Running head: Dynamic influences on decisions

How Decisions Evolve: The Temporal Dynamics of Action Selection

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Abstract

To study the process of decision-making under conflict, researchers typically analyze response latency and accuracy. However, these tools provide little evidence regarding how the resolution of conflict unfolds over time. Here, we analyzed the trajectories of mouse movements while participants performed a continuous version of a spatial conflict task (the Simon task). We applied a novel combination of multiple regression analysis and distribution analysis to determine how conflict on the present trial and carry-over from the previous trial affect responding. Response on the previous trial and the degree of conflict on the previous and the current trial all influenced performance, but they did so differently: The previous response influenced the early part of the mouse trajectory, but the degree of previous and current conflict influenced later parts. This suggests that in this task experiencing conflict may not proactively ready the system to handle conflict on the next trial; rather, when conflict is experienced on the subsequent trial the previous compensatory processing may be re-activated more efficiently.

Introduction

In everyday life, we frequently have to decide between competing action tendencies. Like attractors in a dynamic system, alternative choice options drag the mind into one direction at one moment and another direction at the next moment. When deciders contemplate between alternatives, we assume that they are in conflict. How such conflicts between different action tendencies are resolved by the brain has been studied extensively in the laboratory with tasks inducing response conflicts (cf. Botvinick, 2007) such as the Simon task. In this task, participants have to respond with a left or right key press, for example, to the direction of an arrow pointing to the left or to the right. Since the arrow is presented to the left or to the right of a central fixation point, the irrelevant stimulus location is assumed to automatically activate the spatially corresponding response. This leads to congruent trials (no conflict) when the location of the arrow (e.g., left) corresponds to the direction of the arrow (e.g., left) and to incongruent trials (response conflict) when the location of the arrow (e.g., left) does activate a different response than required by the direction of the arrow (e.g., right). The response conflict is reflected in behavioral indicators such as increased response times (RT) or error rates on incongruent relative to congruent trials (e.g. Simon, 1969), indicating that conflicting information between stimulus identity and stimulus location prolonged decision-making and response selection processes.

While the degree of conflict in the current trial is one influence on the processes determining the final decision in a Simon task, cognitive psychologists have also highlighted the role of other influences such as response and stimulus repetitions (e.g. Wühr & Ansorge, 2005) or previous experience of response conflict as additional factors that determine response selection processes in the current trial (e.g. Egner, 2007; Stürmer, Leuthold, Soetens, Schröter, & Sommer, 2002). Especially the latter one, conflict in the previous trial, has been shown to reduce

the influence of conflicting information in the current trial, an effect that has been termed conflict adaptation (e.g. Egner, 2007).

Although the study of manifold influences on response selection yielded major insights into the process of making the final decision under conflict (Proctor & Vu, 2006), the most common outcome measures such as mean RT or accuracy bear some fundamental limitations, as they provide only indirect access to the temporal dynamics of information-processing (Scherbaum, Dshemuchadse, & Kalis, 2008; Spivey, 2006) by manipulating the task itself (cf. Notebaert & Verguts, 2007).

Whereas previous attempts to uncover the temporal dynamics of response decisions primarily used EEG measures, e.g. the lateralized readiness potential (e.g. Stürmer et al., 2002), and EMG measures (e.g. Burle, Possamaï, Vidal, Bonnet, & Hasbroucq, 2002; Coles, Gratton, Bashore, Eriksen, & Donchin, 1985), more recently, attempts were made to use continuously recorded mouse (McKinstry, Dale, & Spivey, 2008; Spivey, Grosjean, & Knoblich, 2005) or hand movement trajectories (Song & Nakayama, 2008, 2006) to obtain behavioral indicators of the underlying process dynamics. These studies aimed at providing general evidence for the continuous nature of cognitive processing (as opposed to stage-like processing), and indicated that investigating cognitive processing continuously could indeed be a worthwhile extension of the behavioral measures RT and accuracy (Song & Nakayama, 2009; Spivey, 2006).

While movement trajectories have been used before in the Simon task (Buetti & Kerzel, 2008, 2009), we aim to exploit the potential of this behavioral approach by providing detailed analyses of the time course and dynamic interactions of concurrent influences that have been found to determine the ongoing decision. These are, on the one hand, inherent properties of the current trial$_N$ (i.e. stimulus location and stimulus direction), and, on the other hand, typical

influences of the previous trial$_{N-1}$ (i.e. previous response and previous trial congruency). For this, we report two experiments in which we combined for the first time, the tracing of mouse trajectories in a continuous version of the Simon task with a multiple regression (Notebaert & Verguts, 2007) and distribution analytic approach (De Jong, Liang, & Lauber, 1994) to dissect the temporal dynamics of those four competing influences determining the selection of the required response in the Simon task.

Experiment 1

The first experiment aimed at dissecting the different influences and their temporal interactions on the decision process. First, we expected the current irrelevant stimulus location to show a strongly diverging influence on the trajectory of the decision (Spivey et al., 2005). It has been shown indirectly by RT studies, that this influence should show a constant decay in timing, independent of the overall length of each trial (De Jong et al., 1994; Ridderinkhof, 2002). Second, we expected congruency in the previous trial to interact with the influence of the current interfering location, indicating conflict adaptation (Egner, 2007). Third, we expected the direction of the current stimulus to exert its influence at the end of the trial, dragging the trajectory toward the correct response (e.g. Song & Nakayama, 2006). Additional to these basic hypotheses, the first experiment aimed at exploring the potential of the method to dissect and explore the dynamics of the different influences.

Methods

Participants

20 students (17 female, mean age = 21) of the Technische Universität Dresden took part in the experiment. All participants had normal or corrected to normal vision. They gave informed consent to the study and received class credit or 5 € payment.

