UNIVERSITY OF CINCINNATI

Date: January 15, 2009

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hereby submit this original work as part of the requirements for the degree of:

Master of Arts

in Psychology

It is entitled:

Observed Interdependence of Cognition and Action: The Hand Says 'No' to ROWS

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Observed Interdependence of Cognition and Action:
The Hand says 'No' to ROWS

A thesis submitted to the
Division of Graduate Education and Research
of the University of Cincinnati
in partial fulfillment of the
requirements for the degree of
Master of Arts
in the Department of Psychology
of the College of Arts and Sciences
2009

by

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Abstract

A pervasive theoretical assumption is that cognition strictly precedes action, like the old saw, “think before you act”. Information accumulates until enough evidence for one decision over others accrues. Thereafter, action simply executes the decision. This assumption, whether implicit or explicit, is most evident in how cognitive performance is studied (Rosenbaum, 2005). Response outcomes, typically as response latencies or accuracies, are the standard measures of cognitive performance. Measuring only the end of a response suggests what intervenes between the onset of a stimulus and the completion of a response is irrelevant. However, recent work guided by dynamic systems theory suggests the relation between cognition and action may actually be one of reciprocal interdependence, where cognition guides action, but action also feeds back to reinform cognition (Stephen, Dixon, & Isenhower, 2007; Van Orden, Holden, & Turvey, 2003, 2005).

In the current studies, participants perform a yes/no semantic categorization task to exemplars (tulip; a type of flower?), nonexemplars (stove; a type of flower?), ambiguous homophones (rows; a type of flower?), and spelling controls (robs; a type of flower?). Trials are completed by navigating a mouse cursor on computer screen to either a ‘yes’ or ‘no’ response box. Participants’ response trajectories are tracked on-line as they unfold. The current results demonstrate that overt changes from one response to another are anticipated by increased instability in motor performance, just prior to the change.

Surprisingly, ambiguous homophones result in the same number of decision changes as all other words. Ambiguity does not manifest itself as a competition between multiple response options, as is commonly assumed (Gottlob, Goldinger, Stone, & Van

Orden, 1997; Plaut, McClellend, Seidenberg, & Patterson, 1996; Rubenstein, Garfield, & Millikan, 1970; Siakaluk, Pexman, Sears, & Owen, 2007; Spivey, 2006). Instead, the homophone ambiguity effect in semantic categorization appears appears to be a tendency to only making errors when participants are certain those errors are correct. When this confound is controlled for, the widely replicated finding that homophones have longer response latencies than spelling controls (Van Orden, 1987) disappears.

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CHAPTER 1:

Introduction

A pervasive theoretical assumption is that cognition strictly precedes action, like the old saw, "think before you act". Information accumulates until enough evidence for one decision over others accrues. Thereafter, action simply executes the decision. This assumption, whether implicit or explicit, is most evident in how cognitive performance is studied (Rosenbaum, 2005). Response outcomes, typically as response durations or accuracies, are the standard measures of cognitive performance. Measuring only the end of a response suggests an independence of cognition and action.

Theories of Cognition and Action

The planning-control hypothesis of cognition and action makes this assumption explicit (Glover & Dixon, 2001a, 2001b, 2001c, 2002a, 2002b, 2002c). Cognition prepares action, but action is ballistic once it is initiated. This hypothesis will be explained, along with two other recent theoretical frameworks gaining attention, in which cognition and action share more intertwined roles. One is the continuity approach (Spivey 2006), where cognition acts as a continuous monitor to action trajectories. Next is an application of dynamic systems theory (Van Orden, Holden, & Turvey 2003; 2005) that puts emphasis on the interdependence of cognition and action, not one-way causality. We will discuss how research in each of these theoretical veins may in fact be revealing the same effects, simply measured in different ways, and how their findings can be used to predict response changes in a semantic categorization task.

