ABSTRACT

Response trajectories reveal conflict phase in image—word mismatch

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Abstract In the present study, response trajectories were used in a picture–word conflict task to determine the timing of intermediate processing stages that are relatively inaccessible to response time measures. A marker was placed above or below the word ABOVE or BELOW so that its location was congruent or in conflict with the word's meaning. To report either word location (above or below the marker) or word meaning, participants moved a mouse upward toward the appropriate top left or right answer corner on the display screen. Their response trajectories showed a number of distinctive features: First, at about 200 ms after stimulus onset (the "decision moment"), the trajectory abruptly began to arc toward the appropriate answer corner; second, when the word's meaning and position were in conflict, the trajectory showed an interruption that continued until the conflict was resolved. By varying the SOA of the word and marker onsets, we found that the word meaning and word position became available at approximately 325 ms and 251 ms, respectively, after their onsets, and that the delay to resolve conflicts was about 138 ms. The timing of these response trajectory events was more stable than any extracted from the final response times, demonstrating the power of response trajectories to reveal processing stages that are only poorly resolved, if at all, by response time measures.

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Spatial prepositions (words such as *above*, *below*, and *inside*) have been studied extensively in sentence–picture verification studies (Carpenter & Just, 1975; Chase & Clark, 1971, 1972) in which the task was to report whether the spatial preposition accurately described a picture. All of these studies used reaction time measures. In the present study, we investigated response trajectories to gain insight into the time course for the processing of spatial prepositions that is not available in reaction time measures (Brenner & Smeets, 2004; Schmidt & Schmidt, 2009; Song & Nakayama, 2009). In several recent studies, researchers have analyzed the trajectory of a participant's response when selecting the answer with the touch of a finger (Boulenger et al., 2006; Finkbeiner, Song, Nakayama, & Caramazza, 2008; Schmidt & Seydell, 2008; Song & Nakayama, 2008a, 2008b), a saccade (Smit & Gisbergen, 1990) or a computer mouse (Freeman & Ambady, 2009; Spivey, Grosjean & Knoblich, 2005). The response choices are presented at different locations in space so that an in-flight deviation toward the competing, incorrect answer can be revealed.

We studied a processing conflict involving spatial prepositions in which a marker was placed above or below the word ABOVE or BELOW, and in which the participant reported the location of the marker relative to the word, ignoring the meaning of the latter. A very similar task was originally studied by Palef and Olson (1975), who found no significant difference between the reaction times in the congruent and incongruent conditions. Logan and Zbrodoff (1979) also did not find a significant difference in their similar "spatial task." Recently, the same task has been used in fMRI studies (Banich et al., 2000) and ERP studies (Stern & Mangels, 2006), revealing only marginal effects in reaction times. Therefore, in order to accentuate the conflict between spatial position and word meaning, we intermixed this *location* task with a second task—a *word* task— in which the participant had to respond to the word meaning ABOVE or BELOW, ignoring its position relative to the marker. The type of trial was indicated by nature of the marker: X for a location trial but O for a word trial (Fig. 1). This procedure, inspired by Harvey (1984), made word meaning relevant on some trials, increasing the probability of its processing even when it was to be ignored.

Using this interleaved task, we found clear evidence of a conflict period in which the incongruity between the word and its location either delayed the start of the trajectory to the correct answer or interrupted it. The response trajectory measure yields insights into the processing stages of decision making (e.g., see Resulaj, Kiani, Wolpert & Shadlen, 2009) and offers measures of processing times for location and word meaning. To examine the timing of the conflict, we varied the SOA of the word and the location marker (Glaser & Glaser, 1982); the marker also indicated the type of task (for a similar approach, see the speed–accuracy trade-off method of McElree & Griffith, 1995). Crucially, the word always appeared before (or simultaneously with) the marker that indicated the type of task.

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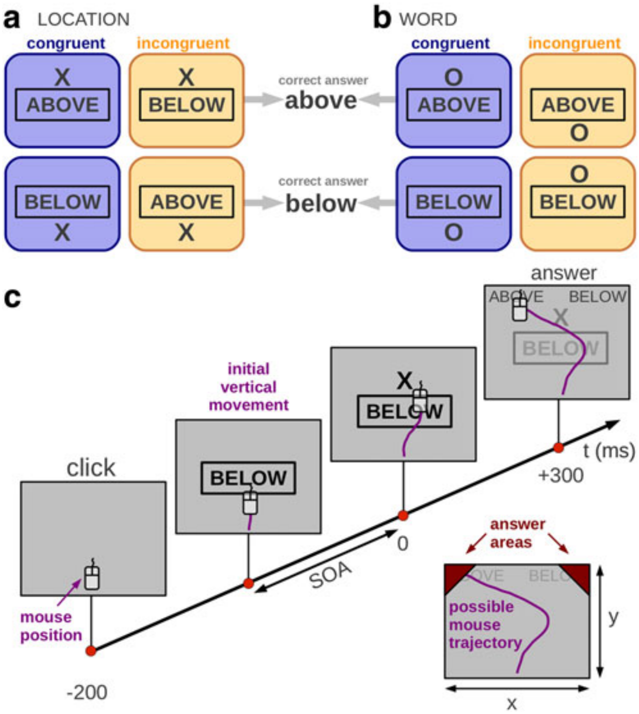

Fig. 1 **a** Stimulus–response contingencies in the location trials in which the marker indicates the trial type: X reports the location of the marker relative to the word; O reports the meaning of the word. **b** Stimulus–response contingencies in the word trials. **c** the order of presentation

The particular analysis that we used for the trajectory (direction vector) was very sensitive to processing stages, more than curvature (e.g., Spivey et al., 2005) or other analyses (see the Supplementary Materials) and, as we will show, was more revealing than the final response time, the time at which the mouse-directed cursor reached one or the other of the two answer locations.

Method

Participants

Six right-handed healthy participants (three male, three female) with normal or corrected-to-normal vision participated in our study.

