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Mouse Tracking Measures Reveal Cognitive Conflicts Better than Response Time and Accuracy Measures

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Abstract

Mouse-tracking is said to provide a real-time record of decision making in a conflict situation (Stillman, Shen, & Ferguson, 2018); yet precise benefit of this method is unknown. Using two versions of the attention network task (ANT-R) (Fan et al., 2009), we investigated the extent to which mouse movement measures capture cognitive conflicts created in flanker and Simon tasks. The movement measures collected in the augmented ANT-R (mouse movement condition) were responsive to both flanker and Simon incongruency but response time and accuracy measures in the regular ANT-R (key-press condition) were responsive primarily to flanker incongruency only. The mouse movement measures were also sensitive to interaction effects involving incongruency and gender, trial order and congruency sequence, while response time and accuracy in the regular ANT-R (key-press condition) were mostly insensitive to these interactions. These results suggest that mouse movement measures are more perceptive to cognitive conflicts.

Keywords: mouse-cursor movement; cognitive conflict; cognitive control; flanker and Simon effect

Introduction

One of the major goals of cognitive science is to elucidate the mental mechanism of cognitive operations (i.e., reverse engineering, Marr, 1981), and developing analytic tools that aide this endeavor has been a main preoccupation in cognitive science. Nearly all theoretical debates in the field involve the assessment and interpretation of behavioral data that these tools provide. Bayesian cognitive models, linear mixed effect models, model-based and model-free experimental designs and tasks are geared to help inference of perceptual, cognitive, and affective mechanisms that enable complex human behavior (Barr, Levy, Scheepers, & Tily, 2013; Daw, Gershman, Seymour, Dayan, & Dolan, 2011; Lee & Wagenmakers, 2014).

Ironically, these sophisticated theories and models are based on the age-old dependent measures—how fast and accurately the subject presses a computer key. Yet, it is unclear how reliable these measures are as analytic tools. The problem is that, until recently, cognitive science has had few other viable measures of human behavior.

Using two versions of the attention network task (ANT-R, Fan et al., 2009)—one that primarily measures response time and accuracy through a key press and the other that uses mouse tracking, we compared the extent to which these measures capture cognitive conflicts created in flanker and Simon tasks.

Detecting cognitive conflicts in motor behavior: Mouse-cursor tracking

The theoretical foundation of the mouse-cursor motion research originated from Michael Spivey's conceptualization of human cognitive processing (Spivey, 2007). Traditional theories suggest that cognitive functions such as reasoning, decision making, and problem solving result from symbol manipulations, and computational algorithms for perception, decision, and action are explained by procedures transforming one representational state to another (Marr, 1981). Spivey conceptualizes cognitive functions as a fluid process where probabilistically weighted perceptual-cognitive processing units interact continuously.

Instrumental in Spivey's continuous cognition theory is a series of experiments that measure goal-directed action and decision making (i.e., choice reaching). In a typical choice reaching task, two competing options are pitted against each other (2AFC) and participants are instructed to select one of the choices by clicking on a button by the computer mouse. Unlike a traditional 2AFC task where response time and accuracy are key dependent measures, a choice reaching task has the subject navigate the computer cursor to select a button. By analyzing the navigational path of the cursor from the initial starting position to the end position, researchers found that trajectory features such as AUC (area under the curve) and MAD (maximum absolute deviation) (the degree of deviations from the straight line connecting the starting position to the end position) reveal the subject's perceptual, cognitive, and social conflicts in the decision process (Maldonado, Dunbar, & Chemla, 2019).

The findings in support of this principle come from a broad range, including numerical judgment (Xiao & Yamauchi, 2015), categorization (Dale, Kehoe, & Spivey, 2007), inductive reasoning (Yamauchi, Kohn, & Yu, 2007), linguistic judgment (Spivey, Grosjean, & Knoblich, 2005), racial and gender judgment of morphed face pictures (Freeman & Ambady, 2009; Freeman, Pauker, Apfelbaum, & Ambady, 2009), attitudinal ambivalence toward certain topics (e.g., abortion) (Schneider et al., 2015; Wojnowicz, Ferguson, Dale, & Spivey, 2009), uncertainty in economic choices (Calluso, Committeri, Pezzulo, Lepora, & Tosoni, 2015), and among others (see for review, Freeman, 2018; Stillman et al., 2018; Yamauchi, Leontyev, & Wolfe, 2017). Studies have shown that mouse movement measures can capture semantic incongruency that is processed subliminally

(Xiao & Yamauchi, 2014, 2015, 2017); they even allow automated recognition of emotion, gender and feelings of computer users (Yamauchi & Xiao, 2018; Yamauchi & Bowman, 2014).

