led hand movements to exhibit sharp shifts in direction, initially pursuing one response and then rapidly redirecting toward the other, especially for negated true statements. Thus, during sentence processing, participants experienced an abrupt shift in their evolving decision. Classic work suggests that negation is an operator that rapidly reverses the truth/falsity of an interpretation and predicts shifts in cognitive dynamics, consistent with other work showing that hand movement may index such rapid transitions (e.g., Resulaj, Kiani, Wolpert, & Shadlen, 2009). These rapid cognitive shifts, however, could not be evidenced by traditional measures.

SOCIAL COGNITION

Hand movements have also been critical in uncovering the temporal dynamics of social cognition. For example, they have provided new insights into social categorization. In one series of studies, participants were presented with sex-typical (e.g., masculinized male) and sex-atypical (e.g., feminized male) faces and asked to categorize the target's sex by clicking on a "male" or "female" response on the screen. During categorization of sex-atypical faces, hand trajectories were continuously attracted to the opposite sex-category before settling into the correct response. This was evidence that social categorization involves dynamic competition, where partially-active category representations (male and female) continuously compete over time to stabilize onto one categorical outcome (Freeman, Ambady, Rule, & Johnson, 2008; also see Dale, Kehoe, &

Spivey, 2007). These findings led to a new model of social categorization, proposing that all available facial, vocal, and bodily cues (among other constraints) simultaneously weigh in on multiple partially-active category representations, and that these dynamically evolve over time into stable categorical perceptions (Freeman & Ambady, 2011a).

This model was supported by further evidence from a similar paradigm with race categorization. Hand movements again showed continuous-attraction effects for atypical targets, but also revealed important dissociations in how the processing of White-specifying and Black-specifying cues evolves across the categorization time-course. Moreover, as the amount of racial ambiguity increased, hand trajectories showed corresponding increases in attraction toward the unselected race-category and increases in motor complexity. This showed that the competition inherent to social categorization sensitively increases and decreases with the amount of ambiguity challenging the perceptual system (Freeman, Pauker, Apfelbaum, & Ambady, 2010). Further, hand movements have revealed not only that multiple facial cues are dynamically integrated, but also that cues across sensory modalities (facial and vocal cues) are dynamically integrated as well (Freeman & Ambady, 2011b). See Figure 1.

The competition during categorization can also bear downstream effects. For instance, Freeman and Ambady (2009) found that, before participants clicked on a stereotypically masculine attribute (e.g., *aggressive*) for male targets or stereotypically feminine attribute (e.g., *caring*) for female targets, their hands partially swerved toward the attribute stereotypically associated with the opposite sex when facial cues partly overlapped with that sex (e.g., masculinized women and feminized men). Thus, not only do facial cues associated with an alternate category trigger a partially-active representation of that category, but this partial activation cascades into the triggering of associated stereotypes. Hand movements can also reveal other types of partial parallel activations otherwise not seen by traditional measures. For example, although White participants almost always explicitly reported liking Black people, an inspection of the hand trajectories leading up to those "like" judgments revealed a parallel consideration to indicate that they "dislike" them (Wojnowicz, Ferguson, Dale, & Spivey, 2009). Such a parallel activation of multiple attitudes that continually coalesce into explicit judgments had important theoretical implications for models of social evaluation.

HIGH-LEVEL COGNITION AND LEARNING
Even high-level decision-making processes can be revealed in manual dynamics. McKinstry, Dale, and Spivey (2008) had participants judge the truth of questions by moving their mouse to "yes" or "no" response options. Questions of greater uncertainty were answered with greater fluctuation than ones