Stimuli

The participant was seated at approximately 50 cm from a 19-in. CRT monitor that presented the 42.3° × 32.3° displays with a screen resolution of 1,024 × 768 at 100 Hz controlled by a Mac G4. The responses were directed with the right hand using a computer mouse whose position was sampled at 125 Hz, and this position trace was resampled by linear interpolation to 40 Hz. The words ABOVE and BELOW were displayed in the center of the screen in white uppercase Verdana font subtending 6.7° × 2.6°. The answer words were displayed at 6.7° × 6.7° from the screen corners and subtended 7.6° × 3.0°. The markers "X" and "O" appeared in the screen center, subtending 1.3° × 1.3°. The answer areas were all positions in these corners that were more than 23.2° from the screen center. Once a participant entered these areas, the corresponding answer was recorded.

Procedure

The task had two conditions: location trials and word trials. The shape of the marker indicated which response was required on each trial: An X indicated that participants were to report the location of the marker relative to the word and to ignore the meaning of the word, whereas an O indicated that they were to report the meaning of the word and ignore the location of the marker (see Fig. 1a, b).

The SOA between the word onset and the marker onset was varied from 0 ms to 200 ms. Consequently, the word appeared either before or simultaneously with the marker so that the word may have triggered significant processing before the marker indicated whether it would be task relevant or not.

To initiate each trial, the participant clicked with the mouse on a button in the bottom of the screen (see Fig. 1c). The word and marker then appeared, their onsets separated by 200, 150, 50, or 0 ms. Both the word and the marker (X or O) remained on screen until the end of the trial. The marker always appeared 200 ms after the participant's click. The response corners were always the same throughout all sessions, but as a reminder, the two corner labels appeared in the top left and top right corners of the screen on each trial 300 ms after the marker. The participant responded by moving the mouse to the screen corner corresponding to the answer, and the trial ended as soon as the pointer entered the corner answer area. This arrival time will be referred to as the *movement finish time*.

Participants were required to start moving the mouse very quickly. If the mouse pointer had not left a circular area around the start button within 400 ms after initiating the trial, the response was discarded, a warning sounded, and the trial was repeated some later time during the experiment. The participants learned to initiate their responses quickly within a few blocks of training trials at the beginning of a session. Crucially, since they initiated their movement before they had made their decision, they started out moving straight up, approaching both answers without yet choosing either one of them. This initial, neutral upward motion was critical for capturing the moment at which the trajectory first veered off toward an answer corner.

Each of the four stimuli in the location and word conditions was presented for each of the four SOAs (200, 100, 50, and 0 ms). These 32 conditions were repeated 15 times to yield a total of 480 trials per block. Participants began with a training session that first introduced the two conditions (location and word responses) separately, followed by a mixed block, and then only in the end was the early movement requirement introduced. The two blocks together with the training lasted a little over an hour.

Results

Incorrect trials were removed from further analysis (7.7%) as were trials in which the participant reached the answer corner more than 4 *SD*s earlier or later than their average (0.9%).

We analyzed a number of properties of the response trajectories and, rather than measures of curvature used in several articles (e.g., Finkbeiner et al., 2008), we found the moment-to-moment direction of the trajectory to be the most sensitive measure (see the Discussion section and the Supplementary Materials). Our analysis therefore focuses on this measure, defined as the tangent to the path at each point in time, with 0° being the vertical tangent and positive values assigned to the direction toward the correct corner (see also Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010).

We investigated the evolution of the movement direction over time for each participant separately using their average movement trace in each of the eight experimental conditions: 2 subtasks × 4 SOAs. As an example, we will present our analysis here for one participant in two such cases for response traces in location trials (Fig. 2).

To describe our analysis, we use the average direction trace from one participant for whom the SOA is 200 ms (Fig. 2, left graphs). The congruent direction curve starts with a consistent direction of 0°, reflecting the participant's initial motion straight upward prior to any deviation toward an answer corner. After around 200 ms, the path starts to arc toward the correct answer, stabilizing at a heading of around 60° until reaching the correct answer. The curve has this shape for all participants in all congruent conditions. We therefore fit a straight line to the upward trend for each participant (see the Supplementary Materials for details of the fitting procedure). We label the intersection of the linear fit with the baseline the *decision moment* (blue arrow in Fig. 2). At that point, the participant has gathered sufficient information to move toward the answer corner.

The trajectory in the incongruent case is similar, showing an initial launch toward the correct answer corner: There were no instances of an initial motion towards the wrong corner followed by a correction toward the correct corner. However, the incongruent trace, as here, often shows an interruption. Most likely, once the word's meaning is processed, the conflict between its meaning and the location response interferes with the answer in progress. To capture this interference, we fit a broken line to the incongruent curve (as shown by the orange curves in Fig. 2). Its initial take-off point is set to the same value as in the congruent case, but the curve can be interrupted by a horizontal plateau at any time before resuming its path to the correct answer corner. This gives us a double step clearly seen in the bottom right-hand panel of Fig. 2. The plateau at which the trajectory pauses defines two time points: a conflict onset and an offset (the green area in Fig. 2). Having performed this analysis for all participants and conditions, we find three time points for each participant in each SOA and each task type (*word* or *location*). These three are: (a) the decision moment (common to congruent and incongruent trials), and for the incongruent trials, (b) the conflict onset, and (c) the conflict offset. This analysis was robust enough to reveal a conflict in all incongruent conditions for all participants except two conditions (out of the eight) for one participant (out of six).

In the location task, a repeated measures ANOVA revealed that the conflict duration in incongruent conditions (conflict offset – conflict onset) was significantly greater than zero, $F(1, 5) = 48.31$, $p < .001$, and did not vary significantly with SOA, $F(1, 5) = 2.66$ $p = .16$. In the word task, the conflict duration was also significantly greater than zero for all SOAs, $F(1, 5) = 65.60$, $p < .001$, and did not interact with SOA.