One critical question is exactly how well these "continuous" motor measures capture cognitive conflicts as compared to traditional response time and accuracy measures. Is there any advantage of assessing motor measures to study executive control? To address this question, we employed two versions of the attention network task (Fan et al., 2009) and compared the extent to which different dependent measures—traditional response time and accuracy measures and mouse-cursor movement measures—capture flanker and Simon effects.

Cognitive Conflicts in ANT-R

Because attention plays a pivotal role in a wide range of perceptual, cognitive and affective behavior (Posner & Rothbart, 2007), the attention network task provides an ideal testbed to investigate how well cognitive conflicts are reflected in different dependent measures.

The attention network theory (Petersen & Posner, 2012) posits that there are three separate but interactive functions of attention—alerting (being vigilant), orienting (selecting stimuli), and executive control (resolving conflict). A revised version of the attention network task (ANT-R, Fan et al., 2009) has been used widely to probe the interaction and integration of these attention functions, especially cognitive conflicts. The task combines the flanker task (Eriksen & Eriksen, 1974) and the Simon task (Simon & Berbaum, 1990) and creates different types of cognitive conflict (Figure 1). In a flanker task, conflicts are generated by surrounding arrows pointing opposite to the center (target) arrow. In a Simon task, conflicts are created by the stimulus location presented opposite to the center (target) arrow (Figure 1). In both cases, the task of the participant is to indicate the direction of the target (center) arrow.

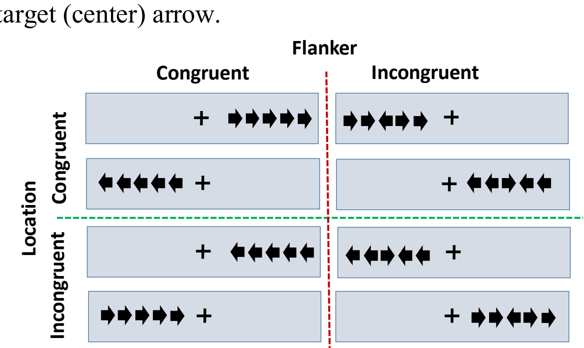

Figure 1: Illustration of flanker and Simon (location) tasks. Flanker congruent and flanker incongruent stimuli are shown in the two columns. Location congruent and location incongruent stimuli are shown in the four rows. The task is to identify the left-right direction of the target (center) arrow.

We devised two versions of the attention network task—traditional and augmented—and contrasted how well traditional response time and accuracy measures and mouse-cursor movement measures can capture the flanker and Simon effects. The traditional attention network task collects only response time and accuracy. Here the subject is to indicate their responses by pressing a designated computer key. The augmented version of the attention network task is identical to the traditional version, except that subjects indicate their response by clicking a button presented on the screen. For this, the subject has to navigate the mouse from the bottom of the screen and press the button. In the augmented version, the x-y coordinate location of the cursor is recorded every 15ms.

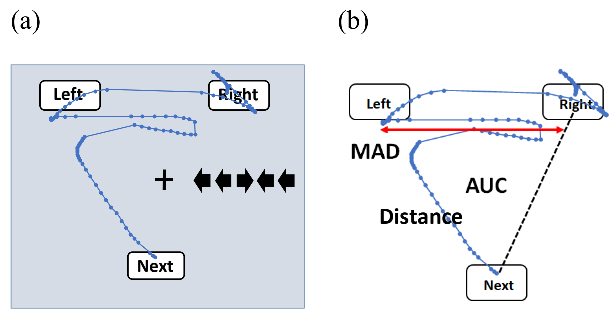

Figure 2: (a) An illustration of an augmented ANT-R trial in the mouse movement condition. To indicate the left/right direction of the target (center) arrow, the participant moves the cursor from the center of the Next button to the final posisiton. The trajectory of the cursor is shown for illustrative purpose and were invisible to participants. (b) AUC (area under curve) is the area enclosed by the trajectory and the straight line connecting the starting position and the end position. MAD (maximum absolute deviation) is the signed maximum absoluite deviation from the direct path. Distance is the sum of Euclidean displacements of the cursor at each sampling point (dots).

