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The developing mind in action: measuring manual dynamics in childhood

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ABSTRACT
Developmental theory has long emphasized the importance of linking perception, cognition, and action. Techniques designed to record the spatial and temporal characteristics of hand movements (i.e., *manual dynamics*) present new opportunities to study the nature of these links across development by providing a window into how perceptual, cognitive, and motoric processes interact and unfold over time. Although manual dynamics are commonly used to explore a range of topics with adults, including language processing, numerical cognition, social perception, and cognitive control, comparatively little research has used hand-tracking techniques to explore these topics with children. The current article aims to bring attention to this methodological gap and discuss how and why developmental researchers might want to address it. The article introduces two hand-tracking techniques, contrasts how the techniques have been used with adults relative to children, and explores how manual dynamics might fit into the broader landscape of research in child development.

An influential metaphor in the history of psychology has held that the mind functions in much the same way that computers of the mid-20th-century processed information: Data are fed into the system through various inputs (perception), the data are manipulated according to a series of rules until a decision is reached (cognition), and finally, an output is generated (action). Although this metaphor proved useful as an early framework for studying cognitive processing (Gigerenzer & Goldstein, 1996), it also reinforced disciplinary boundaries between perception, cognition, and action by encouraging the notion that mental processing occurs in a serial, feed-forward, and stage-based manner (Cisek, 1999). In so doing, the metaphor deemphasized the role of action by presenting behavior as the outcome of perceptual and cognitive processes that had already concluded.

In contrast to the computer metaphor, contemporary research and theory present a more dynamic view of the mind and in particular of action's relation to perception and cognition. This view emphasizes that biological minds are embodied, embedded, and the product of an evolutionary process that required organisms to simultaneously weigh competing opportunities for action (Adolph & Robinson, 2015; Barsalou, 2008; Cisek & Kalaska, 2010; Clark, 2015; Kontra, Goldin-Meadow, & Beilock, 2012; Lakoff & Johnson, 1999; Pexman, 2017; Smith & Gasser, 2005; Spencer, Thomas, & McClelland, 2009; Spivey, 2007). On this view,

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mental processing does not follow a serial, feed-forward, and stagelike progression from perception to cognition to action. Rather, processes across perception, cognition, and action are unfolding in a parallel, interactive, and continuous manner to ensure that organisms maintain an adaptive fit with their environments.

Support for this more dynamic view of the mind has been provided by research that has used hand-tracking techniques to target how unfolding perceptual and cognitive processes are reflected in the spatial and temporal characteristics of hand movements (i.e., *manual dynamics*; Freeman, Dale, & Farmer, 2011; Song & Nakayama, 2009). Two of the techniques frequently used to record manual dynamics are *mouse tracking* and *reach tracking*. In a typical mouse-tracking study, participants complete a computerized task by using a computer mouse to maneuver a cursor from a designated starting location at the bottom center of the screen to response targets presented in the top corners of the screen (see Figure 1A). This approach enables researchers to record the two-dimensional path that a participant's hand travels to the selected response target, and can be used in lab settings or to collect data remotely through online platforms such as Amazon's Mechanical Turk service.

In a typical reach-tracking study, participants perform a computerized task by reaching from a designated starting location on the table in front of them to one of multiple response targets on a digital display (see Figure 1B). In contrast to mouse tracking, reach tracking enables researchers to record hand movements in three spatial dimensions, typically using electromagnetic sensors or an array of high-speed cameras. Reach tracking