On the basis of the distinctive double-step pattern in the incongruent traces, we were able to choose a simple model to estimate the time at which the word and location encodings were available (Fig. 3). Specifically, the initial response was always to the correct answer corner on incongruent trials, even though the response was later interrupted by the conflict. This suggests that the response began once the task marker was decoded in both congruent and incongruent trials and that on incongruent trials, the conflicting information would interrupt once it was available. The double step pattern also allows us to rule out two other models. If the response began as soon as either the word or relative location was available, without waiting to determine which task was required, there would necessarily be some frequency of initial responses to the wrong corner that would be corrected later on. This was never seen. Or, if the response began when both word and relative location were available, congruent trials could begin immediately without waiting to interpreting the task marker, but all incongruent trials would have to be delayed unit the marker was interpreted. In this case, there would never be an initial motion toward the correct corner, starting at the same time as it would in a congruent

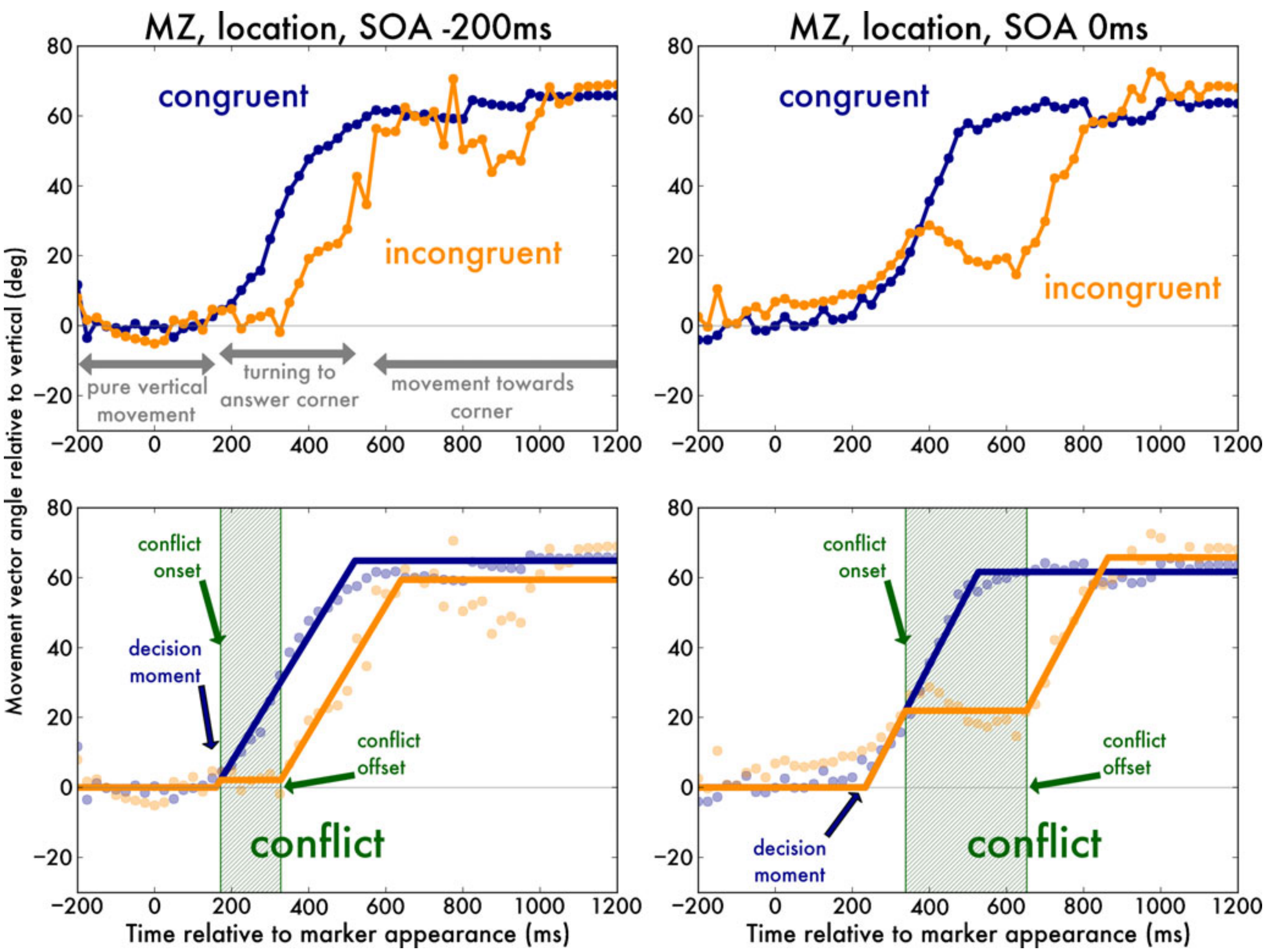

Fig. 2 Direction over time for one participant (MZ) for an SOA of 200 ms (left) and 0 ms (right) for location trials. The traces show the point-by-point mean direction of the 60 trials (minus error trials) of that participant in those conditions. Upper graphs: only the congruent/incongruent traces. Lower graphs: our trajectory analyses applied to the same two direction curves (see the Supplementary Materials' details of the fit). The *blue arrow* indicates the decision moment in the congruent case. The time window between the conflict onset and conflict offset is marked in green

condition that was later paused and then resumed. However, over 50% of the average incongruent traces showed exactly this double step.

In order to model the response trajectories, we assumed that the word and location signals arrive with fixed delay after their onsets, and that the response begins once the task is decoded and the relevant signal has arrived. We further assumed that a conflict emerges on incongruent trials once both signals are available. We used only three free parameters (decision moment, conflict onset, and offset) to fit results on both location and word trials (the two tasks were also fit separately, see below). The least–squares fit of our model (see the Supplementary Materials) to the time points from two tasks (R^2 = .91, χ_{red}^2 = 0.48) gives us an estimate of the processing time of the position and of the word meaning as 251 ms and 325 ms, respectively, and a conflict duration of 138 ms. We plot this fit in Fig. 3 (green lines). To obtain an estimate of the reliability of this fit, we then fit the same model to the data points of each participant individually and found in the cross-participant averages very similar values: position and word processing time of 260 ± 15 ms and 321 ± 16 ms, respectively, and a conflict duration of 131 ± 15 ms.