The critical question addressed here is how well these depend measures collected from the traditional and augmented ANT-R tasks can capture cognitive conflicts (Figure 1). Although researchers claim the advantage of mouse-cursor measures over traditional measures in extracting cognitive conflicts, this idea has never been explicitly tested. By contrasting the two types of the attention network task, the experiment described below investigate this question directly.

Experiment

The flanker and Simon effects are known to produce robust conflict effects (Eriksen & Eriksen, 1974; Stillman et al., 2018). Although the traditional ANT-R is well suited for the assessment of a flanker-type conflict, the task fails to capture a Simon effect (Fan et al., 2009). Indeed, the Simon effect is particularly difficult to replicate unless the stimulus allows explicit spatial coding (Hommel, 2011). With its emphasis on spatial coding (Figure 1), we predict that the augmented ANT-R are suitable for the assessment of both flanker and Simon effects.

What is unknown is the nature of the effects. Both flanker and Simon effects are subject to contextual factors, such as gender and sequential modulation. The flanker and Simon effects are generally larger in women than men (Stoet, 2017); they are also subject to the trial order. For example, flanker and Simon effects are smaller when two incongruent stimuli are shown in sequence (Egner, 2017). The question addressed here is how well these contextual impacts are reflected in the four dependent measures. If mouse-cursor movement measures are more sensitive than traditional response time and accuracy measures, these interaction effects should be well captured by the mouse-cursor movement measures as compared to the response time and accuracy measures collected in the key-press condition.

Method

Participants Participants (N=261) were undergraduate students who enrolled in an introductory psychology course. Participants participated in the experiment for course credit. These participants were randomly assigned to one of two between-subjects conditions—the key-press or mouse movement conditions (key-press = 135, female = 105 male = 30; mouse movement = 126, female = 92, male = 34).

Procedure We employed a revised version of the attention network task (ANT-R, Fan et al., 2009). The ANT-R task is a combination of an arrow flanker (Eriksen & Eriksen, 1974)(Eriksen & Eriksen 1974) and a Simon task (Simon & Berbaum, 1990). A stimulus consisted of five arrows—one center arrow sandwiched by four arrows (two arrows placed both sides). The task of the participant was to indicate the left-right direction of the center arrow (i.e., target arrow). Stimuli (five arrows) were shown either the left or right side of the monitor and the direction of the target arrow was either congruent or incongruent to side arrows (Figure 1).

The key-press and the mouse movement conditions were identical except for one critical point. In the key-press condition, participants indicated the left-right direction of the center arrow by pressing the left or right arrow keys on the keyboard. In the mouse movement conditions, participants used the mouse to indicate the left-right direction of the center arrow. In this condition, two buttons were placed on top left or top right corner of the screen and participants had to navigate the cursor to press the button. (Figure 2a).

ANT-R also incorporates different attention cues (rectangular boxes), which were shown before the presentation of the stimulus at (Figure 3). No cue, double cue, invalid cues, and valid cues were randomly assigned. Because no impacts of attention cues were observed in the present study, the procedure and results involving attention cues are not discussed further.

Altogether each participant received 144 trials, which were divided into eight possible combinations of flanker congruency (congruent, incongruent) and location congruency (congruent, incongruent) and target direction (left, right) (18 trials for each condition and see Figure 1). Eight stimuli in each combination were shown 18 times (8 x 18 = 144), comprising of 144 trials. The order of presenting individual stimuli was determined randomly.

The schedule of stimulus presentation is illustrated in Figure 3. A blank screen with a square is shown; 500ms after the subject clicks the Next button, a fixation sign appears and remains on the screen between 2000ms to 12000ms. The duration between the offset of the target and the onset of the next trial (the cue is shown) varied (approximating an exponential distribution, 2000 to 12,000ms, mean 4000ms). A cue is shown for 100ms. Another fixation is shown for 0, 400, or 800ms (uniform random). A target figure is shown for 500ms. At the onset of the target frame, the cursor is placed at the center of the next button in the mouse movement condition.

