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Abstract

Mouse-tracking provides rich information about temporally sensitive mental processing. In two experiments, we applied this methodology to a phonological cohort task that can be interpreted as a version of the A-not-B task. In the first experiment, participants had to click a word such as "candle" three times in a row on the same side of the computer screen. They then had to click a phonological competitor ("candy") on the other side during the critical trial. This was contrasted with a condition in which the word to be clicked three times in a row was phonologically unrelated to the word at the critical trial. We found that the phonological priming increased attraction toward the competitor. In the second experiment, mouse movements revealed attraction towards the competitor as a function of the number of previous presentations. The results demonstrate that phonological competitors can exert graded influence on motor responses even if the competitors are not simultaneously presented. These results are predicted by and provide evidence for the dynamic field theory of movement preparation and execution. These results can furthermore be interpreted as evidence for continuity underlying the A-not-B task.

Keywords: A-not-B error; deictic pointers; dynamical systems; mouse-tracking

Introduction

The A-not-B error has been investigated with children for over half of a century (Piaget, 1954). In the standard version of the task, the researcher presents an object to the child and hides it in one location ("A"). When this process is repeated multiple times, the child will often reach for the object in "A" even if it was moved *in front of the child's eyes* to another location, "B". Eight to ten month old children reliably commit this error (cf., Marcovitch & Zelazo, 1999).

Smith and Thelen (2003) and Thelen, Schöner, Scheier and Smith (2001) conceptualize the A-not-B task in terms of dynamic field theory (Erlhagen & Schöner, 2002), where the decision to perform a movement towards either A or B develops in a continuous fashion. The theory views the A-not-B error as the result of changes to an activation field, where both A and B are represented as points on a plane. If the researcher hides a toy under A, the point for A increases in activation and sends inhibitory activation to B. The child reaches for A if a threshold of activation is crossed. Crucially, the memory of this reaching "pre-shapes" the field for the next trial. Over multiple trials, the A region of the field becomes stronger and increasingly exerts inhibitory

influence on the B region of the field, ultimately resulting in the A-not-B error.

Dynamic field theory accurately predicts that if posture is changed between A and B trials (Smith, Thelen, Titzer, & McLin, 1999), the child does not commit an A-not-B error as often. This follows from the assumption that changes in posture on A and B trials decrease the similarity of preceding memories to the current trials, thus lessening the strength of the pre-shaping of the field.

This account is also compatible with another area of research, deictic pointers (Ballard, Hayhoe, Pook & Rao, 1997; Chun & Nakayama, 2000; Richardson & Spivey, 2000). By associating content and locations with a deictic pointer, a cognitive agent can reference necessary information and use it to aid action without having to build up a detailed model of the world. We will argue that the formation of dynamic fields can be viewed as the formation of deictic pointers.

In this paper, we explore how previously seen stimuli affect perseveration in a mouse-tracking experiment. Mouse-tracking provides a real-time stream of *x, y* coordinates during movement that has been used to reveal the continuous dynamics underlying a diverse set of cognitive processes, including phonological competition in lexical access (Spivey, Grosjean, & Knoblich, 2005), the comprehension of sentence negation (Dale & Duran, 2011), the categorization of typical and atypical objects (Dale, Kehoe, & Spivey, 2007), and the categorization of faces (Freeman, Ambady, Rule, & Johnson, 2008), among many others (for a review, see Freeman, Dale, & Farmer, 2011).

In Spivey et al. (2005), participants saw two objects in opposite corners of the computer screen, e.g. a candy and a candle. They then heard a target word referencing one of the objects, such as "candy", *while they executed the movement to click it.* When the two objects were phonologically related, the mouse gravitated more toward the competitor object than when they were phonologically unrelated.

Here, we extend the task used by Spivey et al. (2005) to show the graded influence of phonological competitors that are *not* simultaneously present on the critical trial. Similar to the A-not-B task, we present an object such as "candy" multiple times on one side, and then on the next trial we present "candle" *on the opposite side*. Dynamic field theory predicts that multiple memory traces of "candy" on one side should exert graded inhibition when seeing the phonologically related "candle" at a different spatial

location. While adults may not commit the full A-not-B error by accidentally clicking on the wrong object, their mouse movements might still reveal continuous attraction towards previously seen competitors.

Experiment 1

In the first experiment, we presented each participant with phonologically related and phonologically unrelated stimuli. Mouse movements were recorded during each trial to investigate the effects of repeated movements to phonological and non-phonological competitors.

Methods

Participants Thirty-three undergraduates at UC Merced volunteered to participate to receive partial course credit. All participants were right-handed native speakers of English. 3 stimuli were excluded because of computer lag (0.24 %).