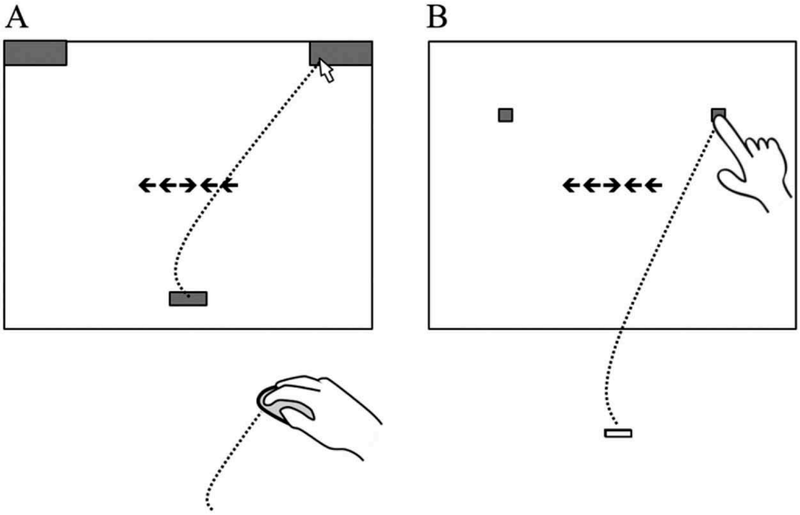

Figure 1. (A) Illustration of a mouse-tracking version of the Eriksen flanker task (Eriksen & Eriksen, 1974). Participants initiate each trial by navigating a computer cursor to a starting location at the bottom center of the screen. Following stimulus presentation, participants maneuver the cursor to one of two response targets located at the top corners of the screen. In the task, the correct response location is cued by the centermost arrow in the stimulus array. The arrows cue competing responses on incongruent trials (e.g., ←←→←←) and the same response on congruent trials (e.g., →→→→→). (B) Illustration of a reach-tracking version of the same task. Participants initiate each trial by resting their finger on a designated starting marker on the table in front of them. Following stimulus presentation, participants reach to touch one of two response targets located toward the top left or right of the screen.

can therefore be used to measure reaches to physical (i.e., nondigital) objects in the participant's environment, and does not require participants to perform visuomotor transformations to account for how physical movements of a computer mouse are translated into the movements of a digital cursor (Gallivan & Chapman, 2014)

In addition to accuracy and response time, hand-tracking techniques provide a number of measures that offer insight into the dynamics of perceptual, cognitive, and motoric processes, including *initiation time* (the time elapsed between stimulus onset and movement onset), *movement time* (the time elapsed between movement onset and response completion), and *movement curvature* (a measure of the degree to which a movement deviated from a direct path to the selected response target; see Figure 2). These measures have been used to explore a wide range of topics in adults, including language processing, numerical cognition, social perception, and cognitive control (for reviews, see Freeman et al., 2011; Freeman & Johnson, 2016; Song, 2017; Song & Nakayama, 2009). Comparatively little research has used hand tracking to investigate these topics from a developmental perspective, however. The following section highlights the nature of this methodological disconnect by providing a brief overview of the hand-tracking literature.

Manual dynamics in psychological research

Language processing

Hand-tracking techniques have played an important role in comparing stage-based accounts of language processing to dynamic accounts positing the parallel, interactive, and continuous processing of information (Farmer, Cargill, Hindy, Dale, & Spivey, 2007; Spivey, Grosjean, & Knoblich, 2005). The former accounts suggest that competing interpretations of a stimulus must be resolved before the next stage of processing begins (e.g., before an action is generated), whereas the latter accounts propose that different interpretations can be maintained in parallel, resulting in the simultaneous activation of competing responses. To test these different accounts, Spivey and colleagues (2005) designed a mouse-tracking study in which pictures of various objects were presented at

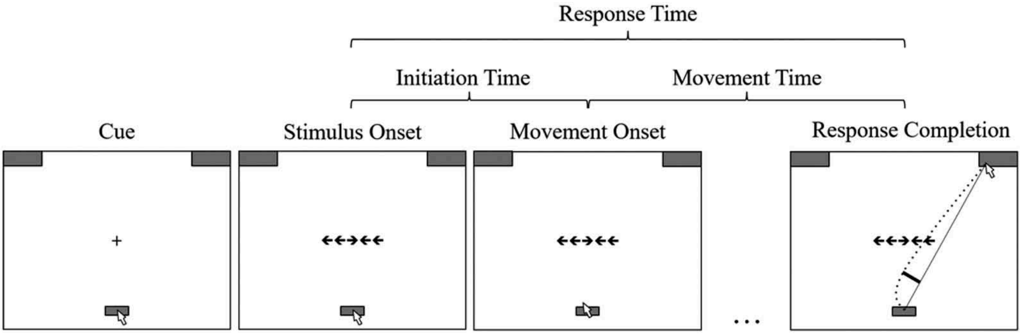

Figure 2. Illustration of common hand-tracking measures. Movement curvature is a measure of the degree to which a movement (displayed as a dotted line in the right panel) deviated from a direct path to the selected response target (displayed as a thin solid line) and is computed by dividing the maximum deviation of the movement from the direct path (displayed as a thick solid line) by the length of the direct path.