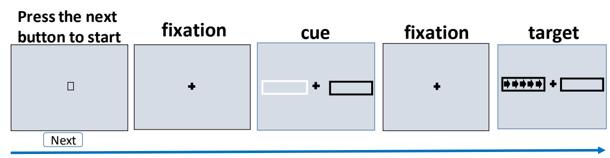

Figure 3: A trial sequence of an ANT-R trial. As the subject press the Next button, a fixation sign appears, followed by a cue, and another fixation sign. Soon after a target frame flashed for 500ms.

Prior to the experiment, all participants received a minimum of 24 practice trials. In the practice trial, corrective feedback was provided after each trial. Practice trials ended when the accuracy was 90% or above in the last 24 trials or a maximum of 48 trials. In 24 practice trials, all possible combinations of flanker congruency, location congruency, and target directions. No cue, double cue, invalid cues, and valid cues were randomly assigned.

Design The experiment had a 2(flanker; congruent, incongruent) x 2(location; congruent, incongruent) x 2 (block order; early, late) x 2 (gender; male, female) design. The key-press and the mouse movement conditions were analyzed separately. Dependent measures in the key-press condition were response time and accuracy (error rate). Dependent measures in the mouse movement condition were AUC, MAD and distance. To analyze the impact of trial sequence, we introduced another factor, congruency sequence (cog_seq; congruent, incongruent), which indicate a congruent or incongruent condition of the stimulus given right before the current stimulus.

To compare the efficacy of the dependent measures, we applied linier mixed-effects models (LMEMs), which are particularly suited to detect population-level systematic effects of manipulations while controlling random variations stemming from individual participants and stimuli. Following the suggestion by Barr et al. (2013), we applied a maximal random-effects structure that was allowed by the experimental design with four fixed factors with two levels; flanker (congruent, incongruent), location (congruent, incongruent), trial order (early, late), and gender (female, male) and two-way interactions among the factors combined with subject-specific random intercepts and item-specific random intercepts. The first three factors, flanker, location, and trial order are within-subjects variables and gender is a between-subjects variable.

Trials that took longer than and equal to 5000 milliseconds and trials shorter than and equal to 100ms were removed from our data analysis. Outliers were removed using the median-based procedure suggested by Wilcox (p. 77, Wilcox, 2003) (9% of the trials were removed in the key-press condition and 7% of the trials were removed in the mouse movement condition). To ensure that each dependent variable was approximately normally distributed in a similar degree, we transformed each dependent variable with ordered quantile transformation using R package bestNormalize. For all LMEM analyses, we used R packages lme4 and afex, and all dependent variables were rescaled to -1 to 1 (mean = 0). All trajectories were time-normalized using linear interpolation method (101 constant time steps, and see Spivey et al., 2005). We used R package mousetrap (Kieslich & Henninger, 2017) for time normalization and feature extraction (AUC, MAD, and distance).

Result

We first report the results from LMEM analysis followed by a direct comparison of effect sizes. Summaries of these results are shown in Table 1 and Figures 4-6. Following this analysis, we report the impact of congruency sequence.

Table 1: *p*-values from LMEM ANOVA

	RT	Accuracy	AUC	MAD	Dist.
flanker	****	****	****	****	****
location	(**)		****	****	****
flanker x location	(****)	+		+	****
flanker x blkOrder	*		****	***	**
location x blkOrder			+	**	****
flanker x gender			+	*	
location x gender			*	*	

Note. $^{+}p < .10$. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$. $^{****}p < .0001$. Dist. = Distance. (*) opposite direction (congruent > incongruent)

Response time. The response time measure in the key-press condition was quite robust in capturing the flanker effect; $F(1, 172.9) = 662.4$, $p<0.0001$. However, this measure was ineffective for the Simon (location) effect. Although we found a significant main effect of location, the direction of the effect was opposite—participants took longer for location-congruent stimuli than location-incongruent stimuli; $F(1, 172.5) = 7.6$, $p<0.01$. A similar significant "opposite" Simon effect was reported in the Fan et al. (2009) study. The flanker-location interaction effect was significant; $F(1, 132.41) = 17.7$, $p<0.001$.