We used only three free parameters and found a quite respectable fit. Clearly we could have allowed different values of these three parameters for the two tasks and different values at each SOA. We had no indication from the data that conflict duration, for example, should vary as a function of SOA, but perhaps it might be different for the two tasks. We therefore fit the model to the two tasks separately. Fitting the location task on its own increased the goodness of fit (R^2 = .98, χ_{red}^2 = 0.07), but the

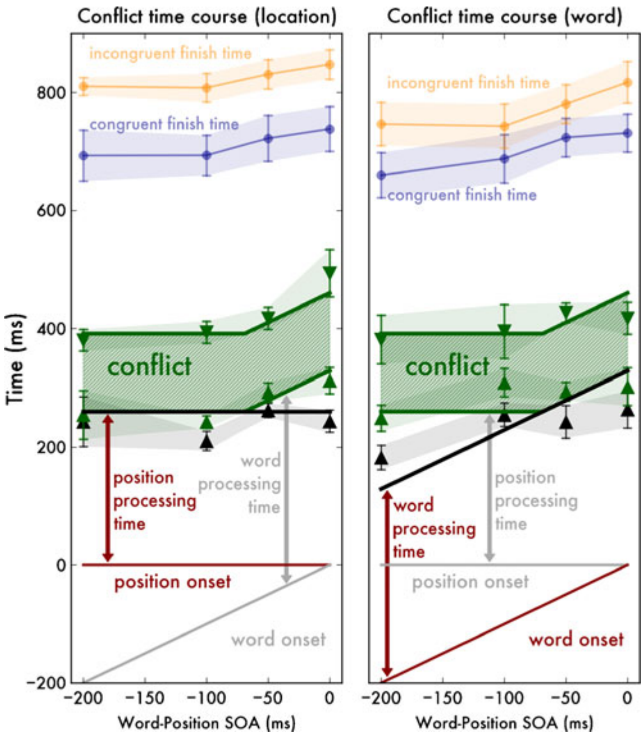

Fig. 3 Signal processing and conflict times for the location (left) and word task (right). The *red and gray lines* in the bottom indicate the onset of the word and position stimuli, where the task-relevant feature is red and the task–irrelevant feature is gray. The *green triangles* indicate the mean conflict onset and offset, determined as described previously. The *black triangles* indicate the decision moment in the congruent and incongruent conditions. Finally, we indicate the movement finish times. The *error bars* indicate the standard errors of the participant means

parameters showed little change: The word and position processing times were 331 ms and 224 ms respectively, and the conflict duration was 146 ms. A similar separate fit for the word task ($R^2 = .86$, $\chi_{red}^2 = 0.32$) also had little effect on the best-fitting parameters: word and position processing times of 327 ms and 274 ms respectively and a conflict duration of 118 ms. Fitting each task separately with individual participant data, we found no significant differences between the three parameters for the word and location tasks, nor between the separate and conjoint fits.

These independent fits are a test of the robustness of the simple model applied to these data. However, the weakest point in the fit is the assumption that the word meaning should be available at a fixed duration following its presentation. Specifically, in the word task, the decision moment must increase with SOA with a slope of 1. This part of the fit is less successful than elsewhere, and the deviations may be accounted for by some delay in the processing of the word meaning while waiting for the appearance and decoding of the task cue. We could add this extra parameter to our model, but we felt that there were not enough data points to support this more complex interaction and that the simple model, despite this deviation for the meaning decision moment, was adequate for our present purposes.

Figure 3 also shows the response finish times for the different conditions, the moment at which the trajectory entered the correct answer corner. These show response times between 700 and 800 ms, typical of many reaction experiments for similar conflict tasks (see the Discussion section). There is a significant delay of 112 ms for the incongruent versus congruent trials in the location task, $F(1,5) = 22.71$, $p = .005$, and of 71 ms for the word task, $F(1, 5) = 21.76$, $p = .005$, but no interaction with word-position SOA that would reveal any details of the word and location processing.

Discussion

Using response trajectories in word and location judgment tasks, we find a remarkably distinctive and stable decision moment at approximately 250 ms when the participant has enough information to begin to respond. In incongruent trials, we also find clear evidence of a conflict that delays or interrupts the response and lasts about 130 ms. This very large congruency effect was not a simple delay but often appeared as a pause in the trajectory well after the initial, correct response had already begun. The timing of these trajectory events also allowed us to derive the processing delay for the word and location signals. As compared with the response finishing time, our response trajectory measures of the conflict show a larger effect and a clearer interaction with the onset delay. Our simple model of the conflict does not capture all of the data with equal accuracy, but it does show a significant measure of success, providing far more information than the final reaction times. Two aspects of our response trajectory measure are critical in this success. The first is that the participant is moving the mouse during the entire trial, beginning before the critical stimuli appear. Therefore, when the word and position are displayed, the participant's trajectory is already underway. As such, we are able to measure the effects of the conflict on the trajectory as it happens instead of deducing that there must have been one from a delayed reaction time registered much later. The second critical aspect is the direction measure that we have used for the trajectory rather than the more typical curvature measures. We found that this measure reveals discrete changes in response trajectory that the curvature measure cannot localize as well or at all (see the Supplementary Materials).