The planning-control hypothesis

The planning-control hypothesis of cognition and action states that human behavior is divided into a planning stage and an execution stage (Glover & Dixon, 2001a, 2001b, 2001c, 2002a, 2002b, 2002c). The formation of goals and outcomes occurs during the planning stage. After these processes run to completion, cognition feeds forward instructions to the motor system, which ballistically executes movement to achieve desired outcomes. Glover and Dixon present evidence that support their hypothesis. In object grasping tasks, effects of cognitive manipulations are most prominent at the initiation of a reach (Glover & Dixon, 2002b). This is consistent with cognition being front-loaded before feeding in to action. For example, when semantic labels for grasp aperture ("large" and "small") are incongruent with the necessary grasp aperture, corrections occur at the beginning of otherwise ballistic movements (Glover & Dixon, 2002b; Gentilucci & Gangitano, 1998). When changes in cognition occur online during a reach, for example in the presence of optical illusions, large corrections occur rapidly after a moment of maximum deceleration rather than being temporally drawn out as a reach unfolds (Glover & Dixon, 2001a, 2001b, 2001c, 2002a). This evidence points to cognition and action being temporally disjoint from one another, with cognition unidirectionally sending commands to the motor system.

The continuity hypothesis

In contrast to the planning-control hypothesis, the continuity hypothesis posits that cognition acts as a continuous monitor and real-time updater of action (Spivey, 2006). In situations where multiple response options exist, competition between those options is resolved in real time as an action unfolds. Physical movements directly reflect navigation through a mental space of response options, and thus the unfolding of a physical response can be viewed as a literal window into the unfolding processes of mind (Dale, Kehoe, & Spivey, 2007; McKinstry, Dale, & Spivey, 2008; Spivey, Grosjean, & Knoblich, 2005).

Experiments in the methodological vein of Spivey (2006) situate participants in a forced-choice scenario where responses are enacted by making a physically and temporally extended movement towards one response or another. Response trajectories are then analyzed in terms of how cognitive variables change movement trajectories. For instance, Dale et al. (2007) had participants perform a categorization task where things to categorize were either atypical category members (whale::fish or mammal) or typical category members (human::fish or mammal). A finding from these experiments is that atypicality is reflected as trajectories more eccentrically curved towards the unchosen response. This is taken as evidence of the on-line resolution of ambiguity, and of cognition playing a continuous updating role on action. An important distinction to note is that the planning-control hypothesis predicts changes in action to be rapid re-corrections of otherwise ballistic movement, whereas the continuity hypothesis predicts graded changes in action as cognition unfolds.

Action-cognition interdependence

A third alternative is that cognition and action form an interdependent system. Cognition feeds into action, but action in turn also feeds back to re-inform cognition. This perspective comes from thinking of organisms as self-organizing systems (Stephen, Dixon, & Isenhower, 2008; Van Orden, Holden, & Turvey, 2003; 2005). An important prediction of this approach is that instability in action will feed back into cognition and anticipate switches in responses or cognitive strategy.

Action may contribute to the organization of cognition and thus will anticipate changes in cognition. Stephen et al. (2008) report empirical support for this hypothesis in problem solving. In their experiments, finger and eye movements were recorded as participants solved gear mesh problems. A mesh of interlocking gears were presented and participants solved the problem by reporting whether the final gear would rotate in the same or opposite direction of the initial gear. Almost all participants start by manually tracing how the gears affect each other through the mesh. Eventually, however, they discover the principle of parity by which an odd number of intervening gears ensures first and last rotate in the same direction, and an even number ensures opposite rotation.

The emergence of a parity solution is anticipated online by instabilities in finger and eye trajectories. Action coordination changes before cognition. Perhaps action instability loosens the grip of the finger tracing solution, in a manner of speaking, by feeding back instability to cognition. Irrespective of whether the origin of instability is cognitive or motor, feedback from action to cognition amplifies instability and facilitates emergence of the parity solution, a novel emergent problem solution. Thus, the parity solution emerges in the bodily interaction with gear mesh problems (see also Grant & Spivey, 2003; Thomas & Lleras, 2007; Glenberg & Kaschak, 2002).