In general, response time was not very effective in capturing interaction effects. Except for the flanker by block order interaction ($F(1, 17474.4)= 4.2$, $p<0.05$), no other

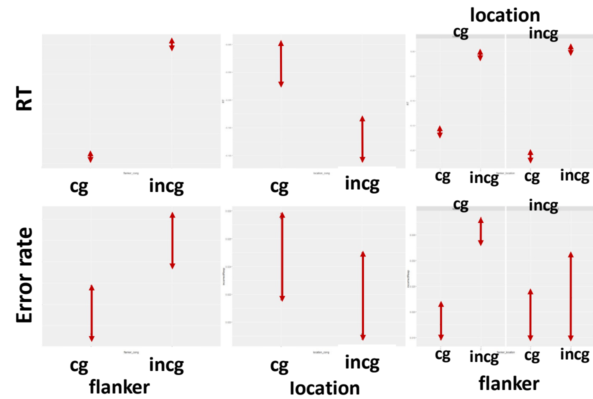

Figure 4: Mean response time (RT) and error rate (accuracy) with flanker (cg=congruent, incg=incongruent, left), location (center), and flanker by location (right) interactions. The arrows represent 95% CI.

interaction effects were significant; location x block order, $F(1, 17473.6)=1.5$, $p=0.22$; flanker x gender, $F<1.0$; location x gender, $F<1.0$ (Figure 4).

Accuracy (error rate) Accuracy (error-rate) was effective in capturing the flanker effect, but not the location (Simon) effect; flanker, $F(1, 133) = 43.0$, $p<0.0001$; location, $F(1, 133) = 1.4$, $p=0.24$; flanker x location, $F(1, 133) = 2.9$, $p=0.09$. No other interaction effects were observed in accuracy; flanker x block order, $F(1, 133) = 1.0$, $p=0.32$; location x block order, $F(1, 133) = 2.0$, $p=0.16$; flanker x gender, $F<1.0$; location x gender, $F<1.0$ (Figure 4).

AUC (Area under curve). AUC was effective in capturing both the flanker and location (Simon) effects very well. This measure was also sensitive to interaction effects involving gender and block order; flanker, $F(1, 198.9) = 371.9$, $p<0.0001$; location, $F(1, 199.2) = 898.8$, $p<0.0001$; flanker x location, $F<1.0$; flanker x block order, $F(1, 16714.4) = 16.0$, $p<0.0001$; location x block order, $F(1, 16709.2) = 2.9$, $p= 0.09$, flanker x gender, $F(1, 16567.9)=3.2$, $p=0.07$; location x gender, $F(1, 16570.9) = 6.3$, $p<0.05$.

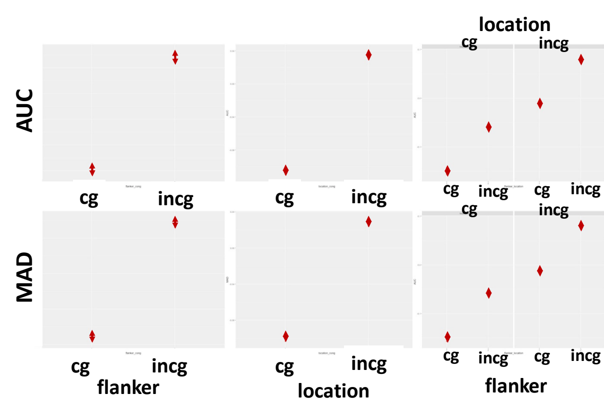

Figure 5: Mean AUC and MAD with flanker (cg=congruent, incg=incongruent, left), location (center), and flanker by location (right) interactions. The arrows represent 95% CIs.

MAD (Maximum Absolute Deviation). MAD was sensitive to flanker and location (Simon) effects, as well as interactions between these terms and block orders; flanker, $F(1, 209.9) = 518.9$, $p<0.0001$; location, $F(1, 210.0)=885.5$, $p<0.0001$; flanker x location, $F(1, 209.8) = 3.3$, $p=0.07$; flanker x block order, $F(1, 17226.3)=12.1$, $p<0.0005$; location x block order, $F(1, 17218.3) = 6.8$, $p<0.01$; flanker x gender, $F(1, 17074.7) = 4.0$, $p=0.05$; location x gender, $F(1, 17075.8) = 4.3$, $p<0.05$.