Stimuli and Procedure The procedure was run using MouseTracker (Freeman & Ambady, 2010). On each trial, two 200 pixel-wide pictures were presented in the top corners of the screen. Using headphones, we presented a target word for which the corresponding object had to be clicked (e.g., "pickle", "pepper"). Each pair of objects was always phonologically unrelated (e.g., "candle" vs. "lobster"). However, there were 16 critical trials that were preceded either by three trials to the same side without a phonological competitor (lighting-left, pepper-left, speaker-left, candy-right) or three trials to the same side with a phonological competitor (candle-left, candle-left, candle-left, candy-right). These two conditions are called "motor-3" and "phonological-3" respectively. The prime was always the target item. So, for example, a participant might have had to click "candy" three times on the left side and then, on the critical trial, "candle" had to be clicked on the right side (see Fig. 1). Across participants, we balanced the position (left vs. right) in which the target and the primes occurred, and we also balanced which of the competitors occurred as prime, and which as target (i.e., "candy-candy-candy-candle" vs. "candle-candle-candle-candy"). In total, there were 8 "motor-3" items and 8 "phonological-3" items (16 critical stimuli)..

There were also 24 filler trials that occurred between critical trials and subsequent priming trials. In the analyses below, we count these filler trials as control trials, as they represent mouse movements toward target objects for which there is no previous prime and no phonological competition. There were thus 88 trials in total. These were preceded by 12 practice trials.

We instructed participants to initialize mouse movements before they heard the sound file. To encourage this, the gain was slowed down to 2 (MouseTracker setting), and the sound file played the target word after a 500 ms delay.
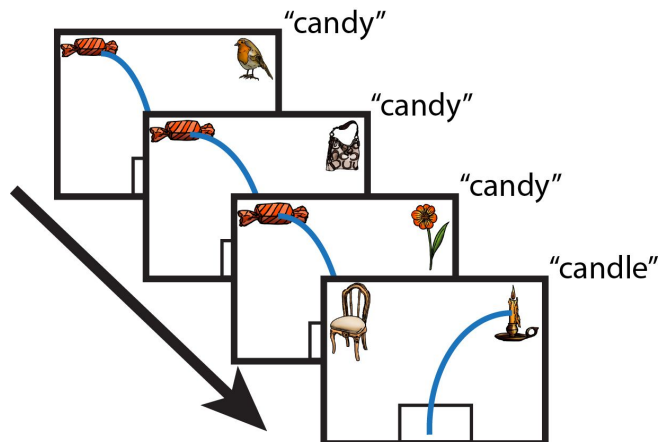

Figure 1: Schematic depiction of experimental trials. Note that on the critical trial, the competitor is not present.

All stimuli were spoken by a native speaker of English. For the prime-3 condition, we recorded three different utterances of the same word by the same speaker to reduce the possibility of selective adaptation effects. Mouse coordinate data was sampled at 60 Hz and was recorded with screen display information, movement durations and final response.

Analyses We inverted the x coordinates of left-going responses so that left- and right-going responses had comparable spatial metrics. We then normalized all responses to have a common origin at (0,0). Mouse-tracking provides a large set of potential dependent measures. We focused on the Euclidian distance of each measured point from the diagonal line that is defined by the origin in the center of the screen and the corner response box. All analyses we present were time-normalized to 101 time steps per trial.

We analyzed our data in two ways. First, we used the R package *lme4* (Bates, Maechler & Bolker, 2012) to perform growth curve modeling (Mirman, Dixon & Magnuson, 2008). Time step (1 to 101) entered the analysis as a fourth order orthogonal polynomial fixed effect (including lower-order polynomials), and the crucial effect of interest was the interaction of condition (prime-1, prime-3, control) with time. In the by-subjects-analysis, we included random intercepts for subjects, as well as subject random slopes for time and condition (following Mirman et al., 2008). In the by-items-analysis, we did the same for items. P-values were derived separately for each coefficient based on normal approximated t-values.

Growth curve analysis allows modeling the precise trajectory; however, for comparability with other mouse tracking studies and to get the exact time points of where trajectories differ, we present an alternative analysis following Dale, Kehoe and Spivey (2007), who have shown by means of simulated random trajectories that 8 consecutive t-tests may count as a significant result at α = 0.01.

With mouse-tracking data, there is always the possibility that average differences between conditions are not due to genuine gradedness in the response, but due to averaging over trials that head straight to a target and trials where participants correct a categorical choice midflight. To assess whether this could explain our results, we computed the bimodality coefficient b (see Freeman & Ambady, 2010) on the z-scored (by subjects and by condition) maximum deviation from the diagonal line and the area under the curve (measures are described in Freeman & Ambady, 2010: 229). b values over 0.555 are interpreted as evidence for bimodality.