As analogy, physical systems self-organize into the configuration most efficient for releasing energy, currently supported by the constraints acting on it. Phase transitions between one configuration and another are anticipated online by a rapid increase in the entropy of system dynamics, which is in turn followed by a rapid decrease in entropy as the system reorganizes into a new stable configuration. For instance, as a layer of thin liquid is slowly heated from below, that energy is dissipated into the surrounding environment by the random collisions between hotter and cooler molecules. As the energy entering the system outpaces the speed at which dissipation releases that energy, the molecules spontaneously reorganize their motions from random movements to the ordered behavior of convection rolls. Hot molecules rise, and in the process cool as they encounter the cooler air above the surface of the liquid, and cool liquid in turn sinks to be reheated by the source below (Rayleigh-Benard convection). Compared to the dissipation from random collisions, convection rolls more efficiently release energy from the system when enough energy is present to support the emergence of ordered structure. Importantly, the phase transition from random movements to convection is anticipated by a rapid increase in the entropy of the system's behavior, followed by a degrease to negentropy as the system reorganizes into ordered, convection rolls. Qualitative changes in behavior are anticipated online by increases in the instability of the system prior to the new behavior. If changes in cognition are likened to phase transitions in physical systems, qualitative changes in cognition should be preceded by measurable increases in the instability of behavior prior to those changes – like the increased entropy and subsequent decrease that Stephen et al. (2008) see in hand and eye movements prior to and just following the transition from manually tracing a gear mesh problem to applying parity.

Reconciling the differences

Interdependence of cognition and action shares surface similarity with the planning-control model. Both predict that changes in action due to cognitive effects can be abrupt. Cognition and action interdependence assumes a self-organizing system in which changes can be qualitative (e.g., from one problem solving strategy to another). Cognition and action are inherently sensitive to changes in each other, and instabilities in action feed back to contribute to rapid changes in cognition. The planning-control hypothesis expects the presence of qualitative change, with abrupt transitions in motion reflecting the finalization of new plans and goals.

In general, differences between how these three theoretical frameworks approach the coordination of cognition and action, and experimental results supporting each, may simply be the product of different methods of measurement. The planning-control model and theories based on action-cognition interdependence both predict and observe the presence of qualitative changes in behavior. A critical component of the latter class of theories is instability, or changes in variability. However, work on the planning-control model has exclusively focused on measures of mean performance, and ignored issues of variability within a response. Prior research does not observe any evidence of feedback from action to cognition, because it has not looked at measures that would reveal such effects.

Comparatively the issue of instability is critical to both the continuity hypothesis and theories based on action-cognition interdependence. In the continuity hypothesis, instability formed by competition of attractors is resolved on-line as an action unfolds. This creates graded strengths of attraction towards one response or another. When discussing action-cognition interdependence, instability is amplified by iteratively feeding it through the system. This eventually results in qualitative changes to new, stable modes of cognition and response.

The particular way instability has been measured by the continuity hypothesis precludes the possibility of identifying qualitative change. Instability is aliased by the area between an actual response trajectory and a straight-line path to the chosen response. The larger this area, the more effort is spent by action in considering multiple response options. The issue, however, is that this method cannot distinguish between late commitments to a response and overt changes in decision (Figure 1). The presence of qualitative change is obscured by other events. Competition of alternative responses is of course seen as a graded effect because the techniques for measuring competition are not capable of identifying anything but graded effects.