the top left and right corners of a computer screen. In each trial, an audio file was played naming one of the pictured objects, and adult participants were instructed to click on whichever object was named. Half the trials featured objects with phonologically dissimilar names (e.g., *jacket* and *candle*), whereas the other half featured objects with phonologically similar names (e.g., *candy* and *candle*).

Consistent with dynamic accounts of language processing, adults' movement curvatures revealed significantly greater attraction toward the incorrect response target when the two objects featured phonologically similar names. That is, in trials in which the early portions of the auditory stimulus (e.g., "can …") cued two different responses (e.g., *candy* and *candle*), participants' hand movements indicated that both responses were partially activated until the unfolding speech stream (e.g., "… dle") resolved the competition between them (see Figure 3A). In addition to offering insight into a fundamental aspect of spoken-language processing, this study provided early evidence that manual dynamics can be used to target how perceptual and cognitive processes unfold over time.

Similar mouse-tracking paradigms have since been used to investigate other aspects of language in adults, including syntactic processing (Farmer et al., 2007), scalar implicatures (i.e., what is implied by words such as "some" or "most" under different circumstances; Tomlinson, Bailey, & Bott, 2013), and negations (Dale & Duran, 2011). However, relatively little research has used hand tracking to investigate language from a developmental perspective. One example is a mouse-tracking study by Cargill, Farmer, Schwade, Goldstein, and Spivey (2007) in which children aged 4 and 5 years old were instructed to move pictures of objects around a computer screen by clicking on different locations. Each trial featured a target object (e.g., an apple on a towel), a distractor object (e.g., a flower), a correct destination (e.g., a box), and an incorrect destination (e.g., a second towel). The instructions were designed to be either unambiguous (e.g., "Put the apple that's on the towel in the box.") or ambiguous (e.g., "Put the apple on the towel in the box."). The researchers found that children's hand movements were significantly more attracted to the incorrect destination (e.g., the other towel) when the instructions featured ambiguity. Interestingly, children with larger vocabularies demonstrated less attraction to the incorrect destination relative to those with smaller vocabularies.

Numerical cognition

Hand-tracking techniques have also played an important role in investigating the extent to which the body shapes and reflects how we represent and reason about numbers (Dotan & Dehaene, 2013; Faulkenberry, Montgomery, & Tennes, 2015; Marghetis, Núñez, & Bergen, 2014; Song & Nakayama, 2008). For instance, in a reach-tracking study by Song and Nakayama (2008), adult participants were instructed to identify whether a centrally presented number was less than, equal to, or more than five by reaching to touch a response target located toward the left, center, or right of the screen, respectively (see Figure 3B). Adults' movement trajectories revealed a *numerical distance effect* (Moyer & Landauer, 1967), with numbers numerically closer to the standard of comparison (i.e., five) generating greater attraction toward the center response target than those numerically farther from the standard. For example, reach movements were more curved toward the center response target for responses to three and seven (a distance of two from the standard of comparison) than for responses to one and nine (a distance of four from the standard).