Apparatus and Stimuli

Target stimuli (left- and right-pointing arrows) were presented in white on a black background on a 17 inch screen running at a resolution of 1280 x 1024 pixels (75 Hz refresh frequency). They had a width of 8.56° and an eccentricity (center of stimulus to center of screen) of 18.61° at 60 cm distance. Response boxes (11.55° in width) were presented at the top left and top right of the Screen. As presentation software, we used Psychophysics Toolbox 3 (Brainard, 1997; Pelli, 1997) in Matlab 2006b (the Mathworks Inc.), running on a Windows XP SP2 personal computer. Responses were carried out by moving a standard computer mouse (Logitech Wheel Mouse USB). Mouse trajectories were sampled with a frequency of 92 Hz and recorded from stimulus presentation until response in each trial.

Procedure

Participants were asked to respond to the direction of a presented arrow by moving the mouse into the respective response box. Each trial consisted of three stages. In the first stage, participants had to click at a red box (11.55° in width) at the bottom of the screen within a deadline of 1.5 seconds. This served to produce a comparable starting area for each trial. After clicking within this box, the second stage started and two response boxes at the right and left upper corner of the screen were presented. Participants were required to start the mouse movement upwards within a deadline of 1.5 seconds. We chose this procedure forcing participants to be already moving when entering the decision process to assure that they did not decide first and then only executed the final movement. Hence, only after moving at least 4 pixels in each of 2 consecutive time steps the third stage started with the appearance of the target stimulus. The trial ended after moving the cursor into one of the response boxes within a deadline of 2 seconds (see Figure 1). If subjects missed the deadline of one of the three stages,

the next trial started with the presentation of the red start box. Response times (RT) were measured as the duration of the third stage, reflecting the interval between the onset of the target stimulus and reaching the response box with the mouse cursor.

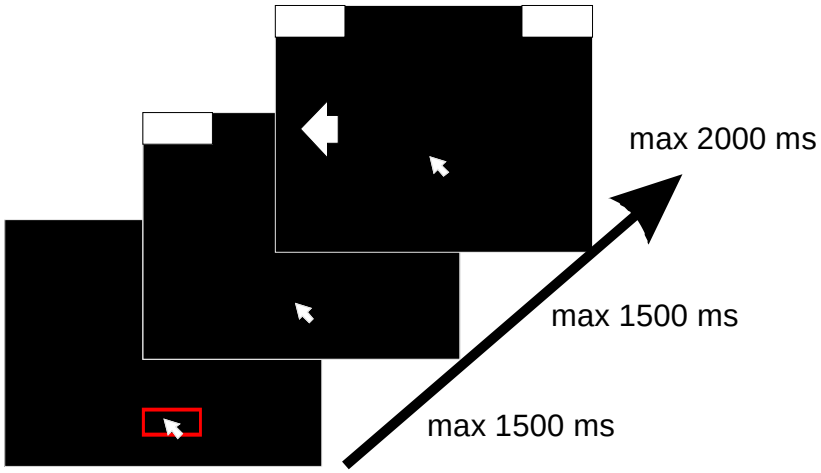

Figure 1. Setup of the experiment: Participants had to click with the mouse cursor into a red box at the bottom of the screen. After clicking, response boxes appeared at the upper edge of the screen and participants had to move the cursor upwards, in order to start the trial. After reaching a movement threshold, the imperative stimulus, a white arrow, appeared and participants had to move the mouse cursor to the left or the right response box according to the arrow direction.

After onscreen instructions and demonstration by the experimenter, participants practiced 40 trials (10 trials with feedback and no deadline for any stage of a trial, 10 trials with feedback and deadline and 20 trials without feedback and with deadline).

The experiment consisted of 2 blocks and 320 trials per block. We varied the following independent variables: for the current trial, $direction_N$ (left/ right) and $location_N$ (left/ right), and

for the previous trial, $direction_{N-1}$ (left/ right) and $location_{N-1}$ (left/ right). This resulted in four combinations for the current trial and four combinations for the previous trial. The sequence of trials was balanced within each block by pseudo randomization resulting in a balanced $Trial_N$ (4) x $Trial_{N-1}$ (4) x trial repetition (20) transition matrix. This way, we obtained a balanced sequence of trials with systematically manipulated congruency of direction/ location within the current trial ($congruency_N$), congruency of direction/ location within the previous trial ($congruency_{N-1}$), and sequences of designated responses.

Data Preprocessing

We excluded erroneous trials and trials following an error (4.2 %). Trials not fitting the RT outlier criterion (>4 *SD*) were also excluded (0.9 %). Mouse trajectories were aligned for common starting position (horizontal middle position of the screen, 640 pixels). Each trials trajectory was normalized to 100 equal time slices (Spivey et al., 2005).

Results

RT data: A repeated measures analysis of variance (ANOVA) revealed main effects for $congruency_N$ (73 ms, $F(1,19) = 183.8$, $p < .001$), $congruency_{N-1}$ (4 ms, $F(1,19) = 5.4$, $p < .05$), as well as an interaction of both ($F(1,19) = 107.624$, $p < .001$). As expected, RT was slower for incongruent trials (Simon effect) and this effect was modulated by previous trial congruency (see Figure 2A).