Results

There were 9 errors in total (0.72% of all trials), all in the control condition. Therefore, there was no indication of a categorical A-not-B error. All subsequent analyses are performed on correct trials only.

Fig. 2 shows the evolution of the Euclidian distances from the diagonal line over time. For the growth curve analysis, likelihood ratio tests revealed a significant difference between the phonological and the pure motor condition by items (p=0.025), and a marginally significant difference by subjects (p=0.079). In both cases, there were significant interaction effects of condition for the cubic and quadratic components of the model (cubic by subjects, p=0.0054, by items, p=0.02; quadratic by subjects, p=0.024, by items, p=0.021).

The phonological competition condition was significantly different from control by subjects and by items (p=0.009, p=0.0065). In both cases, the intercept was higher for phonological competition than for control (by subjects: p=0.016, by items: p=0.027), indicating overall larger Euclidian distances for this condition. In the subjects analysis, there were additionally significant effects for interactions between condition and the linear (p=0.003), cubic (p=0.01) and quadratic (p=0.0034) components of the model. The motor priming condition was significantly different from control only by subjects (p=0.008) and not by items (p=0.175). In both cases there were individual effects for the intercept (higher in motor priming than in control, by subjects: p=0.01; by items: p=0.048), but no effects for higher-order polynomials.

The alternative analysis, following Dale et al. (2007), revealed no consecutive significant differences between phonological and motor priming that passed the 8 t-test criterion. There were 36 significant differences between phonological priming and the control condition in the subjects analysis (time points 59 to 94), and 50 in the items analysis (time points 3 to 25 and 59 to 85). The region that is significant in both analyses is shaded in Fig. 3. There were 29 significant differences (73 to 101) between control and motor priming by subjects, as well as 30 by items (3 to 32). Interestingly, in this case, these regions were not overlapping.
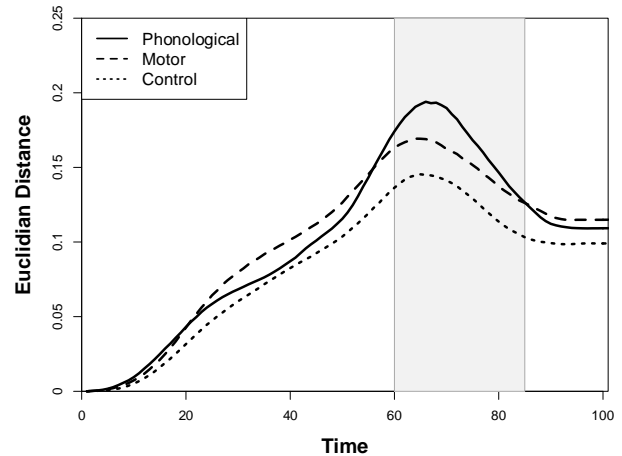

Figure 2: Euclidian distance as a function of time. Gray area indicates significant differences between phonological competition and control (by subjects and items).

Bimodality analyses revealed no subject with $b > 0.555$ for the crucial phonological competition condition, neither for the measure "maximum deviation from the diagonal", nor for the measure "area under the curve". For the motor priming condition, 1 participant had b > 0.555 for maximum deviation (~3%), and 4 participants for area under the curve (~12%). Again, this shows that the results are fairly unimodal across the board.

Discussion

The results for the motor-3 and phonological-3 conditions were interesting. In the growth curve analysis, it was surprising that there were significant differences between the two conditions for items, but only marginally significant differences for subjects. This is surprising because the items-based analyses use a smaller sample than the subjects based analyses (N=33 in the subjects analysis and N=16 in the items analysis). More data will need to be collected to explain this.

Another way to look at the data is to see when and how long the two conditions differed from the control condition in the analysis proposed by Dale and colleagues (2007). While both conditions displayed significant differences from the control by subjects and items, only the phonological priming condition displayed significant differences by both subjects and items simultaneously. In addition, the phonological condition resulted in more total significant differences from the control than the motor priming condition (86 vs. 59). If we take the number of significant simultaneous consecutive differences as a measure of strength of the difference (cf., Dale et al., 2007), then the prime-3 condition showed more gravitation away from the diagonal line (towards previously seen competitors) than the prime-1 condition.

While this experiment has revealed that attraction toward a previously displayed stimulus is modulated by said stimulus being a phonological competitor, there is more to

dynamic field theory. Experiment 2 was designed to further investigate how well dynamic field theory could be applied to these results by varying the number of phonological primes before the critical trial.