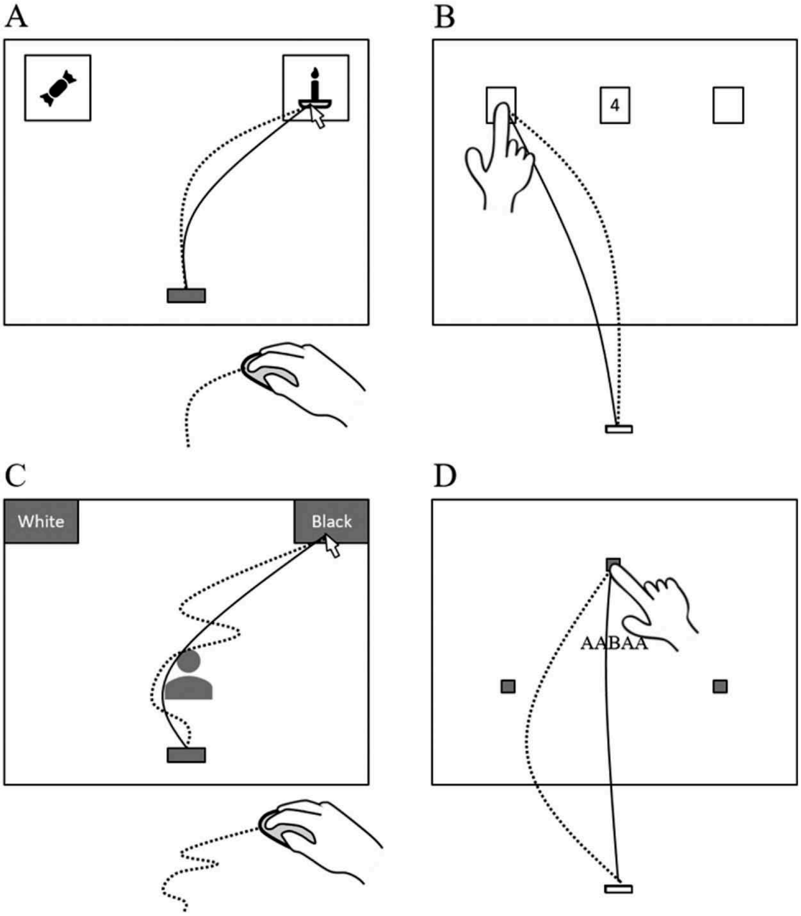

Figure 3. (A) Illustration of the task used by Spivey et al. (2005) to investigate language processing in adults. The dotted line illustrates a response on a trial featuring items that overlapped phonologically (e.g., "candy" and "candle"), and the solid line illustrates a response on a trial in which the items did not overlap phonologically (e.g., "jacket" and "candle"). (B) Illustration of the task used by Song and Nakayama (2008) to investigate the numerical distance effect in adults. The dotted line illustrates a response to the number "4," and the solid line illustrates a response to the number "1." (C) Illustration of the task used by Freeman et al. (2016) in which adult participants categorized faces that had been morphed along a continuum to appear more prototypically Black or White. The dotted line represents the abrupt changes in direction that were more likely to be observed in the movements of participants with less exposure to Black individuals in their daily lives, and the solid line illustrates the type of movements that were more characteristic of individuals with more exposure to Black individuals in their daily lives. (D) Illustration of a three-response version of the Eriksen flanker task used by Erb et al. (2016, Experiment 2). In the task, adult participants identified whether the centermost letter presented in a row of five letters was an "A," "B," or "K" by reaching to touch response targets at the bottom left, top center, or bottom right portions of a digital display, respectively. The dotted line illustrates a response to an incongruent trial ("AABAA"), and the solid line illustrates a response to a congruent trial ("BBBBB").

Manual dynamics have also been used to explore other aspects of numerical cognition in adults, including arithmetic operations (Marghetis et al., 2014), the temporal dynamics of fraction representations (Faulkenberry et al., 2015), and the processing of multidigit numbers (Dotan & Dehaene, 2013). Again, few studies have used hand tracking to investigate numerical cognition from a developmental perspective. However, a reach-tracking study by Erb, Moher, Song, and Sobel (2018) revealed that the numerical distance effect observed by Song and Nakayama (2008) is evident in children's movement trajectories by as early as 5 to 6 years of age, indicating that the spatial representation of numerical symbols are linked by as early as the preschool years. Given recent research exploring the links between gesture and mathematics during childhood (Gunderson, Spaepen, Gibson, Goldin-Meadow, & Levine, 2015; Novack, Congdon, Hemani-Lopez, & Goldin-Meadow, 2014), numerical cognition presents a particularly promising avenue for future developmental research to incorporate hand tracking.