One could argue that we slowed the participant's response time down by making him or her cross the entire screen with the mouse pointer. But previous studies using similar spatial Stroop tasks and various other response modalities have found response times in the same range as the movement finish times in our experiment. For instance, researchers in several studies (Banich et al. 2000; Seymour, 1973; Walley, McLeod, & Weiden, 1994) had their participants say their responses out loud and found smaller congruency effects of between 15 and 45 ms (with response times in the range of 600 to 900 ms). However, exact comparisons are difficult since some studies used more than two spatial words. Palef and Olson (1975), who had participants respond by pressing a button to only what we called the location task, found earlier reaction times of around 360 ms (or converging to that value across practice). However they did not find a conflict effect at all. This may be because they presented the two tasks (word and location) in separate blocks, thus allowing the participants to switch strategies between blocks.

Conclusion

In the present study, we provided evidence of a reliable Stroop-like effect with spatial prepositions in participant's movement trajectories. Instead of the reaction time (i.e., the moment the participant registers his or her response) we investigated the response tendencies by analyzing the movement direction of the trajectory.

By proposing that the position and meaning information are processed in parallel and that the conflict occurs when both become available, we can deduce that the meaning of spatial prepositions "above" and "below" are processed in approximately 325 ms. Relative position is processed in a much shorter time of approximately 250 ms. The conflict they give rise to lasts for some 138 ms.

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Supplementary Materials

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The Direction Measure

We will illustrate how the direction measure is calculated by using the response trajectory from a single trial (Fig. S1). At every point in time, we calculate the tangent to the response trajectory. We then find the angle of this tangent vector, where 0° is vertical. Previous studies (e.g., Spivey et al., 2005) have investigated the curvature, as defined by the deviation at each point in time from a straight line connecting the beginning and endpoint of the path. As is clear from the illustration (Fig. S1, below), this quantity is much less revealing than the direction over time. For this reason, we have not analyzed it further in the present study. Our movement direction measurement is furthermore similar to the measurement of the initial movement angle as proposed in Dale, Kehoe, and Spivey (2007); however, rather than just taking the initial movement angle, we extend this method by tracking how the direction varies during the decision making process.

To see what the response trajectories look like in slow-motion, we invite the reader to visit our YouTube video, which shows all responses to congruent and incongruent trials of all participants for the location task in slow motion.

Details on Our Fitting Procedure

There are two sequential steps: First, we characterize the response trajectories to extract time points, and second, we model the resulting decision and conflict times as a function of SOA, trial type, and task.

For the trajectories, we fit "stair-steps" to the direction data with one "step" for congruent trials and two "steps" for incongruent trials in which the conflict could intervene and create a momentary pause before the trajectory resumed toward the response corner (see two schematic plots below). Here is how the stair-steps were fit to the data, starting with the simpler congruent case and a single step (for an example of such trace, see Fig. 2 in the original article).

Fit to average trajectories of individual conditions for each participant.

The robust linear portion of the rise in the direction measure was evident when we investigated the mean direction trace for each participant and each condition separately (each such trace was based on 60 trials minus discarded incorrect trials, in our case 7.7%). We wished to capture the moment that this distinctive "launch" began—the decision point—by fitting a linear function to the rise and determining its intersection with the flat prelaunch segment. Note that the linear change in the movement vector does not represent a linear movement in space but rather a curved one, where the participant changes his or her course from vertical to the corner corresponding to his or her answer.