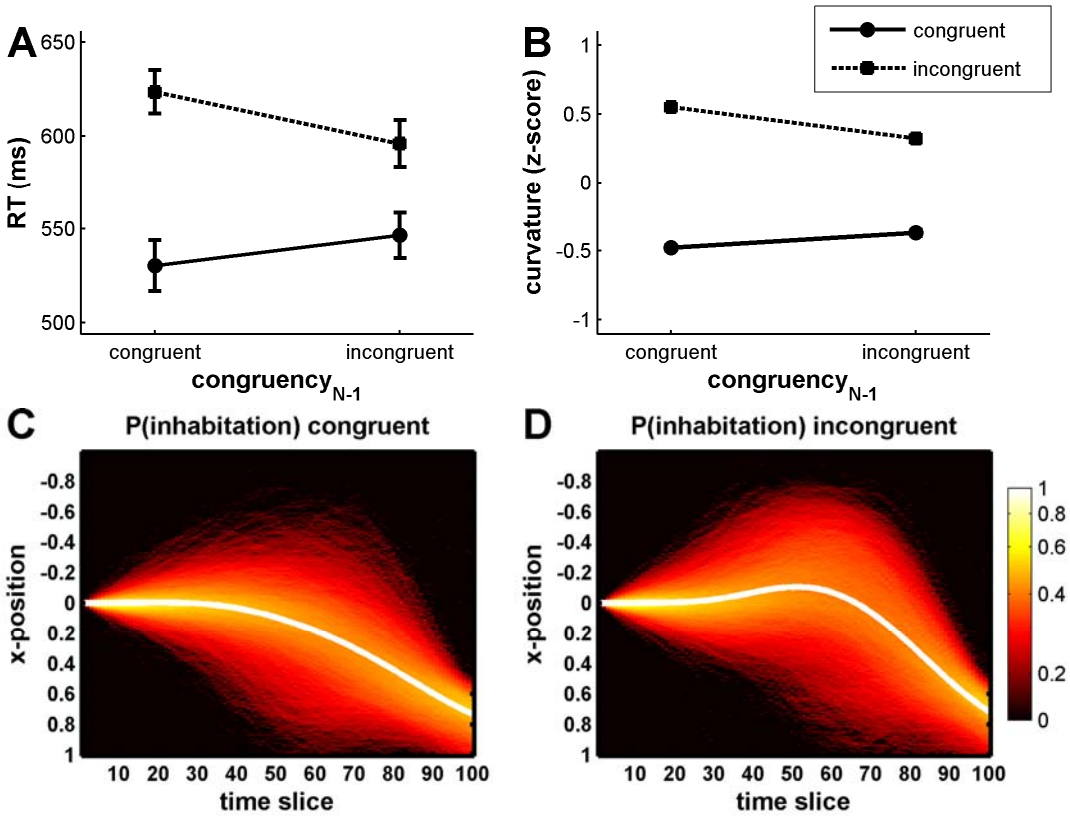

Figure 2. Summary of RT and mouse data. A: RT as a function of current and previous trial congruency. B: z-transformed curvature (area under the curve) of trajectories as a function of current and previous trial congruency. Error bars in A and B represent standard errors of the mean. C and D: Heat maps showing log transformed probability distribution for each trial's trajectory to pass through (inhabit) bins of normalized [-1,1] x-coordinates. Right side response trials were mirrored to be shown together with left side response trials. Trials were pooled for all participants for congruent (C) and incongruent (D) condition.

Mouse trajectories: According to previous mouse studies (e.g. Spivey et al., 2005) we calculated as a rough measure the degree of curvature for each trial's trajectory. Curvature is defined as the area between each trajectory and a straight line from the start point to the end

point of this trajectory. An ANOVA ($congruency_N$ x $congruency_{N-1}$), revealed significant effects for $congruency_N$ ($F(1,19) = 280.38$, $p < .001$), $congruency_{N-1}$ ($F(1,19) = 14.51$, $p < .01$), and a significant interaction of both ($F(1,19) = 51.48$, $p < .001$), mirroring the effects of the RT analysis. Incongruent trials show greater curvature, being dragged toward the wrong response box first. As expected, this effect is modulated by previous trial congruency (see Figure 2B).

For further analyses, we focused on the trajectory angle on the XY plane. Trajectory angle was calculated as the angle relative to the y-axis for each difference vector between two time steps (see Figure 3 C and D). This measure has two advantages over the raw trajectory data. First, it better reflects the instantaneous tendency of the mouse movement since it is based on a differential measure compared to the cumulative effects in raw trajectory data. Second, it integrates the movement on the x/y plane into a single measure.

Since it was our aim to dissect the influences of the independent variables on mouse movements within a trial we applied a four step procedure to the trajectory angle in the following. In the first step, we distinguished trials of different duration using a method analogous to the one used by De Jong et al. (1994): we created two bins of trials by a split at the median RT for each subject (bin 1, fast trials: M(RT) = 501 ms; bin 2, slow trials: M(RT) = 652 ms). In the second step, we coded for each participant four predictors for all trials: $direction_N$ (left/ right), $location_N$ (left/ right), $response_{N-1}$ (left/ right), and $congruency_{N-1}$. $Response_{N-1}$ reflects the previous (correct) response and hence the $direction_{N-1}$ of the stimulus in the previous trial. $Congruency_{N-1}$ reflects the expected influence of the $direction_{N-1}$ /$location_{N-1}$ congruency in the previous trial on the strength of the potentially conflict inducing $location_N$ influence of the current trial. Hence, it was coded as an interaction term $congruency_{N-1}$ x $location_N$, predicting how strong the mouse trajectory is deflected into the direction of the current stimulus location in

dependence of previously induced conflict. To provide comparable beta weights in the next step, we coded the predictors with values of -1 and 1. In the third step, we calculated multiple regressions with these predictors (100 time slices → 100 multiple regressions) on the trajectory angle, that had also been standardized for each participant from -1 to 1 to provide comparable results. This yielded four time-varying beta weights (4 weights x 100 time slices) for each participant. Finally, in the fourth step, we computed grand averages of these four time-varying beta weights yielding a time-varying strength of influence curve for each predictor (see Figure 3 A and B).

Strength of peaks of the four influences were extracted and tested statistically with one sample t-tests of the peak beta weight against zero. For differences between bins in the timing of peaks, we used paired t-tests of time slices. For all t-tests, we used a jackknifing procedure as has been used previously, e.g. for peak detection in lateralized readiness potentials (LRP) (Miller, Patterson, & Ulrich, 2001)[1].

The influence of the $direction_N$ predictor peaked at slice 80 (M(time) = 402 ms, M(beta) = 0.52, SE(beta) = 0.01, $t(19) = 45.65$, $p < .001$) for the first bin, and at slice 85 (M(time) = 555 ms, M(beta) = 0.45, SE(beta) = 0.01, $t(19) = 37.14$, $p < .001$) for the second bin, showing no significant shift for time slices between bins ($t(19) = 0.47$, $p = .35$).

The $location_N$ predictor peaked at slice 48 (M(time) = 244 ms, M(beta) = 0.2, SE(beta) = 0.02, $t(19) = 12.38$, $p < .001$) for the first bin, slice 37 (M(time) = 257 ms, M(beta) = 0.2, SE(beta) = 0.01, $t(19) = 15.84$, $p < .001$) for the second bin. The peak shifted significantly to earlier time slices for slower trials ($t(19) = 2.23$, $p < .05$), but stayed constant in absolute timing, indicating a stimulus-locked nature of this influence.