Experiment 2

In this experiment, we modified Experiment 1 slightly. Rather than presenting three motor primes or three phonological primes, the two critical conditions now both used phonological primes. One condition used three primes ("prime-3"), while the other condition used just one prime before the critical trial ("prime-1").

Methods

Participants Thirty-two undergraduates at UC Merced volunteered to participate and received partial course credit. All participants were right-handed native speakers of English. 9 trials were excluded because of computer lag (0.8%).

Stimuli and Procedure This experiment had a similar setup to Experiment 1 and made use of the same stimuli. The prime-3 condition was identical to the phonological-3 condition in Experiment 1. There were 18 filler items.

Results

There were 9 errors in total (0.8% of all trials), 8 in the control condition ("fillers") and 1 in the prime-3 condition. Crucially, this means that there were no noteworthy differences between the prime-3 and prime-1 error rates, indicating that no categorical A-not-B-like error was committed. Subsequent analyses will be performed on correct trials only.

Fig. 3 shows the evolution of the Euclidian distances from the diagonal line over time. There was a significant interaction between the prime-3 and the prime-1 condition for the linear component of the growth curve model in the items analysis (p<0.02), and a nearly significant interaction in the subjects analysis (p=0.053). This linear component indicates a steeper rise for the trajectory of the prime-3 condition than of the prime-1 condition. However, a likelihood ratio test comparing the full model with the factor "condition" against the model without indicates an only marginally significant overall effect of "prime-3 vs. prime-1" (subjects: p=0.066, items: p=0.09).

There were, however, significant differences between prime-3 and control both by subjects (p=0.0008) and by items (p=0.015). This difference seems to stem from the linear component of the model (subjects: p=0.0018, items: p=0.026), and for the subjects analysis, there also was a significant difference in intercept (p=0.0049), reflecting overall larger Euclidian distances for the prime-3 condition than for trials without phonological competition and without previous movements towards the competitor. Finally, there was no significant difference of the overall model between prime-1 and the control condition (all p's > 0.1). Comparing this to the effect of the prime-3 condition, this suggests that

the prime-3 trials did in fact deviate more strongly from control trials.

In terms of Dale et al. (2007)'s approach, there were 12 consecutive significant differences between prime-3 and prime-1 (time points 90 to 101) by subjects and none by items. There were 48 consecutive differences for prime-3 versus control (time points 54 to 101) by subjects, and 28 (74 to 101) by items. In contrast, there were 41 consecutive differences for prime-1 versus control (time points 20 to 34, and 64 to 101) by subjects and none by items. The shaded gray area in Fig. 2 shows the portions of prime-3 versus control that are significant in both the subjects and the items analysis.

By-subject bimodality coefficients for maximum deviation of the prime-1 and prime-3 conditions were all below 0.555 for maximum deviations, indicating that the present results are unlikely due to averaging over bimodal responses. Bimodality coefficients for the area under the curve were above 0.555 for only three participants (~9%) in the 3-prime condition and for 4 participants (12.5%) in the prime-1 condition.
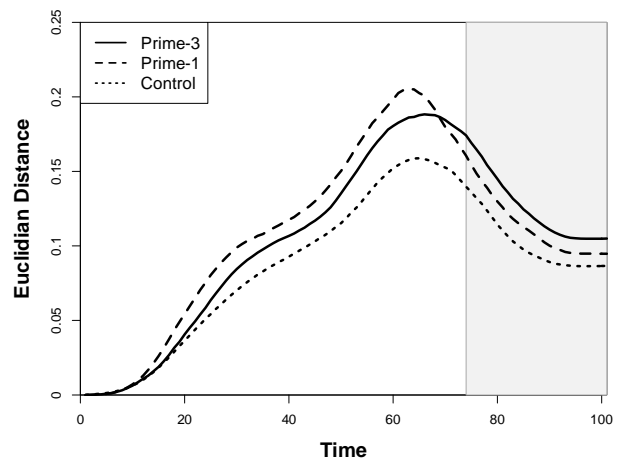

Figure 3: Euclidian distance as a function of time. The shaded gray area indicates where prime-3 and control are significantly different from each other by subjects and items.

General Discussion

In Experiment 1, we found a difference between a purely motor priming condition and a condition that had both a motor priming and a phonological priming aspect. This difference seems to lie within the higher-order polynomials of the curve fit, suggesting that complex details in the shape of the trajectories are of importance in characterizing the difference between the two conditions.. Experiment 2 further established that previous exposure to critical stimuli did affect the trajectory of upcoming trials, and there was indication that the strength of this effect was modulated by the number of previous priming trials.