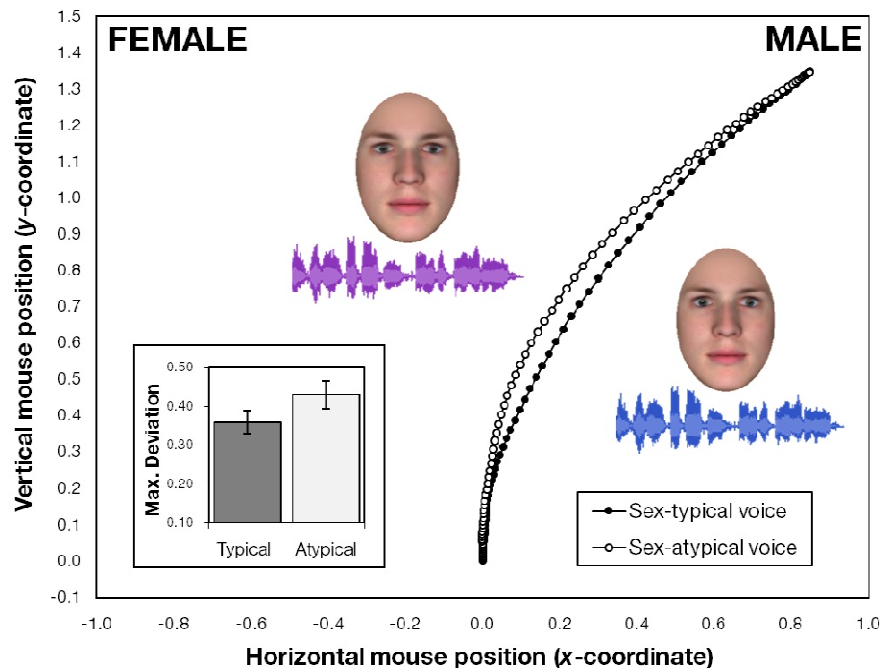**Figure 1**. Freeman and Ambady (2011) found that when categorizing a face's sex, the simultaneous processing of a sex-atypical voice led participants' mouse trajectories to be continuously attracted to the opposite sex-category response before settling into the response consistent with the face's correct sex. Mean mouse trajectories from one study are depicted (aggregated across male and female targets). In this figure, trajectories for all targets were remapped rightward, with the opposite sex-category on the left and the sex-category consistent with the face's sex on the right. A sample male face stimulus is displayed (all male and female face stimuli were somewhat sex-ambiguous). A voice stimulus typical for the face's sex (masculine) is shown on the right (audio waveform depicted in blue), next to the mean trajectory for sex-typical trials. Its atypical (feminine) counterpart is shown on the left, next to the mean trajectory for sex-atypical trials (audio waveform depicted in purple). During an actual trial, a single face was centered at the bottom of the screen while the voice stimulus played. The bar graph shows trajectories' maximum deviation toward the opposite sex-category from a direct line between trajectories' start and end points (error bars denote standard error of the mean). The continuous-attraction effect shows that ongoing voice-processing results were dynamically integrated with ongoing face-processing results over time.

with greater certainty. Thus, hand movements revealed parallel competition across the process of high-level decision-making and showed how this competition is affected by certainty in graded fashion. Hand movements also revealed a strong confirmation bias throughout the response, because answers of low probability had overall slower trajectories.

Duran, Dale, and McNamara (2010) used the same basic design, and revealed that this "truth-bias" persists when people answer autobiographical questions falsely. After participants were presented with the final word, they were cued to respond either falsely or truthfully. 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. As such, hand trajectories revealed the ongoing process of "overcoming the truth" during deceptive responding. See Figure 2.

Finally, at an even longer timescale than decisions, Dale, Roche, Snyder, and McCall (2008) studied how growing knowledge, across many trials, covaries with manual dynamics during a learning task. They had participants learn random pairs of shapes in a paired-associate memory design. Participants were shown a shape at the bottom of the screen, and instructed to pick one of two in the upper-most corners that goes with that bottom shape. They were given feedback and gradually learned these pairings. The researchers found that hand movements (measured with a wireless Nintendo Wii remote) covaried in a gradient way with emerging knowledge of the pairs. Moreover, growing knowledge correlated with stronger force responding on the remote, and that when new shapes appeared (unbeknownst to participants) this "bodily confidence" was modulated in response. Thus, hand movements revealed the longer timescale dynamics of the knowledge itself, as the participants exhibited learning across the task. Interestingly, at even longer timescales (e.g., hours), gesturing patterns of hand movement have long been used to index learning and transitions of knowledge, especially in children (Goldin-Meadow & Alibali, 2002).

FURTHER QUESTIONS AND CONCLUSIONS

The work discussed above suggests that the intimate link between manual and mental dynamics may be used to provide critical insights into psychological phenomena. It also emphasizes an integrative approach to these phenomena by demonstrating a deep coextension of processes typically investigated independently, such as action, perception, basic and social cognition. Insights from simple manual actions may therefore serve as an unforeseen bridge between far-reaching areas of psychological science.

This action-dynamics approach to the mind holds particular promise given the practicality of measuring hand movements. There now exists freely available, user-friendly software to run and analyze data from computer mouse-tracking experiments (Freeman & Ambady, 2010). Thus, rather than measure an ultimate response time, researchers can easily open up such responses into continuous streams of rich cognitive output through nothing more than a computer and mouse. Mouse-tracking also permits the recording of on-line mental processing in young children at an age where on-line data are often difficult to obtain. With the capturing of hand movements now just as available and affordable as recording the classic response time, we are hopeful that a growing number of studies will employ the methodology.
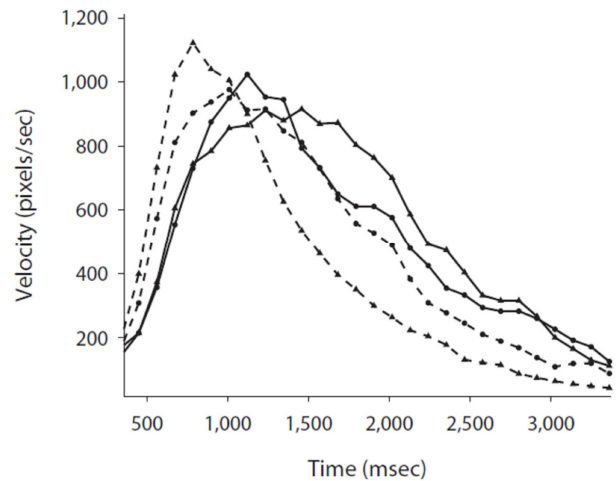