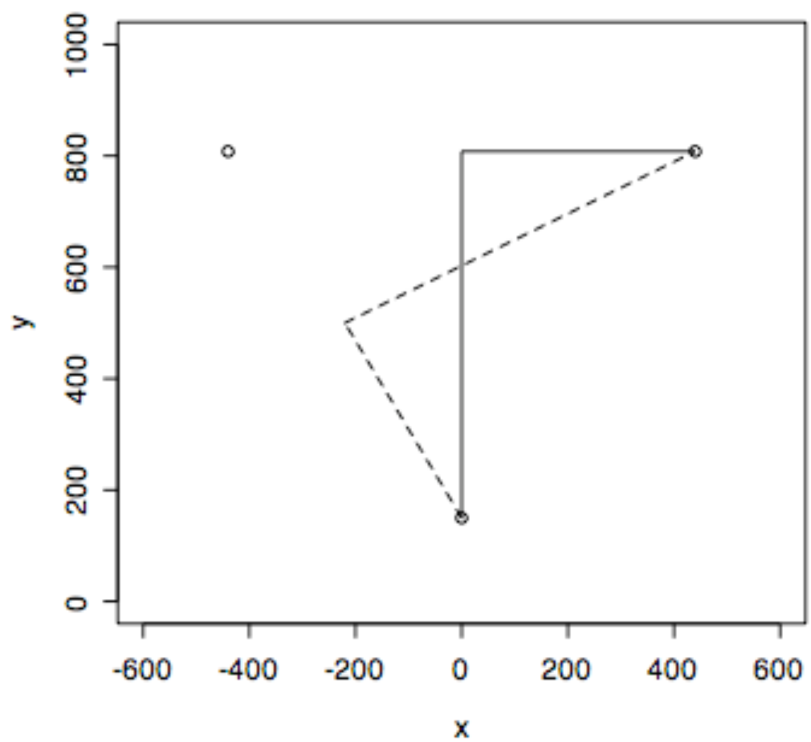

Figure 1. Plotted are two mock trajectories from the response paradigm used by Spivey, Grosjean, and Knoblich (2005). Both encompass the same area between their boundaries and the straight-line path to the chosen response. One demonstrates qualitative change from one response to another (dotted lines), and the other does not.

Work based on the planning-control model sees front-loaded cognition sending discrete commands to the motor system because the methods employed only allow for the observation of qualitative change. Work based on the continuity hypothesis sees continuous modulation of action by cognition because the method employed only allows for the observation of graded change. When a task that allows for both types of change to be observed is employed, yet another picture is seen – one where graded increases in variability (instability) leads to qualitative changes in behavior (e.g., Stephen et al., 2008).

In the problem solving study of Stephen et al. (2008), the stimulus gear mesh supports two alternative solution strategies, and the transition from one to the other is anticipated by motor instability prior to the "tipping point" from one strategy to the other. Change in strategy is a process that unfolds over many trials. Typically, cognitive psychology is interested in what happens on a *single* trial; how is a single grasp response conducted, or how does a person decide if a word is a member of one category or another?

The present research is concerned with how the relationship of action and cognition can be characterized in trial-level data. Outcome measures are blind to fine details of motor kinematics. Summary trial data sample phenomena across intervals of time too long, or too sparse to capture this level of detail. To see this detail requires measurement procedures that sample the continuous unfolding of action. For example, densely sampled mouse-cursor trajectories have been used with categorization and judgment tasks (e.g., Dale, Kehoe, & Spivey, 2007; McKinstry, Dale, & Spivey, 2008; Spivey, Grosjean, & Knoblich, 2005). And, more recently, the Nintendo Wii remote has been used to densely sample three-dimensional response trajectories (Dale, Roche, Snyder, & McCall, 2008). The present research uses densely sampled mouse-cursor trajectories to reveal response dynamics as participants change their mind on-line during a semantic categorization task.

CHAPTER 2:

Experiment 1 – Observed Interdependence of Cognition and Action Within Individual Decisions

In the current study we use homophone words, which create ambiguity during semantic categorization (e.g., rows::kind of flower) to study trial-level response behavior. Van Orden (1987) previously examined the very high rate of false-positive category responses to homophones, about 30% on average, to establish the presence of phonology in reading. Here we examine densely sampled response trajectories to better understand cognition and action interdependence during trial-level performance.