The $response_{N-1}$ predictor peaked at slice 1 (*M*(time) = 11 ms, *M*(beta) = 0.03, *SE*(beta) = 0.01, $t(19) = 2.282$, $p < .05$) in the first bin, and at slice 2 (*M*(time) = 17 ms, *M*(beta) = 0.03, *SE*(beta) = 0.01, $t(19) = 2.47$, $p < .05$) in the second bin. It showed no significant change of time slices between bins ($t(19) = 0.3$, $p = .37$).

Finally, the $congruency_{N-1}$ predictor, representing the interaction of $congruency_{N-1}$ x $location_N$, peaked at slice 51 (*M*(time) = 259 ms, *M*(beta) = 0.03, *SE*(beta) = 0, $t(19) = 9.62$, $p < .001$) for the first bin and at slice 54 (*M*(time) = 354 ms, *M*(beta) = 0.05, *SE*(beta) = 0.01, $t(19) = 6.85$, $p < .001$) for the second bin. It showed no change in slice timing ($t(19) = 0.53$, $p = .34$), indicating a surprising independence in timing to the influence of $location_N$.

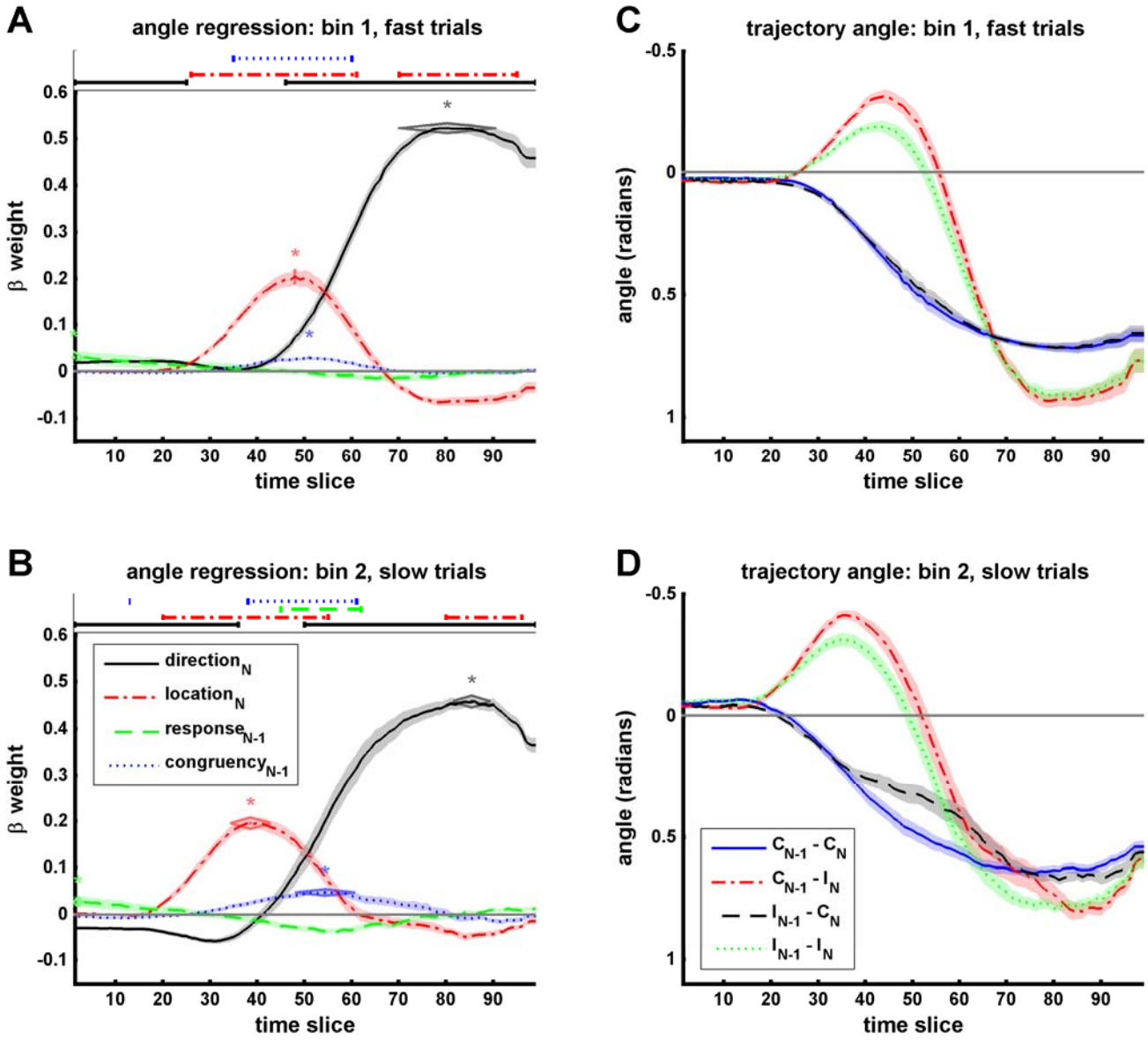

Figure 3. A and B: Regressor weights over time, dissecting the mouse trajectory angle on the XY plane, for fast (A) and slow (B) trials. Diamonds indicate jackknife corrected standard errors (see Footnote 1) for beta weights (vertical size) and time slices (horizontal size), gray areas around the curves indicate the standard error of beta weights for each time slice. Segment lines in the upper part show significant time slices for each beta weight (t-tests against zero,

bonferoni corrected alpha level = 0.0005). C and D: Mouse trajectory angles on the XY plane over time slices for fast (C) and slow (D) trials, split up by current trial congruency and previous trial congruency. C_N and I_N denote congruency in the current trial, C_{N-1} and I_{N-1} denote congruency in the previous trial. Right side response trials were mirrored to be shown together with left side response trials. Shaded areas represent the standard error for each time slice.