Social perception

In social psychology, manual dynamics have played a central role in comparing traditional feed-forward models of social perception to the *dynamic interactive* model (Freeman & Ambady, 2011a). Feed-forward models emphasize how perceptual information is processed in a bottom-up manner, with perceptual cues (e.g., facial or vocal features) leading to the activation of higher-level social categories (e.g., Asian man) that subsequently activate related concepts (e.g., stereotypes) or evaluations (e.g., attitudes). The dynamic interactive model, on the other hand, emphasizes how bottom-up and top-down processes interact and unfold over time and allows for higher-level processes (e.g., stereotypes and attitudes) to shape how lower-level processes unfold. In support of the dynamic interactive model, Freeman and colleagues (Freeman & Ambady, 2009; Freeman, Ma, Han, & Ambady, 2013; Freeman, Pauker, & Sanchez, 2016) have conducted numerous mouse-tracking and reach-tracking studies with adults to explore how various bottom-up perceptual cues and top-down factors impact social categorization.

For example, in a recent mouse-tracking study, Freeman and colleagues (2016) presented White adults with pictures of male faces that were morphed along a 9-point continuum from more prototypically White to more prototypically Black. Participants categorized the faces as either White or Black by moving a mouse cursor to response targets at the top left and right of the screen. The researchers found that participants with less exposure to Black individuals in their daily lives exhibited more frequent shifts between the categories in their hand movements on trials featuring faces that were less prototypically White or Black (i.e., hand movements were more likely to abruptly change directions from one target to the other target multiple times during the course of a single trial; see Figure 3C). This finding suggests that participants with less exposure to Black individuals were bouncing back and forth between the categories on trials that featured a less prototypical face, rather than fluidly integrating the facial cues over time. Further, the frequency of abrupt category shifts observed in participants' hand movements was found to predict how trustworthy they rated mixed-race faces in a separate task, with more frequent category shifts predicting lower trust of mixed-race faces. It is important to note that the researchers would have been unable to examine these abrupt shifts in categorization had the spatial and temporal characteristics of hand movements not been recorded.

Similar studies with adults have used manual dynamics to investigate stereotype activation (Freeman & Ambady, 2009), contextual influences on face categorization (Freeman et al., 2013), and how visual and auditory cues are integrated in social perception (Freeman & Ambady, 2011b). However, little if any research has used hand-tracking techniques to investigate the development of social perception with similar tasks. Consequently, many avenues for developmental research remain underexplored. For example, hand tracking could be used to shed light on how children learn to identify and integrate cues to particular social categories and how the dynamics of social perception impact children's subsequent judgments and behaviors.

Cognitive control

In the cognitive control literature, hand-tracking techniques have been used to target how different processes underlying conflict detection and resolution unfold during the course of a response (e.g., Erb, Moher, Sobel, & Song, 2016; Erb, Moher, Song, & Sobel, 2017a, 2017b; Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010). Current models of cognitive control propose that the ability to resolve conflict between competing responses is supported by a number of dissociable processes that perform distinct functional roles. These processes include a *monitoring* process that registers conflict resulting from the coactivation of competing responses, a *threshold adjustment* process that temporarily puts the "brake" on behavior by inhibiting motor output when conflict is detected, and a *controlled selection* process that recruits top-down support to "steer" response activations in favor of the appropriate response (Shenhav, Botvinick, & Cohen, 2013).

In a recent reach-tracking study with adults, Erb et al. (2016) tested the proposal that two of the measures afforded by reach tracking—initiation time and movement curvature—can be used to target the functioning of the threshold adjustment process and the controlled selection process, respectively. Across multiple tasks that required participants to override a prepotent response with a more controlled alternative response, the researchers found evidence that initiation times reflected the threshold adjustment process by indexing how long the "brake" was put on behavior when conflict was detected at the outset of a trial, with higher levels of conflict resulting in greater inhibition of motor output and, consequently, longer initiation times. Their findings also indicated that movement curvatures reflected the controlled selection process by capturing the degree to which competing responses were coactive during the course of a response, with larger curvatures indicating that participants were more pulled toward the prepotent response before top-down support could "steer" response activation in favor of the appropriate response (see Figure 3D).