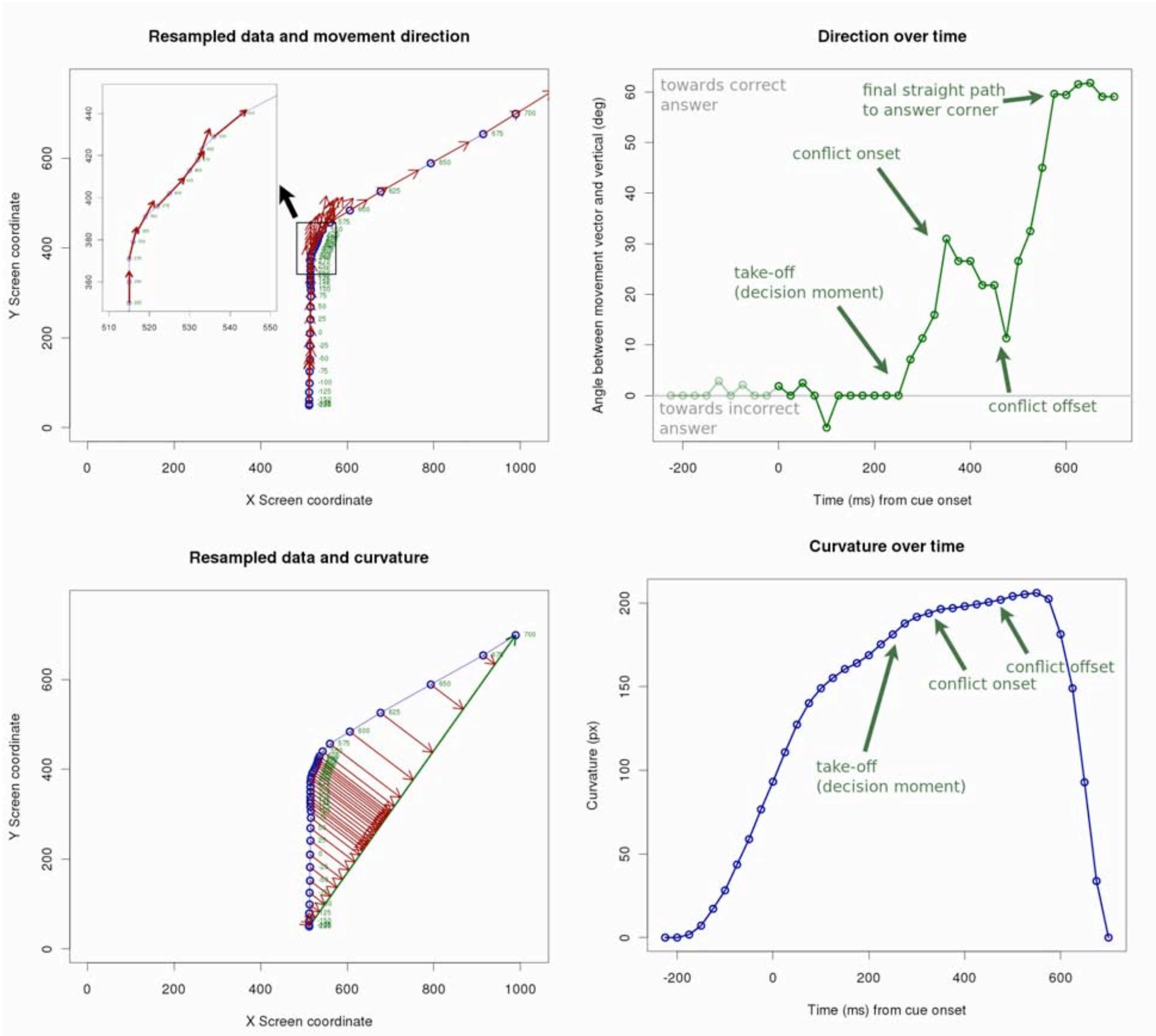

Fig. S1 Top left: The response trajectory of a single incongruent trial. The *green numbers* are the points in time when the mouse was at the indicated position, and the *red arrows* show the movement direction. The inset shows a close-up of the time span over which the trace turns first toward the correct corner, then starts to return to vertical, then resumes its arc toward the correct corner. Top right: the movement direction plotted over time with the features that correspond to the double-step pattern we extract from the average traces (see below). Bottom left: the curvature measure (e.g., Spivey et al., 2005) as the deviation from a straight path. Bottom right: curvature as a function of time with the *arrows* indicating the times at which the distinctive features were seen on the direction plot above. Nothing distinctive emerges at or near those locations in the curvature plot

First, we estimated the time window of this linear increase. To do this automatically, we fitted a cumulative Gaussian to the congruent curve and selected the range of 3 *SD*s centered at the midpoint of the Gaussian for the data to be fit with a linear function (the red points in Fig. S2). This is one of many possible ways to specify the data over which to fit the linear function, but visual inspection confirmed that this singled out the time window in which the direction trace showed robust linearity fairly accurately. We then extrapolated that linear fit to the baseline and took the intersection as the decision point. We also determined the ceiling point at which the participant stopped curving toward the destination and began a straight, final approach. The height of this ceiling point is determined as the average direction after t = 800 ms (green points in the figure below), since our visual inspection revealed that from that point onward the direction traces remained stable for all participants.

The fit for the incongruent trace involves identifying two such steps, the first in which the participant begins the trajectory to the correct answer, then stops when the conflict intervenes, then begins again when it is resolved. The incongruent traces show this two-step pattern in over half of the 48 conditions (4 SOAs x 6 participants), and in these cases, the initial segment begins at a time quite close to that seen in the congruent traces, as we would expect if the response begins before any evidence of conflict is available. On the other hand, the remaining traces show effectively only a single step that begins with a substantial delay as compared with the initial segments of the corresponding congruent traces.

We assume that, in these cases, the conflict was already active before the response could begin, delaying the response until the conflict was resolved. This single step therefore corresponded to the response resumption in the two-step patterns. However, this means that we did not have any explicit features on these single-step incongruent traces to define the two other time points, denoting the decision moment and conflict onset. To model both the single- and double-step conditions consistently, we assumed that the decision moment of the incongruent trials was at the same time as the response onset of the congruent trials in the same condition. In other words, processing on the congruent and incongruent trials should be the same up to the moment that the conflicting information intervenes since there is no other factor differentiating the two trials. We therefore started with the first two parameters for all incongruent traces (decision point and first linear slope, if present) as determined from the congruent trials only. These values were checked by visual inspection of the average traces

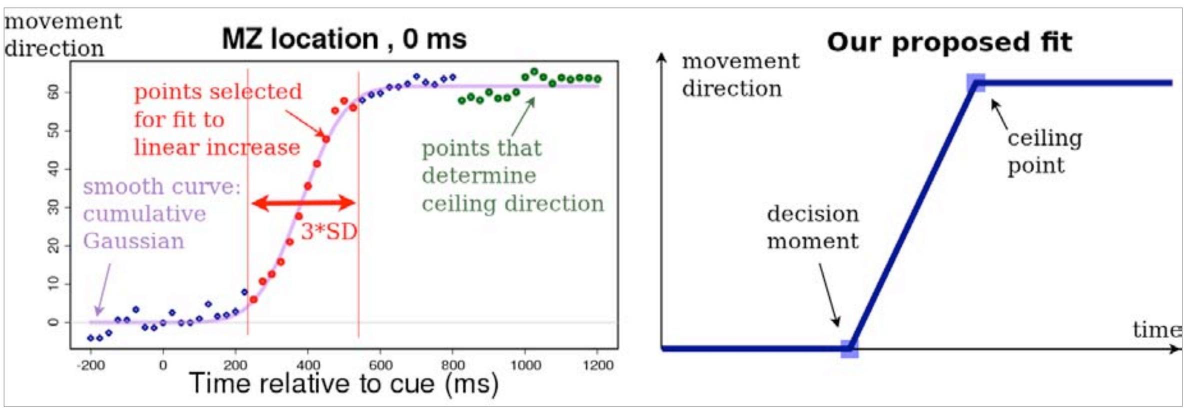

Fig. S2 Example fit to the average congruent trace for one participant (RN) and one SOA (-100). The left panel shows the elements that are used as a basis of the fit. The right graph shows the fit of our model with the decision moment and ceiling points that we derived of the two-step patterns, and this appeared to be quite representative of the incongruent preconflict data (these traces are not included in the present article, but are available on request). If there was only one step in the incongruent trace, we also assumed that the conflict onset was the same as the decision moment.

This means that the new parameters for the incongruent trials identify only the conflict onset (for two-step traces) and offset (for all traces) and the slope of the second linearly increasing segment (or first if it was a delayed single-step trace). The ceiling point then follows as the intersection of the second linear part with the maximum of the direction trace. We constrained the conflict onset to occur at or after the take-off point and the conflict offset after the conflict onset.