We replace Van Orden's (1987) key press and oral response measures with ones based on streaming x-y coordinates densely sampled from a computer mouse. We collected mouse-cursor trajectories during homophone trials (rows::kind of flower) and control trials to examine the directional dependence of cognition and action. Mouse trajectories fall into two prominent modes of responding. The first mode is to move directly to a response option and select it. The second mode is to move to one response option, and then switch to the other once it is reached. We demonstrate that measured instability in the mouse cursor's velocity as it approaches a response predicts the spontaneous change from one response to the other.

The semantic categorization method used here is modeled on experiment 1 in Van Orden (1987) combined with a response methodology similar to Dale et al. (2007). Participants perform semantic categorizations to homophones (rows::kind of flower) and control words (robs::kind of flower) by navigating a mouse to either a *yes* or *no* response box.

Method

Apparatus

Experiments were conducted on a standard Dell desktop computer running Windows XP. The computer monitor was a 17” CRT and was set to 1280x1028 pixel resolution.

Procedure

On each trial, participants were presented with a category (e.g., kind of flower) centered at 100 pixels below the top of the screen. Under the category name to the left and the right were 200x60 pixel boxes containing the response words *yes* and *no*, offset from the sides of the screen by 100 pixels. Which side of the screen the two options appeared on was counterbalanced between participants. Below those options was another 200x60 pixel box, centered, initially containing a pattern mask ######. At the bottom of the screen was a staging area, a circle, with 100-pixel radius, centered, and offset from the bottom edge of the screen by 100 pixels (see Figure 2). Participants began each trial by clicking the center dot of the staging area and moving their mouse outside of its radius. As the mouse left the staging area, the pattern mask was replaced with a target word. Thus participants were forced to initiate a trajectory before a target was presented. This procedure counters a previously observed response strategy in which participants wait until target perception is complete before initiating a trajectory, which would hide cognitive dynamics of categorization (Spivey, Grosjean, & Knoblich, 2005).