To evaluate how the threshold adjustment process and controlled selection process contribute to developmental differences in cognitive control, Erb and colleagues (2017b) presented 5- to 10-year-olds and adults with a reach-tracking version of the Eriksen flanker task. The results revealed different age-related gains in initiation times and movement curvatures, with only movement curvatures revealing significant improvements in cognitive control between older children (8- to 10-year-olds) and adults. This finding suggests that the age-related improvements in cognitive control observed after childhood are primarily driven by changes in the functioning of the controlled selection process. Again, it is important to note that traditional button-press measures of accuracy and response time would have been unable to target the different developmental trajectories observed in initiation times and movement curvatures. Other recent studies investigating the development of cognitive control with hand-tracking techniques include: (a) a reach-tracking study by Erb and colleagues (2017a) investigating rule switching in children aged 5 to 8 years old, and (b) a mouse-tracking study by Hermens (2018) evaluating how children aged 3 to 11 years old respond to different spatial cues in the presence of a distractor (e.g., a hand cueing a left response accompanied by a distracting arrow cueing a right response).

Addressing the methodological gap

Each of the studies reviewed in the preceding section provide evidence against the serial, feed-forward, and stage-based view of mental processing encouraged by the computer metaphor of mind. These studies instead support a more dynamic view of the mind in which processes across perception, cognition, and action often—though not necessarily always—unfold in a parallel, interactive, and continuous manner (Cisek & Kalaska, 2010; Lakoff & Johnson, 1999; Smith & Gasser, 2005; Spencer et al., 2009; Spivey, 2007). Taken together, these studies also demonstrate that manual dynamics present a more detailed view of mental processing than traditional button-press measures of performance.

There are a number of reasons that one might expect hand-tracking techniques to feature prominently in developmental research. For example, developmental theory has long emphasized the links among perception, cognition, and action (Piaget, 1952), and hand tracking is well suited to explore the nature of these links. Additionally, hand tracking is not new to developmental research. On the contrary, hand-tracking techniques have been used for decades to study topics related to the development of motor control (e.g., Clifton, Rochat, Robin, & Berthier, 1994; Gauthier, Vercher, Ivaldi, & Marchetti, 1988; Thelen et al., 1993). Yet, as the preceding section illustrated, hand tracking has not been widely adopted as a developmental research method. Why might this be?

One possibility is that researchers have been dissuaded from incorporating hand tracking into their work by certain barriers to adoption, including equipment costs and the use of specialized software. Although reach tracking does require specialized equipment, the cost to develop a reach-tracking system is not prohibitive relative to other techniques such as eye tracking. For example, a reach-tracking system similar to the one used in the numerical cognition study by Song and Nakayama (2008) can be assembled for less than US$10,000. Mouse tracking, on the other hand, does not require specialized equipment beyond a standard computer and mouse. Further, a software package is freely available online for researchers interested in using the technique (Freeman & Ambady, 2010). This software package greatly simplifies study design, data collection, and analysis, and it is compatible with most versions of the Windows operating system (for further information, see the Additional Hand-Tracking Resources section).

Researchers may also have concerns about how reliable and informative children's hand-tracking data are at different points in development. Although relatively few studies have been published using these techniques with children, the studies reviewed in the preceding section present preliminary evidence that mouse tracking and reach tracking are suitable for use with a wide range of ages (Cargill et al., 2007; Erb et al., 2018, 2017a, 2017b; Hermens, 2018). However, as these techniques become more common, it will be important for researchers to develop best practices regarding testing procedures, data interpretation, and the relative strengths and weaknesses of using each technique with children of different ages. The following paragraphs briefly address each of these topics and offer some preliminary suggestions concerning best practices.