Discussion

By dissecting mouse trajectories with multiple regression analyses over bins of median split RT, we were able to confirm our basic hypotheses and acquired further information about the time-course and temporal interaction of four distinctive influences on the decision process in the Simon task, namely task-relevant information ($direction_N$), task-irrelevant and potentially conflicting information ($location_N$), the previous response ($response_{N-1}$), and conflict in the previous trial ($congruency_{N-1}$).

At the beginning of a trial, when the imperative stimulus had not yet been processed, the previous response ($response_{N-1}$) slightly influenced the trajectory, indicating a perseverative movement tendency. Though small and not surrounded by a large segment of significant time slices, this effect is nevertheless remarkable given that participants had to return the mouse to the starting box. In slow trials, this influence even showed negative segments, indicating compensatory movements in the later stage of the trial. The first stimulus-induced effects are caused by the influence of the task-irrelevant stimulus location ($location_N$). As expected, the timing of this influence was independent of the overall duration of each trial, indicating the expected stimulus-locked nature (De Jong et al., 1994). Again, this influence showed late negative significant segments, indicating a compensatory rebound effect. The influence of

location$_N$ seems to interact with *congruency*$_{N-1}$, reflecting a modulatory influence of conflict in the previous trial on conflicting information as expected following accounts of conflict adaptation (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Egner, 2007; Mansouri, Tanaka, & Buckley, 2009) . This modulation showed two surprising effects. First, it set in later than the effect of *location*$_N$ itself. Second, it seemed to remain constant over bins in normalized time indicating a process that might, on the hand, be dependent on the onset of the imperative stimulus, and, on the other hand, be related to the overall time of each trial. This suggests that the modulation of the influence of the location$_N$ by previous conflict might not reflect an advance suppression of the irrelevant location information (as would be predicted by proactive gating or suppression accounts, e.g. Botvinick et al., 2001; Stürmer et al., 2002). Rather, it possibly reflects a reactive mechanism by which inhibition of distracting information is triggered online, e.g. by conflict in the current trial (J. W. Brown, Reynolds, & Braver, 2007; Goschke & Dreisbach, 2008). Hence, this mechanism could not inhibit irrelevant information prior to the occurrence of conflict, but could start enhanced inhibition after being triggered by the occurrence of conflict. We will discuss this in depth in the general discussion. Finally, the *direction*$_N$ seemed to be effective primarily in later phases of the trial, reflecting execution of the correct response. In addition, however, *direction*$_N$ revealed also slight effects in earlier segments of a trial. In particular, for fast trials this influence was in a positive range whereas for slow trials it was in a negative range. This could indicate a striking explanation for the overall variance in trial duration: slow trials are wrong guesses, with subjects moving into the wrong direction at the start of the trial, while fast trials are right guesses.

Summarizing this experiment, we were able to provide evidence that this continuous Simon task produces results similar to the effects in the standard version of the task. The effect

of high conflict on incongruent trials showed up both in increased RTs and a more pronounced curvature of mouse trajectories towards the incorrect response. Moreover, evidence for a conflict-adaptation effect was obtained in both measures as indicated by a reduced RT cost and smaller curvature towards the incorrect response box on incongruent trials preceded by incongruent trials. Importantly, reproducing basic effects as obtained in previous RT, EMG and LRP studies (Burle et al., 2002; Stürmer et al., 2002) indicates, that we maintained the nature of the task, lending further credibility to the analyses of the time course of the different sub-processes. On top of that, the dissection of the different influences and their temporal interaction allowed us to discover surprising effects for the timing of conflict adaptation, arguing for a reactive account, and for the difference between fast and slow trials, arguing for effects of blind guessing.

Experiment 2

While we were able to replicate standard findings and dissected the influences of different trial properties on processing at specific time windows, the procedure in experiment 1 leaves room for further improvement. First, with respect to the influence of conflict in the previous trial, it has been argued that such sequential modulations need not reflect effects of previous trial congruency on enhanced recruitment of cognitive control (so called gating, suppression or conflict adaptation accounts), but may rather reflect episodic priming and/or binding effects due to stimulus feature repetitions and binding processes (Hommel, Proctor, & Vu, 2004; Mayr, Awh, & Laurey, 2003). To avoid, or at least reduce the confound of previous trial congruency and feature repetitions, in experiment 2, we combined the Simon task with a number judgment task (Fischer, Dreisbach, & Goschke, 2008; Song & Nakayama, 2008).

Increasing the stimulus set to more than two response-relevant stimulus features allowed us to exclude identical stimulus repetitions. If the effect of previous trial conflict is due to conflict-adaptation rather than stimulus repetitions, the modulation of conflict by previous conflict (predictor $congruency_{N-1}$) should remain reliable even after sorting out these critical stimulus repetition trials (Fischer et al., 2008; Ullsperger, Bylsma, & Botvinick, 2005)[2]. This would also support our interpretation of the temporal delay of conflict-adaptation.

Secondly, we aimed at replicating the results of experiment 1. Especially the novel results of the $congruency_{N-1}$ predictor, the peak effects of the $response_{N-1}$ influence, and the differences at the beginning between fast and slow trials for the $direction_N$ ask for a replication that confirm their reliability and validate the new research approach.

Methods

Participants

20 new students (17 female, mean age = 21.1) of the Technische Universität Dresden participated in the experiment. All participants had normal or corrected to normal vision. They gave informed consent to the study and received class credit or 5€ payment.

Apparatus and Stimuli

Target stimuli (numbers 1-4 and 6-9) were presented in white on a black background. They had a width of 6.44° and an eccentricity (center of stimulus to center of screen) of 20.10°. No other changes were included.

Procedure

The procedure was identical to experiment 1, except that participants were instructed to move the cursor into the upper left response box for digits smaller than 5 and to the upper right

response box for digits larger than 5. The experiment consisted of 3 blocks and 256 trials per block.

Data Preprocessing

To exclude the possibility that the conflict modulation across trials was due to episodic priming, we excluded all trials with identical stimulus repetitions (6.4 %). We also excluded erroneous trials, trials following an error (8.8 %), and trials not fitting the RT outlier criterion (>4 *SD*, 0.3 %). Mouse trajectories were lined up for common starting position, normalized, and right side response trials were mirrored, similar to experiment 1.