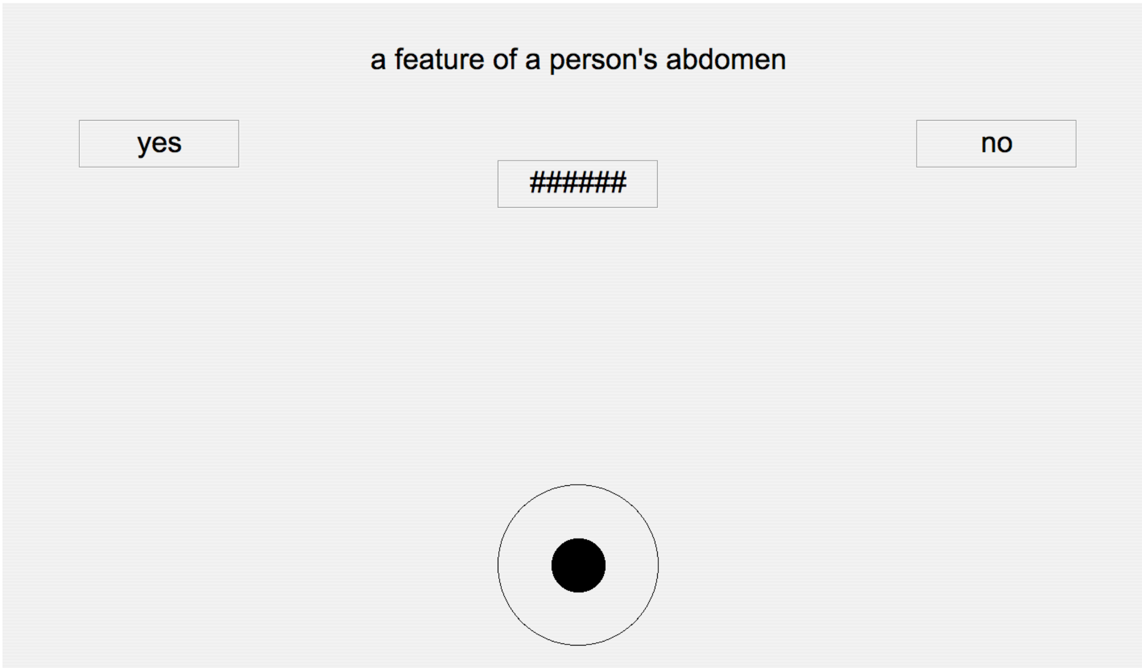

Figure 2. One example trial from Experiment 1. Participants were instructed to click on the target area, and then move their mouse out of its radius. At this time, the mask ###### would be replace by a word. Participants would have to identify the word as being a member of the displayed category or not.

Participants moved the cursor to respond by clicking the *yes* box, if the target was an exemplar of the displayed category, and the *no* box otherwise. Once a response was made, the next trial began immediately, presenting the next category phrase and re-displaying the pattern mask. Mouse position was sampled at 66 Hz.

Each participant completed a total of 100 trials. The first 20 trials presented a fixed set of 10 exemplars and 10 nonexemplar pairs in a fixed order as practice trials. The remaining 80 trials contained 30 exemplars (e.g., tulip::a type of flower), 30 nonexemplars (chair::type of flower), 10 homophone foils (rows::type of flower), and 10 control nonexemplars (robs::type of flower). Control foils were matched to homophones for frequency and orthographic similarity (see Van Orden, 1987). Stimuli in the test trials appeared in random order. A total of 8 categories were displayed in the test session. For each category, there were 3 exemplar words, 3 nonexemplar words, 1 homophone foil, and 1 control word. The homophone foils, control foils, and category names were taken from Appendix A of Van Orden (1987).

Participants

21 undergraduates from the University of Cincinnati participated for course credit. Inspection of the response trajectories found one participant who traced the border of the screen before making a decision. That participant's data were excluded from analyses.

Trial filtering

Responses longer than 8 seconds were dropped from the analysis (0.6% of all responses). These responses involved participants repeatedly cycling back and forth between response options without making a selection. While possibly interesting in their own right, these responses did not fit with the two modes of responding we observe across all the other trials and have been excluded based on this.

Recurrence Quantification Analysis

RQA is a tool for quantifying temporal properties of a time series in phase space (Webber & Zbilut, 1994). Relevant to this experiment, it provides estimates of stability of behavior within a phase space, as well as estimates of the structure of that phase space. Two measures of stability we analyze are longest diagonal line (MAXLINE) and percent determinism (%DET). MAXLINE is a count of the longest consecutive sub series composed of points that are neighbours in phase space. It is directly related to attractor strength, and in turn, stability. %DET is the proportion of points in a recurrence plot that occur along a diagonal line. Thus, it can be viewed as the extent to which forces are actively constraining behavior and again, in turn, a measure of stability. These measures will be used to compare the stability of different response modes in this experiment. We will also look at the Shannon entropy of diagonal line lengths in phase space (LENTR). This is a measure of how homogeneous the phase space is; it is informative of the amount of temporal structure that a trajectory has.

Results

False positive errors

We first compare false positive error rates with the previous findings of Van Orden (1987), to establish comparable outcomes. To count as a false positive, Van Orden required both the category decision and the actual exemplar pronunciation to be false positives (e.g., response 'yes' that *rows* is a *type of flower*, followed by the pronunciation /roz/, i.e. 'yes' /roz/). Homophone foils yielded 29% false positives (SE = 6.9%); control foils yielded 5% (SE = 3.1%). The present experiment's outcomes were similar with homophone foils yielding 31.5% false positives (SE = 2.8%) and control foils 7.5% (SE = 2.0%) (homophones $t(28) < 1$; controls $t(28) < 1$). Also in the present experiment, false positives to non-control nonexemplars were 3.2% (SE = 0.7%) and miss errors to exemplars were 12.8% (SE = 1.8%).