Testing procedures

Children as young as 3 years of age can use a computer mouse to complete simple tasks (e.g., maneuvering a computer cursor to a target; Costigan, Light, & Newell, 2012; Donker & Reitsma, 2007; Hermens, 2018). However, substantial developmental and individual differences in proficiency with a computer mouse have been observed, particularly when more complex behaviors are required (e.g., clicking and dragging; Joiner, Messer, Light, & Littleton, 1998; Lane & Ziviani, 2010). Similarly, children's reaching proficiency continues to improve until as late as 12 years of age (Kuhtz-Buschbeck, Stolze, Jöhnk, Boczek-Funcke, & Illert, 1998; Schneiberg, Sveistrup, McFadyen, McKinley, & Levin, 2002). For example, Kuhtz-Buschbeck et al. (1998) found that children's reach trajectories became increasingly direct to targets when they were aged 4 to 12 years old, although other kinematic features such as movement duration and peak velocity did not show significant age-related changes during this period.

In light of these findings, those interested in conducting hand-tracking research with children should consider taking the following steps to measure and minimize developmental and individual differences in manual dexterity: (a) *Collect baseline trials*. Before the primary task, have participants complete movements to each of the response targets using a simplified task (e.g., "Touch the square when it appears."). In addition to familiarizing participants with the basic hand-tracking procedures (e.g., navigating to the starting location, moving to a target, returning to the starting location), baseline trials can be used to identify individuals whose manual dexterity falls outside of a predefined acceptable range. (b) *Simplify responding*. The demands placed on participants' dexterity can be minimized by avoiding the use of small response targets (e.g., targets smaller than 2.5 cm in diameter; Costigan et al., 2012) and, in the case of mouse-tracking studies, by avoiding procedures that require clicking or dragging behaviors (e.g., Hermens, 2018; Joiner et al., 1998). (c) *Be mindful of order and practice effects*. Participants may become more comfortable with executing manual responses during the course of a session. Consequently, it is important to counterbalance the order with which different tasks or conditions are presented and then evaluate the extent to which order or practice effects contributed to developmental or individual differences in performance.

Interpretational issues

Movement curvatures are often interpreted to reflect the degree to which competing responses were coactivated during the course of a movement. However, as Fischer and Hartmann (2014) noted, larger movement curvatures need not indicate that participants' movements were pulled more toward a competing response. For example, participants may initiate a movement toward the center of the display before deciding on a specific response. The longer it takes participants to decide on a response, the larger movement curvatures will be, even if the alternative response was never activated during the movement. Fischer and

Hartmann therefore proposed that movement trajectories should only be interpreted to reflect the activation of a competitor if the movement crosses into the portion of space (e.g., the side of the display) associated with the competitor.

As noted by Faulkenberry and Rey (2014), there are a number of reasons to suspect that Fischer and Hartmann's (2014) criterion for determining the coactivation of competing responses was too stringent. For example, Santens, Goossens, and Verguts (2011) observed a numerical distance effect in movement curvatures in a mouse-tracking study even when movement trajectories remained on the same side of the display. Regardless of whether a single criterion for assessing the coactivation of responses could be agreed on, Fischer and Hartmann's overarching concerns remain valid. Researchers interested in incorporating hand-tracking measures into their work should therefore exercise caution when interpreting the spatial characteristics of manual dynamics (for further discussion of this topic, see Faulkenberry & Rey, 2014).

Comparing hand-tracking techniques

Mouse tracking presents a number of strengths relative to reach tracking. As noted previously, mouse tracking does not require specialized equipment beyond a computer and mouse, and therefore, presents a low-cost and portable solution for researchers interested in gathering data outside the laboratory. However, children can vary greatly in terms of their familiarity with using a computer mouse (e.g., Lane & Ziviani, 2010). Additionally, mouse-tracking studies often place pressure on participants to initiate movements soon after if not before a stimulus is presented to ensure that decision processes are captured in movement parameters (e.g., Scherbaum et al., 2010). Consequently, mouse tracking may be less effective than reach tracking for targeting different patterns of effects in response initiation times and movement curvatures. Future research should therefore compare the relative merits of these techniques by having children of varying ages complete mouse- and reach-tracking versions of the same tasks.