Distance. Distance responded well to flanker and location effects; flanker, $F(1, 215.3)=214.2$, $p<0.0001$; location, $F(1, 215.3)=109.1$, $p<0.0001$; flanker x location, $F(1, 214.5) = 17.6$, $p<0.0001$. This measure was also sensitive to interactions between these terms and block order; flanker x block order, $F(1, 15822.2) = 9.5$, $p<0.002$; location x block order, $F(1, 15818.9) = 22.7$, $p<0.0001$, but not gender; flanker x gender, $F(1, 15698.3) = 1.2$, $p=0.28$; location x gender, $F<1.0$.

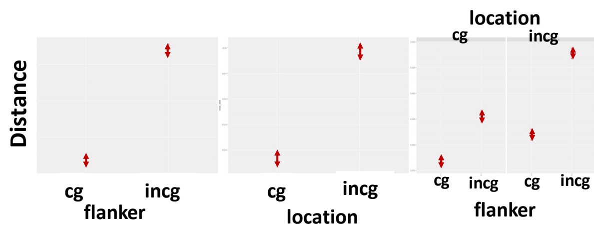

Figure 6: Distance with flanker (cg=congruent, incg=incongruent, left), location (center), and flanker by location (right) interactions. The arrows represent 95% CI.

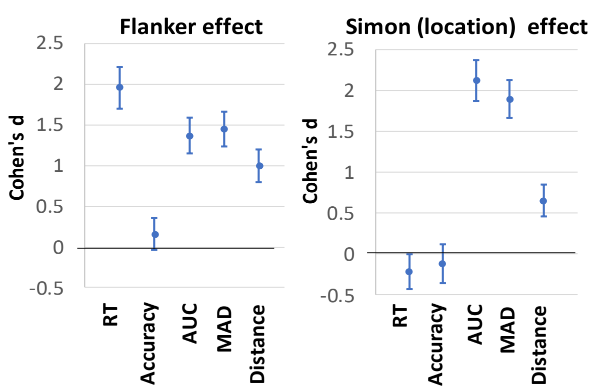

Figure 7: Effect sizes (95% CIs) of flanker (left) and Simon (location) effects. Following Cumming (p. 290, 2012), effect sizes and their CIs for congruent and incongruent conditions were calculated as independent groups.

Effect sizes We compared effect sizes of the flanker and location (Simon) effects captured by the five dependent measures (Figure 7). We observed a large effect size of the flanker effect in the response time measure, as compared to AUC, MAD, and distance; for all comparisons Z's> 2.9, p's<0.001. However, both response time and accuracy measures were ineffective for the location (Simon) effect. In contrast, the effect sizes obtained in the mouse-cursor movement measures were considerably above chance level (Figure 7).

Congruency sequence effects Another important characteristic of cognitive conflict is congruency sequence effects. Flanker and Simon effects are generally smaller when two incongruent stimuli are shown in sequence (Egner, 2017). We examined sequence effects with another factor, congruency sequence (cog_seq; congruent, incongruent), which informs whether preceding stimuli were congruent or incongruent (e.g., flanker (cog, incog) x seq(cog, incog)). This analysis shows that congruency sequence effects were well captured by AUC, MAD, and distance, but not response time and accuracy (Table 2); flanker x seq, RT and accuracy, F's<1.0; AUC, MAD, distance, F's>37.0, p's<0.0001; location x seq, RT and accuracy, F's<1.0; AUC, MAD, F's<1.0; distance, $F(1, 162.4)=4.2$, $p<0.05$ (Table 2).

Table 2: *p*-values for congruency sequence effects

	RT	Acc.	AUC	MAD	Dist.
flanker x seq			****	****	****
location x seq					*

Note. $^{+}p < .10$. $^{*}p < .05$. $^{**}p < .01$. $^{***}p < .001$. $^{****}p < .0001$. Dist.=Distance, seq=congruency sequence, RT=response time, Acc.=accuracy (error rate)

Discussion

The cursor movement measures, AUC, MAD, and distance, collected in the mouse-movement condition were responsive to incongruency created in flanker and Simon (location) tasks but response time and accuracy measures in the key-press condition were primarily responsive to flanker incongruency but not location (Simon) incongruency. The mouse movement measures were also sensitive to interaction effects involving incongruency and gender, trial order and congruency sequence, while response time and accuracy in the key-press condition were mostly insensitive to these interactions. These results suggest that the mouse movement measures, as compared to traditional response time and accuracy measures, are more perceptive to flanker and Simon (location) effects.