In both experiments in comparison to the control condition, only the phonological-3 condition produced a

significant deviation in both the subjects and the items analysis simultaneously (shaded area Figs. 2 and 3). This was regardless of the two analysis approaches that we used above.

These results fall straightforwardly out of a dynamic field theory account of how the brain treats memory traces of objects and locations in general (Erlhagen & Schöner, 2002; Spencer, Barich, Goldberg, & Perone, 2012), and the A-not-B error in particular (Smith & Thelen, 2003; Thelen et al, 2001). However, in contrast to children, repeatedly clicking on a location ("A") did not lead to a categorical error (there were no significant differences in error rates between the conditions). Instead, there was evidence for a continuous, graded attraction toward the competitor.
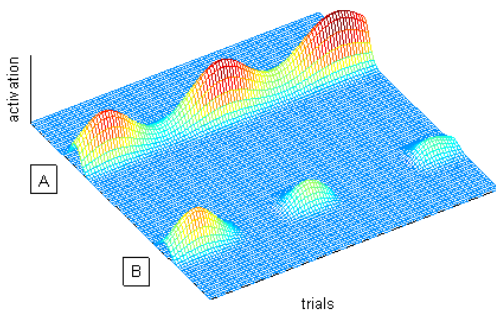

Figure 4: Schematic activation patterns of the movement layer in a hypothetical dynamic field simulation of repeated left-moving trials (towards "A").

A similar type of finding comes from Diamond and Kirkham's (2005) adaptation of Zelazo, Frye and Rapus's (1996) Dimensional-Change Card Sort task, typically used with children. After doing multiple trials with one card-sorting rule, Diamond and Kirkham's participants were then told explicitly that the sorting rule has changed for the next block of trials. Children routinely make sorting errors on the first trial of the new block. Adults do not make categorical errors, but they do produce significantly longer reaction times on the first trial with the new sorting rule. Hindy and Spivey (2008) extended this finding by showing that adults also curve their mouse movements significantly toward the old rule's response option.

These results can also readily be interpreted from the theoretical perspective of deictic pointers or visual indices (Ballard et al., 1997) – such that peaks in the dynamic field may function as the pointers. Chun and Nakayama (2000) state that "…memory traces interact with attentional mechanisms to guide eye movements, cognition, and action." In the case of our experiment, these memory traces are built up from preceding trials, similar to the "pre-shaping" done by the previous trials in the A-not-B task. Fig. 4 provides a visual illustration of these cognitive processes. A peak on one trial builds a memory trace in the field that increases the activation of subsequent trials in that

location ("A"). In addition, inhibitory connections between A and B suppress the activation of the other ("B") location, making these peaks progressively smaller.

The observed difference between the motor priming condition and the phonological priming condition also provides clues as to how semantic tags get associated with deictic pointers. In the motor condition, the only information that is repeatedly associated with the spatial location is the movement. In contrast, the phonological condition had repeated phonological information *and* visual content in addition to the movement. These richer associations may help account for the greater spatial attraction in these trials.

Conclusions

In Experiment 1, we showed that presentations of phonological cohort stimuli result in increased spatial attraction toward the competitor's location, *even though the cohort is not simultaneously present on the critical trial*. There was evidence that this spatial attraction increased due to a genuine effect of phonological competition. In Experiment 2, we modified the conditions to test the dynamic field theory prediction that multiple presentations of similar stimuli result in greater competition. We found evidence that the prime-3 condition resulted in increased spatial attraction toward the competitor in comparison to the prime-1. This can be interpreted as showing that phonological similarity and repeated presentations influence the landscape of the dynamic field. Dynamic field theory as applied to the A-not-B task readily predicts the observed results. For Experiment 1, phonological similarity should influence spatial attraction because the memory traces developed during the repeated trials are stronger than those without phonological similarity. In regards to Experiment 2, repeated presentations should also increase the strength of the memory trace (represented as a pre-shaped field), and cause increased spatial attraction.

Overall, this study and its results add to the literature by providing a indication of how dynamic field theory may be able to account for the data of an A-not-B like task in adults, as well as a novel way of investigating the formation of deictic pointers. The various processes of visual cognition and language in our experiment are spread out in time in such a way that each experimental trial is not independent of previous trials. The landscape of the dynamic field itself is an important theoretical construct for understanding these temporal dynamics. Taken together, these results are powerful support for the value of dynamic field theory modeling and the mouse-tracking experimental methodology. In the future, we intend to conduct additional control experiments within this research program as well as model human data explicitly with dynamic field theory simulations.

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