Implications and conclusion

The incorporation of hand-tracking techniques into developmental research presents a number of important implications for the field of developmental psychology. On a practical level, manual dynamics present a more detailed view of behavior that can be used to explore new questions, test competing models, and shed light on the nature of developmental and individual differences. For example, many of the standardized assessments used with children are based on button-press measures of response time and accuracy (e.g., National Institutes of Health Toolbox: Cognition Battery; Zelazo et al., 2013). However, as the research on cognitive control discussed earlier has highlighted (Erb et al., 2016, 2017a, 2017b), these button-press measures offer relatively limited insight into how different processes underlying performance function. Hand-tracking techniques present untapped potential for studying developmental and individual differences in childhood and for identifying behavioral signatures of conditions such as attention-deficit/hyperactivity disorder or autism spectrum disorder (Anzulewicz, Sobota, & Delafield-Butt, 2016).

On a methodological level, reach tracking can be used to complement other developmental research methods such as eye tracking, electroencephalography, and functional near-infrared spectroscopy to explore how manual, oculomotor, and neural dynamics coordinate across different tasks and different points in development. Again, it is important to emphasize that the prospect of combining hand tracking with other developmental research methods is not without precedent; researchers have used measures of manual and oculomotor dynamics to study the development of hand–eye coordination since the 1980s (Gauthier et al., 1988). However, modern hand-tracking techniques present new opportunities for investigating the links among hand and eye movements with greater precision and across a broader range of tasks. For example, recent work with adults has combined reach tracking and eye tracking to investigate putative perception–action dissociations in visual illusions (Gamble & Song, 2017). Similarly, researchers have begun to develop techniques that combine reach tracking and eye tracking to study how infants coordinate hand and eye movements when reaching to three-dimensional objects in their environment (Corbetta, Guan, & Williams, 2012).

Finally, on a theoretical level, hand tracking presents new opportunities to link seemingly disparate developmental research programs. Despite the emphasis that developmental theory has placed on linking perception, cognition, and action, the field is not immune to disciplinary divisions (Rakison & Woodward, 2008). Hand tracking presents a space where models of low-level visual processing and motor control can meaningfully interface with models of stereotype activation and cognitive control. Although much work remains to be done to determine how manual dynamics can be best incorporated into the field of developmental psychology, the available research indicates that hand tracking is a promising—and currently underutilized—developmental research method.

Additional hand-tracking resources

MouseTracker

MouseTracker is a software package developed by Dr. Jon Freeman. The package is freely available for download at http://www.mousetracker.org. This website also provides a running list of published research that has utilized the software package, a sample data set for new users to explore, a help manual, and a MouseTracker support forum.

Reach-tracking technology

Multiple solutions are available for recording reaching behavior. Many of the reach-tracking studies reviewed in this article (e.g., Erb et al., 2016, 2017a, 2017b; Song & Nakayama, 2008) used an electromagnetic position and orientation recording system produced by Polhemus (http://www.polhemus.com). Polhemus produces a number of motion-tracking systems with different sampling rates, varying from 120 Hz to 240 Hz (measurements per second). These systems also allow for data to be collected from multiple sensors simultaneously, thereby enabling researchers to record more complex actions such as grasping. Northern Digital Incorporated (http://www.ndigital.com) also offers a range of motion capture systems, including the Optotrak Certus, which allows for wireless data collection.

Recommended reading

- Fischer and Hartmann (2014) highlight some of the challenges associated with using mouse tracking to investigate numerical cognition and offer a checklist for researchers preparing to conduct a mouse-tracking study.
- Freeman et al. (2011) present a general review of the hand-tracking literature, addressing topics such as language processing, social cognition, and learning.
- Freeman and Johnson (2016) offer a focused review of the hand-tracking literature on social perception and categorization.
- Gallivan and Chapman (2014) present a detailed but accessible discussion of how hand-tracking data are processed, analyzed, and interpreted. The authors also provide a brief discussion of the relations among mouse tracking, reach tracking, and eye tracking.
- Song (2017) reviews recent research exploring how action plans are modified during online movements.
- Song and Nakayama (2009) provide a general overview of the benefits of incorporating manual dynamics into psychological research, and review research from a range of topics, including attention, numerical cognition, and decision-making.
- Spivey (2007) explores how manual and oculomotor dynamics can be used to capture the dynamics of mental processing, and offers a detailed articulation of the continuous view of mental processing discussed throughout this article.

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