Researchers have advocated that mouse tracking measures are advantageous for the examination of cognitive conflicts (Freeman, 2018; Stillman et al., 2018). Our results provide empirical support for this idea: the mouse movement measures are statistically more sensitive to various aspects of cognitive conflicts than traditional response time and accuracy measures.

Our results are also consistent with recent findings that performance-based behavior tests for cognitive control (e.g., go/No-go task and stop signal task) can be improved with augmentation of mouse movement measures. Although go/No-go and stop signal tests have been applied widely for the assessment of mental disorders (e.g., ADHD), these tests are ineffective in assessing sub-clinical populations (Toplak, West, & Stanovich, 2013). By augmenting regular go/No-go or stop signal tasks with mouse movement measures, Leontyev et al. (Leontyev, Sun, Wolfe, & Yamauchi, 2018) demonstrated that these cognitive tests become more reliable in separating individuals with weak and strong symptoms of ADHD-related impulsivity.

Given that the mouse motion measures allow more nuanced examination of cognitive conflict, mouse-tracking measure helps further our theoretical understanding of cognitive control. For example, determinants, boundary conditions, and neural correlates of the congruency sequence effect have been developed, revised and evaluated primarily on the basis of how well the theory accounts for response time and accuracy performance (Egner, 2007). Our results show that different dependent measures can produce different outcomes. In this vein, the validity of these theories (e.g., bottom-up associative theory and top-down control-based theory) can be reexamined with mouse-tracking measures.

Conclusion

For decades, scientific analysis of human behavior has been made mainly on the basis of how fast and accurately an individual responds to a task. Response time and accuracy has served as the primal dependent measures and formidable theories have been developed from these two measurements. The results from this study show that these traditional measures can be supplemented with motor measures, and the mouse-cursor motion analysis provides a viable analytic tool to probe cognitive conflict.

References

Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001

Calluso, C., Committeri, G., Pezzulo, G., Lepora, N., & Tosoni, A. (2015). Analysis of hand kinematics reveals inter-individual differences in intertemporal decision dynamics. *Experimental Brain Research*, *233*(12 LB-Calluso2015), 3597–3611. https://doi.org/10.1007/s00221-015-4427-1

Dale, R., Kehoe, C., & Spivey, M. (2007). Graded motor responses in the time course of categorizing atypical exemplars. *Memory & Cognition*, *35*(1), 15–28.

Daw, N. D., Gershman, S. J., Seymour, B., Dayan, P., & Dolan, R. J. (2011). Model-based influences on humans' choices and striatal prediction errors. *Neuron*, *69*(6), 1204–1215.

Egner, T. (2007). Congruency sequence effects. *Cognitive, Affective & Behavioral Neuroscience*, *7*(4), 380–390. https://doi.org/10.3758/CABN.7.4.380

Egner, T. (2017). Past, Present, and Future of the Congruency Sequence Effect as an Index of Cognitive Control. *The Wiley Handbook of Cognitive Control*, 64.

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149.

Fan, J., Gu, X., Guise, K. G., Liu, X., Fossella, J., Wang, H., & Posner, M. I. (2009). Testing the behavioral interaction and integration of attentional networks. *Brain and Cognition*, *70*(2), 209–220. https://doi.org/10.1016/j.bandc.2009.02.002

Freeman, J B, & Ambady, N. (2009). Motions of the hand expose the partial and parallel activation of stereotypes. *Psychological Science*, *20*(10 LB-mouse movement), 1183–1188.

Freeman, J B, Pauker, K., Apfelbaum, E. P., & Ambady, N. L. B. move. (2009). Continuous dynamics in the real-time perception of race. *Journal of Experimental Social Psychology*, *46*, 179–185.

Freeman, Jonathan B. (2018). Doing psychological science by hand. *Current Directions in Psychological Science*.

Hommel, B. (2011). The Simon effect as tool and heuristic. *Acta Psychologica*, *136*(2), 189–202. https://doi.org/10.1016/j.actpsy.2010.04.011

Kieslich, P. J., & Henninger, F. (2017). Mousetrap: An integrated, open-source mouse-tracking package. *Behavior Research Methods*, *49*(5), 1652–1667.