In some cases, the best fit had the conflict onset time equal or practically equal to the decision moment, and in those cases, the incongruent case was reduced to a single-step trace. There were occasionally quite small differences between the decision moment and the conflict onset (e.g., in the left part of Fig. 2 of the article) in which we considered that the pattern was effectively a single step. The decision moment and conflict onset were strictly equal in 6.3% of our fits, whereas in 22.9% of the fits, the difference was less than a millisecond. Beyond these single-step cases and the marginal cases with a small initial step due perhaps to noise in fitting, the majority of conditions showed a clear double step. In a total of 54.1% of the fits for incongruent conditions, the initial rise between the decision moment and the plateau at the start of the conflict lasted longer than 20 ms. Furthermore, 29.1% of the fits show an initial rise toward the correct answer corner, lasting more than 50 ms before the conflict began and the response direction paused (e.g., the right part of Fig. 2, or in Fig. S3).

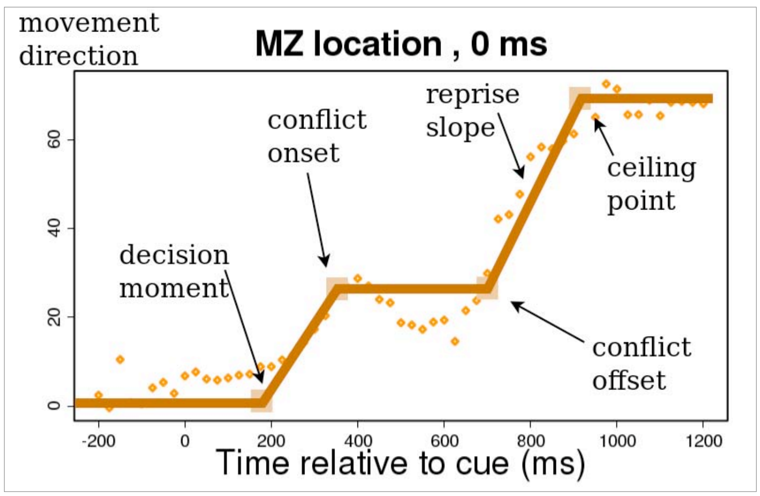

Fig. S3. Illustration of our fit to the incongruent direction trace for one participant (MZ) and SOA (0 ms)

Finally, we allowed the second slope following the conflict to deviate from the first slope (as we could see that it did), but we biased the fit (with a penalty in the least squares sum) to favor values close to the initial slope. The selection of data for fitting the linear second slope used the same Gaussian procedure as the first slope. Overall, the besting fitting second slope was about 18% steeper than the initial slope with this constraint included. This tighter curve is to be expected since the trajectory resumes from farther up on the display and has to curve more sharply to reach the corner. The fit of these stair step trajectories to the averaged trajectories gave an average R-squared of .96 across all the congruent conditions and participants, and of .95 for all the incongruent conditions and participants.

Our informal criterion for these fits was that stability of each derived time point was similar to the stability of the response time measures (similar standard errors). Any excessive variability would signal that the derived value was poorly fit and possibly not a real feature of the trajectory. None of the time points showed a variability (standard error) within a participant in excess of two times the standard error for that particpant's response time (final answer arrival) data. In other words, the stair-step fits to the trajectories are very good, and the time points that result appear to be stable features of the processing, not artifacts of the fitting procedure.

Fit to the average decision point and conflict onset and offset time points.

We performed the aforementioned stair-step fits for all participants and all conditions, yielding decision and conflict onset and offset times. Then, we averaged these across participants. These are the results shown in Fig. 3 of the article.

In our next step, we fitted a simple model to these average decision and conflict times, also as shown in the Fig. 3 of the article. Three signals are involved (task, position, and word), but only two vary independently. The task cue indicates either a location or a word meaning trial, the spatial signal codes the relative spatial positions of the cue and word, and the word carries the ABOVE or BELOW meanings.

For the location trials, we assume that the decision waits until the cue is interpreted and the relative position of the cue and the word is available. As soon as it is, the trajectory begins an arc toward the corresponding answer corner. On incongruent trials, the trajectory toward the answer will be interrupted once the word meaning is also available, and this depends directly on the time of the word presentation. If the word is presented well before the cue, the conflict begins at the same time as the decision, delaying the initial launch until the conflict is resolved, resulting in a single stair step. If the word arrives later, the launch is already underway when the conflict intervenes to interrupt it, producing two stair steps.

For the word task, the assumptions are the same, but now the decision moment occurs at a fixed time after the word appearance. On incongruent trials, the conflict begins when both position and word meaning are available. It follows that the conflict onset times must be the same in the two subtasks. Therefore, we fitted our model to both tasks at the same time, forcing the conflict onset times to be the same.

At this point, we return to our assumption that for incongruent traces, a single, rather than double, step will show up if the conflict is already apparent when the initial response is ready to go (decision moment). The conflict introduces a delay before any curve to the answer corner is seen. Does this single step pattern show up at the appropriate conditions? Yes. In the location subtask (left part of Fig. 3 in the article), for example, the conflicting word information is available first at the long SOAs (-200 ms, -150 ms). This is where we expect the conflict to already be established, delaying the initial response and producing only a later "resumption" step. Here, the data show the delayed single step patterns in the incongruent trials, and the model fits the data with the decision moment equal the conflict onset. Then, when the SOA becomes smaller and the conflicting information stream is not yet present when the initial response is ready to go, we see mostly two-step patterns in the data, and the model fits have the conflict onset occurring later than the decision moment. Moreover, note that the delay of the single step relative to the decision moment (taken from the congruent trials), defines the conflict duration for these conditions. The single-step conflict durations (at long SOAs) match the conflict durations taken between the first and second step when the double-step pattern was seen (shorter SOAs).As reported in the main text, there was no interaction of SOA and conflict duration. We had used the double-step pattern as the motivation for our model and we interpret the timing of the transition from single- to double-step patterns and the maintenance of a constant conflict duration across single- and double-step conditions as strong evidence for the logic of the model.