Figure 2. Duran et al. (2010) had participants answer autobiographical questions either truthfully or falsely by clicking a "yes" or "no" response on the screen. Trajectories' velocity profiles are plotted as a function of time for truthful responses clicking "no" (dashed line with circles), truthful responses clicking "yes" (dashed line with triangles), false responses clicking "no" (solid line with circles), and false responses clicking "yes" (solid line with triangles). Hand trajectories during false responses reached peak velocity later in the movement. This, among other differences between false and truthful responses in movement complexity and curvature toward the opposite response, suggests the presence of a truth bias that pulls processing off course during the production of a deceptive response.

In this action-dynamics approach, researchers are afforded many ways to measure and analyze hand trajectories. The computer mouse is by far the most practical, but other options include a wireless remote (e.g., Dale et al., 2008) or a position sensor (e.g., Song & Nakayama, 2008). Although the techniques are quite similar, one notable difference is that mouse-tracking captures only 2D movement, whereas the others could potentially capture 3D movement. The techniques also provide different motoric experiences; for example, tasks using a wireless remote can measure large, free-ranging arm movements. Another consideration is that, in mouse-tracking, hand movements are stabilized by a surface. Moreover, mouse-tracking can be carried out through online data collection systems like Amazon Mechanical Turk (Dale & Duran, 2011). Once trajectories are recorded, several measures may be computed, including maximum deviation toward an unselected response (e.g., distractor), curvature area, switches in direction, or movement complexity. The time-course of the hand's position, velocity, acceleration, or proximity to a selected or unselected response, can also be examined. Each analysis carries its own advantages with respect to the theoretical and practical interests at hand. Freeman and Ambady (2010) provide a more complete discussion of measures and analytic techniques for trajectory data. They also describe a user-friendly software package that permits the recording, measurement, and analysis of mouse trajectories from highly customizable experimental tasks.

Despite the headway made by the work reviewed here, however, the moving hand still has much to reveal about the mind. For example, in a recent critique of the method and its interpretation, van der Wel, Eder, Mitchel, Walsh, and

Rosenbaum (2009) discussed whether a model of discrete processing could produce, through (continuous) linear combinations of motor plans, the evidence for continuous processing often obtained from hand-tracking experiments. The authors argued that the inference of processing continuity from hand-tracking data is not yet fully warranted. In response, Spivey, Dale, Grosjean, and Knoblich (2010) argued that the measures drawn from hand trajectories are of sufficient richness that the proposed model of van der Wel et al. does not capture their full range of nuances. Both sets of authors agree, however, that such debate is central to further understanding the manner in which cognition flows into action.

There is also not yet a clear understanding of the particular cognitive processes directly indexed by hand movements. For instance, several of the studies described here reported effects of motor competition, but one might wonder whether the competition may be mediated by attentional mechanisms (e.g., see Rizzolatti, Riggio, Dascola, & Umilta, 1987). Recent mouse-tracking work has found that such competitive effects can also reflect embodied cognitive processes leaking out into the motor system (Miles, Betka, Pendry, & Macrae, 2010). In addition, one might wonder whether average graded attraction effects, like that seen in Figure 1, reflect parallel competing responses (e.g., parallel pursuits toward both "female" and "male") or perhaps strategic response switching (e.g., an initial pursuit toward "female", which is then corrected by a later pursuit toward "male"). Indeed, previous work found that hand movements can distinguish between these two possibilities. For example, Farmer, Cargill, & Spivey (2007) demonstrated distinctly different hand-trajectory distributions for scenarios involving parallel competing responses versus scenarios involving strategic midflight corrections (see Figure 3). Freeman et al. (2008) provided a second demonstration of this in the more typical two-choice mouse-tracking design as well. In short, more work is needed to provide a comprehensive mapping of hand movements in these paradigms with specific underlying cognitive processes. Nevertheless, at this early stage of the action-dynamics approach, hand movements do show an unusually sensitive ability to tap into real-time cognition.