Feedforward effects of cognition to action

Ambiguity in response options creates the opportunity for decision change. We analyzed the closest horizontal distance that each response trajectory gets to its alternative response option. This is the point along the x-coordinate where participants change their direction of movement. Or, if no direction change is made, it is where along the x-coordinate participants iniate their response from. If participants are making decision changes, this changes should be revealed as bimodality in the distribution of closest horizontal distances to the alterative response. There should be a qualitative difference between trials that go straight to a response versus those that first move to an alternative and then change directions. Results are displayed in Figure 3.

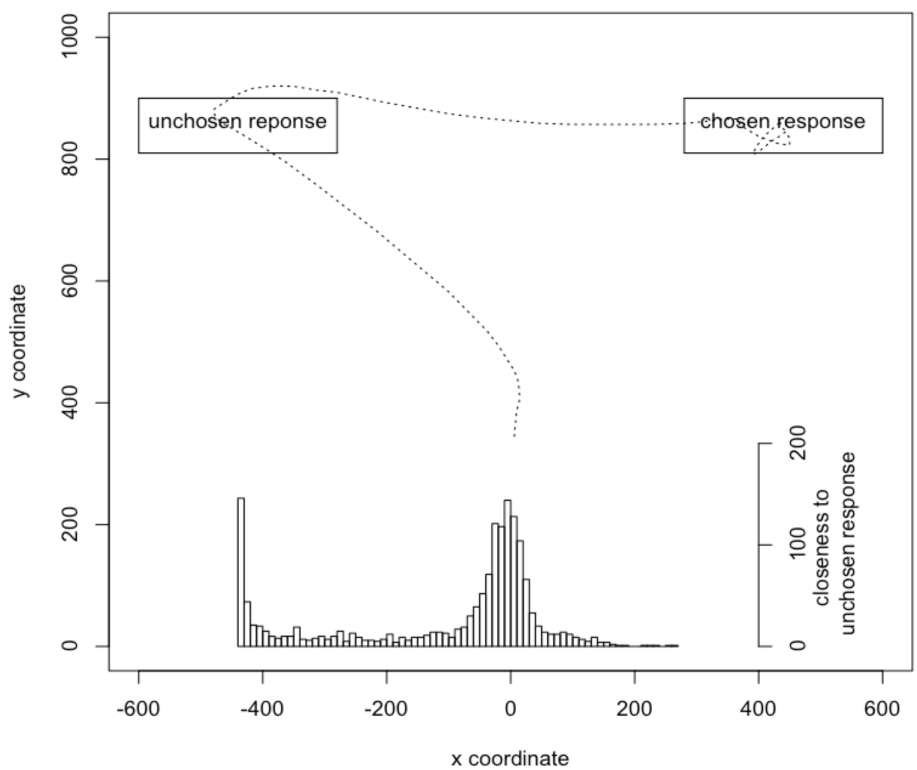

Figure 3. The distribution of closest horizontal distance to the unchosen response is displayed, superimposed on a sample trial.

Horizontal proximity to the alternative response is a bimodal distribution. Strikingly, change in direction almost exclusively happens when a person's mouse cursor is horizontally aligned with a response box. In Figure 3, this is evidenced by the mode at an x-coordinate of -440 pixels, which is the center of the unchosen response option. If participants move towards an unchosen response, they are likely to move all the way to it and do not change their direction of movement mid-flight. Mid-flight changes are indexed by the mass of the distribution falling between the center-line of the screen (x-coordinate 0) and the center-line of the unchosen response (x-coordinate -440). The gradation starting at the center of the unchosen response box out to -340 pixels all occurs within its horizontal space, and is reflecting accuracy on aligning with the center of a response box, not direction changes occurring on the way to it (response boxes are 200 pixels wide, and thus have a width of 100 pixels to either side). Direction changes almost always occur *at* the horizontal position of a response box, rarely on the way to it.