Results

RT data: An ANOVA yielded the expected effects of $congruency_N$ (42 ms, $F(1,19) = 45.24$, $p < .001$), $congruency_{N-1}$ (3 ms, $F(1,19) = 11.33$, $p < .01$) and a significant interaction ($F(1,19) = 45.51$, $p < .001$), replicating the effects of experiment 1. Hence, the modulation of the Simon effect was present, despite the removal of repetition trials (Figure 4A).

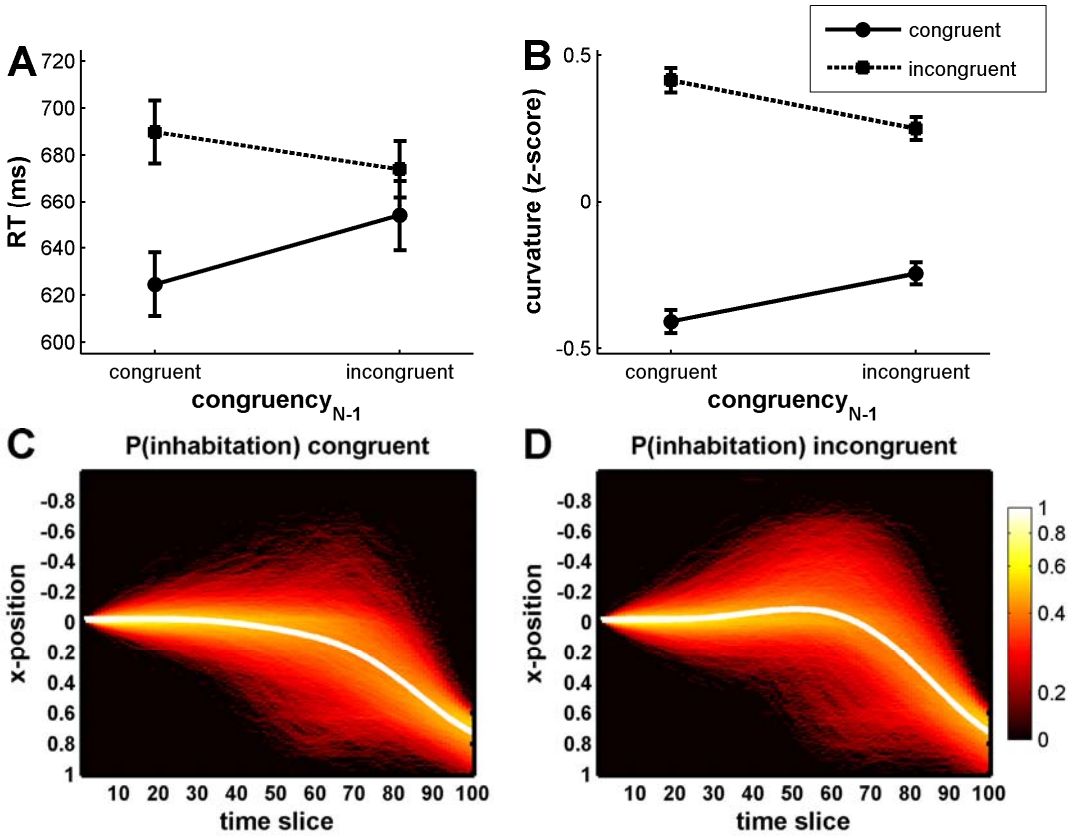

Figure 4. Summary of RT and mouse data. A: RT as a function of current and previous trial congruency. B: z-transformed curvature (area under the curve) of trajectories as a function of current and previous trial congruency. Error bars in A and B represent standard errors of the mean. C and D: Heat maps showing log transformed probability distribution for each trial's trajectory to pass through bins of normalized x-coordinates . Right side response trials were mirrored to be shown together with left side response trials. Trials were pooled for all participants for congruent (C) and incongruent (D) condition.

Mouse trajectories: An ANOVA on curvature revealed significant effects for *congruency*$_N$ ($F(1,19) = 56.69$, $p < .001$) and a significant interaction of *congruency*$_N$ x

congruency$_{N-1}$ ($F(1,19) = 94.02$, $p < .001$). Comparable to RT, the deflection of incongruent trials was modulated by previous incongruency (Figure 4B).

Similar to experiment 1, we created two bins of trials by a split at the median RT for each subject (bin 1, fast trials: *M*(RT) = 578 ms; bin 2, slow trials: *M*(RT) = 744 ms). We then calculated the time varying beta weights as in Experiment 1, separately for each RT bin, coding the predictors *direction*$_N$, *location*$_N$, *response*$_{N-1}$, *congruency*$_{N-1}$ (Figure 5). Again, all predictors and trajectory angles were standardized to range from -1 to 1. Statistical testing was performed as described for experiment 1.

The peak of influence of the *direction*$_N$ predictor was found at slice 81 (*M*(time) = 469 ms, *M*(beta) = 0.5, *SE*(beta) = 0.01, $t(19) = 38.81$, $p < .001$) for the first bin, and at slice 85 (*M*(time) = 633 ms, *M*(beta) = 0.48, *SE*(beta) = 0.01, $t(19) = 32.22$, $p < .001$) for the second bin. It showed no significant shift in time slices between the two bins ($t(19) = 0.83$, $p = .28$),

The *location*$_N$ predictor peaked at slice 46 (*M*(time) = 269 ms, *M*(beta) = 0.15, *SE*(beta) = 0.02, $t(19) = 7.59$, $p < .001$) for the first bin, slice 37 (*M*(time) = 277 ms, *M*(beta) = 0.14, *SE*(beta) = 0.02, $t(19) = 7.1$, $p < .001$) for the second bin. The peak shifted to earlier time slices for slower trials ($t(19) = 9$, $p < .001$), but stayed constant in absolute timing, again indicating a stimulus-locked nature of this influence.