Another issue is to relate this methodological approach to the long-established precedent of reaction times and reaction time distributions (e.g., Van Zandt, 2000). The reaction time is still the most widely used across psychological studies, and because of its ease of measurement and interpretation, we would not argue that hand-tracking should serve as any full substitute. Instead, approximately continuous hand-tracking data from an unfolding decision provides a unique behavioral junction point for certain theoretical debates. For example,
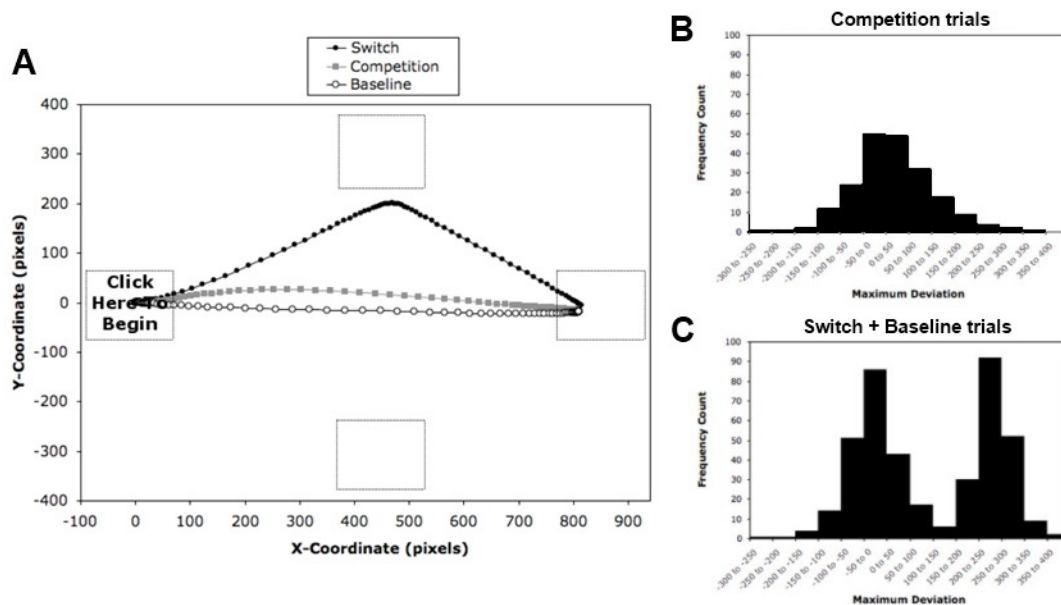

Figure 3. Farmer, Cargill, & Spivey (2007) conducted an additional study where participants were presented with three colored squares and asked to click on the green square. In the baseline condition, the top and bottom squares were red and the rightward square was green, corresponding to a condition where no attraction to another object on the screen would be predicted. In the switch condition, the green square originally appeared at the top-center, with the other two squares being red. Once the cursor exited the leftward "Start" box, however, the green square turned red, and the leftward square that was originally red became green. This simulates a situation where participants initially commit to an incorrect response, and then subsequently switch their commitment to the correct response. In the competition condition, the bottom square was red, the rightward square was green, and the top-center square was a blue-green. Here, the blue-green square served as a distractor. Panel A shows average trajectories. In the baseline condition, the average trajectory showed a direct pursuit toward the correct response. In the switch condition, the average trajectory showed a strong initial movement toward the original location of the green square, followed by a sharp redirection toward the ultimate location of the green square. In the competition condition, the average trajectory was smooth and showed graded attraction toward the location of the distractor. If an given experimental condition, if half of trajectories showed zero attraction (like the baseline condition) and half showed discrete switches (like the switch condition), the average trajectory would appear smooth and graded (like the competition condition), although in reality it reflected discrete switches rather than competition. Panel B shows the distribution of trial-by-trial deviations for trajectories in the competition condition, illustrating unimodality. Panel C shows the distribution of trial-by-trial deviations for trajectories pooled across the switch and baseline conditions, illustrating bimodality. The average trajectories and distributions elicited by these conditions show how the hand-tracking methodology can identifiably tap into a variety of cognitive processes (e.g., parallel competition, strategic response switching).

theoretical debate anchored methodologically in reaction time eventually sought mitigation in reaction time distribution analyses (e.g., Ratcliff, Van Zandt, & McKoon, 1999). Dynamic data from an action trajectory may, in some cases, more directly reveal the cognitive processes under dispute. These same points may be made about eye-tracking, now widely used as an ongoing measure of cognitive processing (e.g., Tanenhaus et al., 1995). The same caveats hold: Future work should tease apart the relative merits of all these methodological approaches and determine where they are most usefully employed.

A final pressing question is how fine-grained mental dynamics provided by hand movements relate to higher-level phenomena, such as behavior, educational and clinical outcomes, or social interaction. More work is needed to tie together data across these multiple time scales. Moreover, future research would benefit from combining hand movements with eye-movement and electroencephalography (EEG) data for a more complete characterization of the time-course of perception, cognition, and action, and their many interactions. Ultimately, this work could be used to bridge diverse domains of psychological science and help form truly integrative accounts of the mind.

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