Lee, M. D., & Wagenmakers, E.-J. (2014). *Bayesian cognitive modeling: A practical course*. Cambridge university press.

Leontyev, A., Sun, S., Wolfe, M., & Yamauchi, T. (2018). Augmented Go/No-Go Task: Mouse Cursor Motion Measures Improve ADHD Symptom Assessment in Healthy College Students. *Frontiers in Psychology*, *9*, 496.

Maldonado, M., Dunbar, E., & Chemla, E. (2019). Mouse tracking as a window into decision making. *Behavior Research Methods*. https://doi.org/10.3758/s13428-018-01194-x

Marr, D. (1981). *Vision*. New York: Freeman.

Petersen, S. E., & Posner, M. I. (2012). The Attention System of the Human Brain: 20 Years After. *Annual Review of Neuroscience*, *35*(1), 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Posner, M. I., & Rothbart, M. K. (2007). Research on Attention Networks as a Model for the Integration of Psychological Science. *Annual Review of Psychology*, *58*(1), 1–23. https://doi.org/10.1146/annurev.psych.58.110405.085516

Schneider, I. K., van Harreveld, F., Rotteveel, M., Topolinski, S., van der Pligt, J., Schwarz, N., & Koole, S. L. (2015). The path of ambivalence: tracing the pull of opposing evaluations using mouse trajectories. *Frontiers in Psychology*, *6*, 1–12.

Simon, J. R., & Berbaum, K. (1990). Effect of conflicting cues on information processing: the 'Stroop effect'vs. the 'Simon effect.' *Acta Psychologica*, *73*(2), 159–170.

Spivey, M. J. (2007). *The Continuity of Mind*. Oxford: Oxford University Press.

Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous attraction toward phonological competitors. *Proceedings of National Academy of Sciences of the United States of America*, *102*(29), 10393–10398.

Stillman, P. E., Shen, X., & Ferguson, M. J. (2018). How mouse-tracking can advance social cognitive theory. *Trends in Cognitive Sciences*.

Toplak, M. E., West, R. F., & Stanovich, K. E. (2013). Practitioner review: Do performance-based measures and ratings of executive function assess the same construct? *Journal of Child Psychology and Psychiatry*, *54*(2), 131–143.

Wilcox, R. R. (2003). *Applying contemporary statistical techniques*. Elsevier.

Wojnowicz, M. T., Ferguson, M. J., Dale, R., & Spivey, M. J. (2009). The self-organization of explicit attitudes. *Psychological Science*, *20*(11), 1428–1435.

Xiao, K., & Yamauchi, T. (2014). Semantic priming revealed by mouse movement trajectories. *Consciousness and Cognition*, *27*(1). https://doi.org/10.1016/j.concog.2014.04.004

Xiao, K., & Yamauchi, T. (2015). Subliminal semantic priming in near absence of attention: A cursor motion study. *Consciousness and Cognition*, *38*. https://doi.org/10.1016/j.concog.2015.09.013

Xiao, K., & Yamauchi, T. (2017). The role of attention in subliminal semantic processing: A mouse tracking study. *PLoS ONE*, *12*(6). https://doi.org/10.1371/journal.pone.0178740

Yamauchi, T., Kohn, N., & Yu, N.-Y. (2007). Tracking mouse movement in feature inference: Category labels are different from feature labels. *Memory and Cognition*, *35*(5). https://doi.org/10.3758/BF03193460

Yamauchi, T., & Xiao, K. (2018). Reading Emotion From Mouse Cursor Motions: Affective Computing Approach. *Cognitive Science*, *42*(3). https://doi.org/10.1111/cogs.12557

Yamauchi, T, & Bowman, C. (2014). Mining cursor motions to find the gender, experience and feelings of computer users. *IEEE International Conference on Data Mining (ICDM 2014): Workshop on Domain Driven Data Mining*, 221–230. https://doi.org/10.1109/ICDMW.2014.131

Yamauchi, Takashi, Leontyev, A., & Wolfe, M. (2017). Choice reaching trajectory analysis as essential behavioral measures for psychological science. *Insights in Psychology*, *1*(4), 1.