For the *response*$_{N-1}$ predictor, the peak was found at slice 3 (*M*(time) = 22 ms, *M*(beta) = 0.04, *SE*(beta) = 0.01, $t(19) = 4.54$, $p < .001$) in the first bin, and at slice 2 (*M*(time) = 18 ms, *M*(beta) = 0.03, *SE*(beta) = 0.01, $t(19) = 3.49$, $p < .01$) in the second bin. The peak showed no significant change of time slices ($t(19) = 1$, $p = .24$).

Finally, the c*ongruency*$_{N-1}$ predictor, peaked at slice 57 (*M*(time) = 332 ms, *M*(beta) = 0.03, *SE*(beta) = 0, $t(19) = 7.17$, $p < .001$) for the first bin and at slice 54 (*M*(time) = 403 ms,

M(beta) = 0.04, *SE*(beta) = 0.01, *t*(19) = 7.25, *p* < .001) for the second bin. It showed no change in slice timing (*t*(19) = 0.32, *p* = .37).

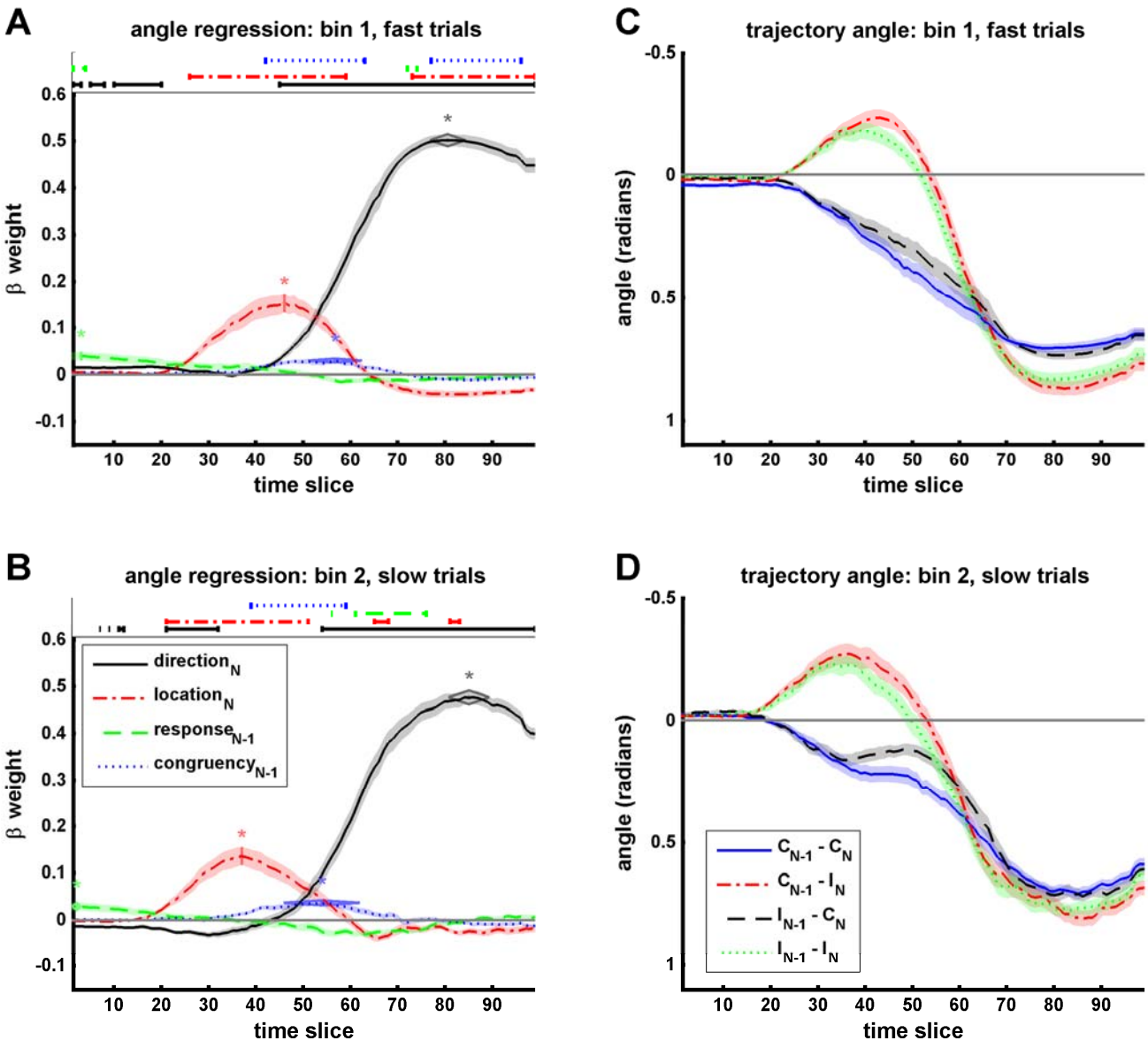

Figure 5. A and B: Regressor weights over time, dissecting the mouse trajectory angle on the XY plane, for fast (A) and slow (B) trials. Diamonds indicate jackknife corrected standard errors (see footnote 1) for beta weights and time slices, gray areas around the curves indicate the

standard error of beta weights for each time slice. Segment lines in the upper parts show significant time slices for each beta weight (t-tests against zero, bonferoni corrected alpha level = 0.0005). C and D: Mouse trajectory angles on the XY plane over time slices for fast (C) and slow (D) trials, split up by current trial congruency and previous trial congruence. C_N and I_N denote congruency in the current trial, C_{N-1} and I_{N-1} denote congruency in the previous trial. Right side response trials were mirrored to be shown together with left side response trials. Shaded areas represent the standard error for each time slice.

Discussion

Overall, the results of experiment 2 replicated the results of experiment 1 by showing similar effects for the used predictors. Hence across different settings, our method provided reliable results. Furthermore, despite the removal of complete repetition trials that could have been critical for the modulatory influence of the predictor $congruency_{N-1}$. If the effects, attributed to conflict adaptation had been caused by stimulus repetition effects only, they should have vanished by this manipulation. Hence, the replicated finding of the modulatory influence of $congruency_{N-1}$, its replicated shift in time from fast to slow trials, and its shifted peak compared to the influence of $location_N$ could reflect reactive conflict adaptation.