Note that we assume that the word processing may begin even before the task cue is interpreted, a time point that we have left unspecified. This is made more plausible by assuming that the participant will use the optimal strategy of processing the word as soon as it appears but will respond to it only once the cue appears and indicates a word trial. This assumption allows us to avoid adding a fourth parameter for the cue processing time and its interactions. The fit of our three-parameter model does not leave enough unexplained variance to justify this additional parameter, but it would be a logical addition if we had a richer

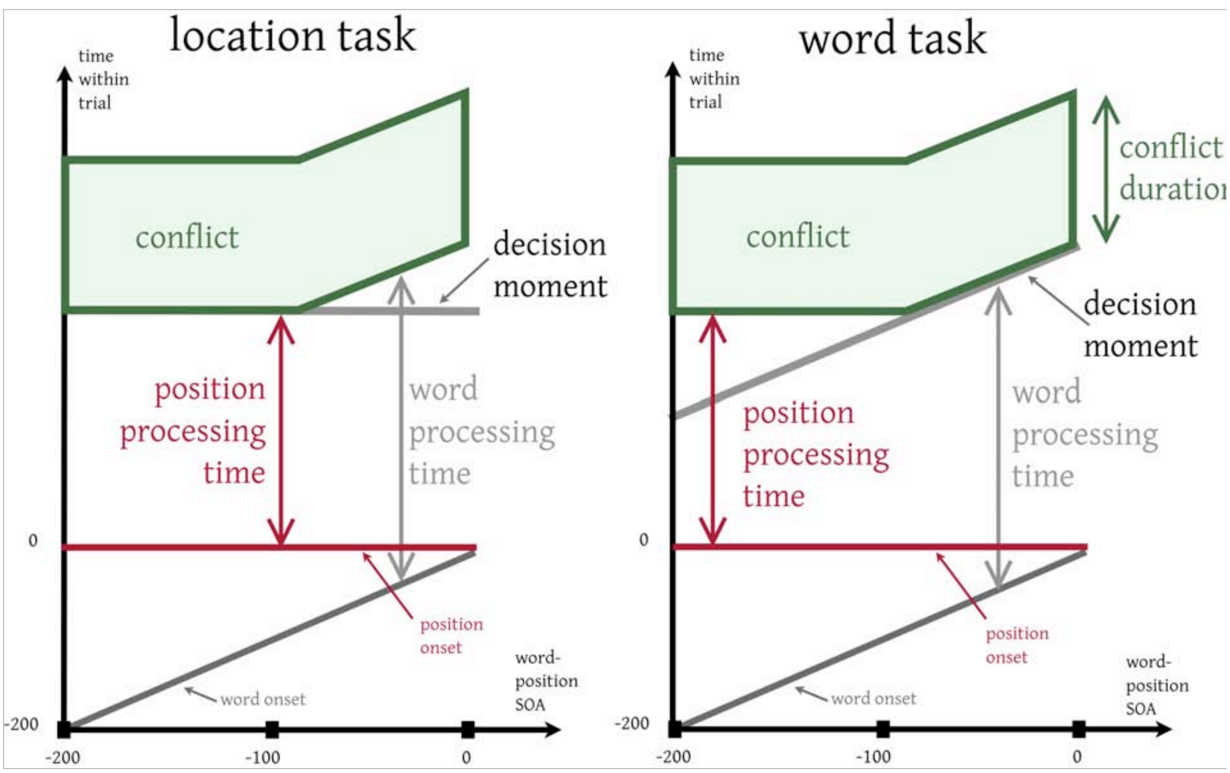

Fig. S4 Overview of the parameters of our model fit set of data on which to test it.

We fit the following three parameters, using the data from the meaning and word subtasks simultaneously:

(a) word processing time, (b) position processing time, and (c) conflict duration.

The resulting equations for the dependent variables are:

conflict onset = max(325 ms + SOA, 251 ms)

conflict offset = conflict onset + 138 ms

In the location task: decision moment = 251 ms

In the word task: decision moment = 325 ms + SOA

The fit gave an *R*-squared of .91 to the average data. In order to further evaluate our fit, we calculate $\chi^2=\sum_i((\text{observed}_i-\text{predicted}_i)^2 / \text{stdev}_i)$, where we use the sample standard deviation as an estimate of the population standard deviation. We report in the article the corresponding $\chi^2_{red}=\chi^2/(N-n)$, where N is the number of measurements and n the number of parameters in the model (three, in our case).

As indicated in our article, we computed this same fit to the data of the individual participants as well. This enabled us to calculate error margins for the fit parameters. We computed three fits: (a) to the location data separately, (b) to the meaning data separately, and (c) to both tasks at the same time—that is, taking the conflict onset/offset and conflict duration parameters to be the same in both tasks. Our finding is that the parameter estimates are very close for all these fits, as reflected in small standard errors, and, furthermore, they are close to the fit to the mean data of all participants (which we reported in our article). For completeness, we list the obtained parameter values listed in Table S1.

References

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Table S1. Overview of the parameters of various alternative fits.

	Position Processing Time (ms)	Word Processing Time (ms)	Conflict Duration (ms)
Simultaneous fit for location and word			
Fit to pooled mean data of all participants	251	325	138
Mean (*SE*) of the fits to individual participants	260 (15.3)	321 (16.1)	131 (14.7)
Separate fit to location task			
Fit to pooled mean data of all participants	224	331	146
Mean (*SE*) of the fits to individual participants	240 (26.8)	321 (20.4)	145 (21.0)
Separate fit to word task			
Fit to pooled mean data of all participants	274	327	118
Mean (*SE*) of the fits to individual participants	268 (25.1)	305 (30.5)	116 (14.4)