General Discussion

The present study investigated the dynamics of information-processing underlying response selection in an ambiguous decision situation. To study how the resolution of conflict unfolds over time, we used a continuous version of the Simon task (Simon, 1969) and discriminated four influences on the process of conflict resolution within a trial: stimulus location and stimulus direction in the present trial, and carry-over of the response and response

conflict in the previous trial. For these influences, we obtained information about their temporal order and interaction.

The first effective influence was the response of the previous trial, biasing participants to move into the direction of the previous response. Since participants had to move the mouse back to a common starting position before every trial, this effect is quite remarkable. Strategic influences could be ruled out due to the randomization of trials, such that the last response did not allow predicting the forthcoming response. Two explanations are conceivable. On the one hand, this effect could reflect dynamic embodied perseverative tendencies that can be observed across trials in classical reaching paradigms (Thelen, Schöner, Scheier, & Smith, 2001). From this view, residual activation of movement fields might control the motor system as long as there is no stronger competing input from the imperative stimulus. Another possible interpretation could be based on episodic retrieval (Hommel, Müsseler, Aschersleben, & Prinz, 2002; Hommel et al., 2004): having only the empty screen showing the response boxes as retrieval cue, participants automatically retrieve and initiate the motor program from the most recent similar episode, i.e. the previous trial.

The second effective influence was the irrelevant location of the current stimulus. On incongruent trials, this information conflicted with the task-relevant stimulus direction and induced a clear deflection of the mouse trajectory away from the correct target. Consistent with previous RT based studies (De Jong et al., 1994; Hommel, 1994; Simon, Acosta, Mewaldt, & Speidel, 1976), this influence showed stimulus-locked timing, independent of total trial duration. In accordance with these previous studies, this explains the finding of a reduced Simon effect in RT indicating less conflict in slow trials: The onset of the execution of the final response occurs later than the (already decayed) stimulus-locked influence of stimulus location. Lacking the

temporal overlap between decayed location information and onset of the response execution, the influence of stimulus location is reduced in RT but is still preserved and thus, detectable in the dissected mouse trajectories. Hence, this finding demonstrates the validity of our approach.

The third effective influence, previous trial congruency, revealed an unexpected and remarkable finding about its temporal interaction with the irrelevant stimulus location in the current trial: its activation set in *after* the peak of the influence of stimulus location. This finding stands in contrast to gating or suppression accounts (e.g. Botvinick et al., 2001; Stürmer et al., 2002), predicting that effects of so called conflict adaptation set in at *the same time* as the influence of stimulus location becomes effective, since enhanced cognitive control should have been recruited after a conflict trial and before the start of the next trial (Botvinick et al., 2001; Verguts & Notebaert, 2008). This finding indicates that conflict adaptation found here reflects a reactive mechanism to occurring conflict (J. W. Brown et al., 2007; Goschke & Dreisbach, 2008): Instead of preparing the system to ignore irrelevant information before the start of the trial, adaptation sets in after being triggered by reoccurring conflict. Even more surprising, its peak of influence shifted in time, occurring sooner in fast trials and later in slow trials. Hence, the window in which conflict adaptation exerted its strongest effect was dependent on the overall length of a trial, in contrast to the purely stimulus-locked peak of the irrelevant location information. Taken together, this indicates that, though conflict adaptation found here may be triggered by reoccurring conflict, it then leads to more efficient conflict resolution, facilitating the final generation of the response.

The fourth effective influence, direction of stimulus, mainly reflected the final execution of the correct response. Additionally to this main influence, it also revealed a surprising pattern of activation earlier in the trial. Timed in parallel to the effect of the previous response, our

method extracted a difference between fast trials, starting in a positive range, and slow trials, starting in a negative range. Since the categorization of fast and slow trials was performed post-hoc, this suggests that slow trials are trials where participants simply guessed wrong before completely perceiving the stimulus, while in fast trials, they guessed right. Hence, this unexpected pattern could partly explain further variance in RT data.

While the finding of deflected trajectories in conflict trials is in line with previous studies that investigated within-trial processes, either in the Simon task (Buetti & Kerzel, 2009, 2008; Burle et al., 2002) or other tasks (Song & Nakayama, 2009; Spivey et al., 2005), the novel combination of multiple regression analysis and distribution analysis to continuous mouse trajectories enabled us to reveal new time-varying patterns of separate influences on response decisions. An inherent shortcoming of this method is the use of known predictors for the regression analysis, that is, we were only able to analyze the time course of influences known in advance, because they are inherent to the Simon task. In this respect, combining continuous behavioral measures with methods of blind source separation such as independent component analysis (Makeig, Bell, Jung, & Sejnowski, 1996; McKeown et al., 1998) may further our insight into decision processes by extracting possible influences without prior knowledge. Moreover, from future experiments using continuous measures we expect important insights into the causal interplay between the here investigated and possible additional sub-processes influencing the decision process, for instance, with respect to the properties of different kinds of conflict (Egner, 2007) or the influence of specific strategies (cf. Hommel, 1994) on conflict-resolution and response decisions. These would be further steps to a continuous dynamic investigation of decision making under conflict (Scherbaum et al., 2008; Spivey, 2006).

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Footnotes

[1]Jackknifing represents one of several possible resampling methods: for each dataset d in a group of n datasets, the jackknife produces a new mean dataset consisting of all datasets in the group, except dataset d. Hence, for dataset 1, the method creates a mean dataset averaging across the data in datasets (2, 3, …, n). For dataset 2, it creates a mean dataset averaging across the data in datasets (1, 3,4,…,n). While this reduces the noise occurring in time-series data, e.g. LRP data, it also reduces the degrees of freedom. Hence, for statistical testing, test parameters have to be adjusted (for further details, see Miller et al., 2001).

[2] Controlling for response repetition would be a further step to exclude priming-like effects as an explanation for the found effects of sequential modulation. As a first step, we performed an ANOVA on RT including response repetition as a third factor. However, the factor did not interact significantly with the other two factors $congruency_N$ and $congruency_{N-1}$.