Feedback from action to cognition

Feedforward effects of cognition to action exist, and changes in decision are qualitative. If action is reciprocally feeding back to cognition, cognitive changes should be anticipated by increased instability in action just prior to a change in direction. We tested this possibility by looking for instability in trajectory velocity (measured in pixels/msec) prior to the locus of a decision change on correct homophone trials, relative to the same values prior to an actual response.

The presence of a decision change was operationalized as a change in direction after exceeding a threshold amount of movement towards one response. Our threshold was a horizontal distance of 220 pixels from the center of the unchosen response box (see

Figure 3). This is midway between the horizontal center of the screen and the unchosen response's box. Analyses were rerun with thresholds ranging from 300 to 100 pixels in increments of 10, with no change in results. Thus, we only discuss the 220 pixel results.

The locus of a decision change was marked as the first zero crossing of the x-coordinate derivative, within the largest change in direction along the x-coordinate (Figure 4). The x-coordinate derivates were noisy time series. Before using them to identify the locus of a decision change, they were first smoothed. This was done with the *LOESS* smoothing algorithm, which sets the value at each observation as a weighted average of adjacent points. Exact details of the algorithm can be found in Cleveland (1979).

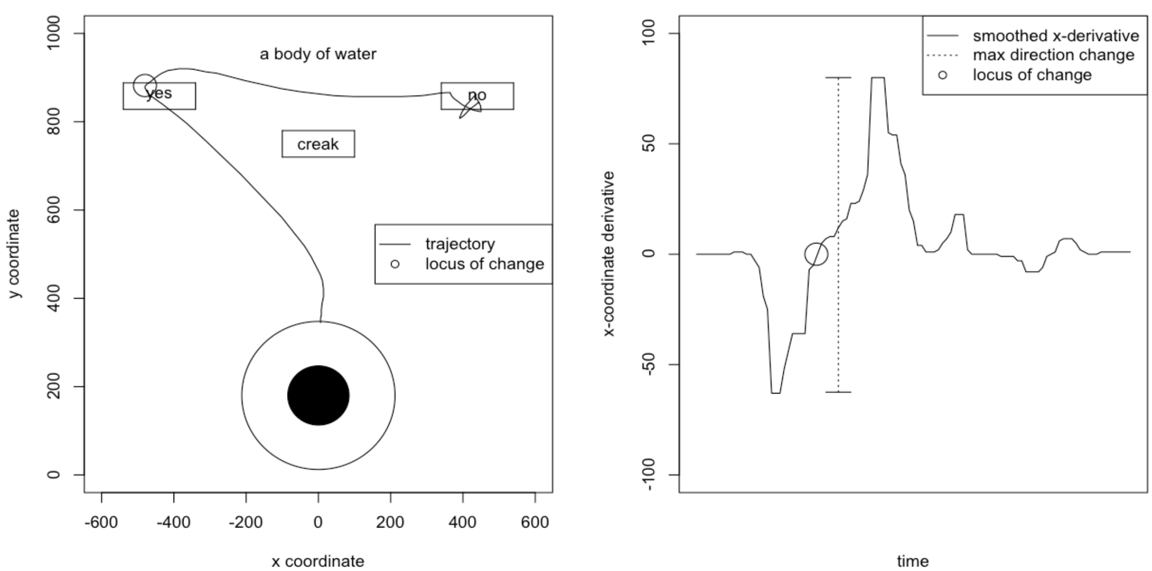

Figure 4. The locus of a decision change was identified as the first zero crossing of the x-coordinate's derivative prior to the largest monotonic change in direction.

Instability was estimated by the standard deviation of velocity within successive 50msec windows prior to a decision change or response. Nine different windows were examined: 0msec to 49msec, 50msec to 99msec, up to 400msec to 449msec prior to a decision change or response. Standard deviations of velocity within these windows are averaged over participants, and plotted in Figure 5. An increase in variability is seen around 200-150msec prior to a decision change. Increase in the variability of motor performance is anticipating qualitative changes in cognition.

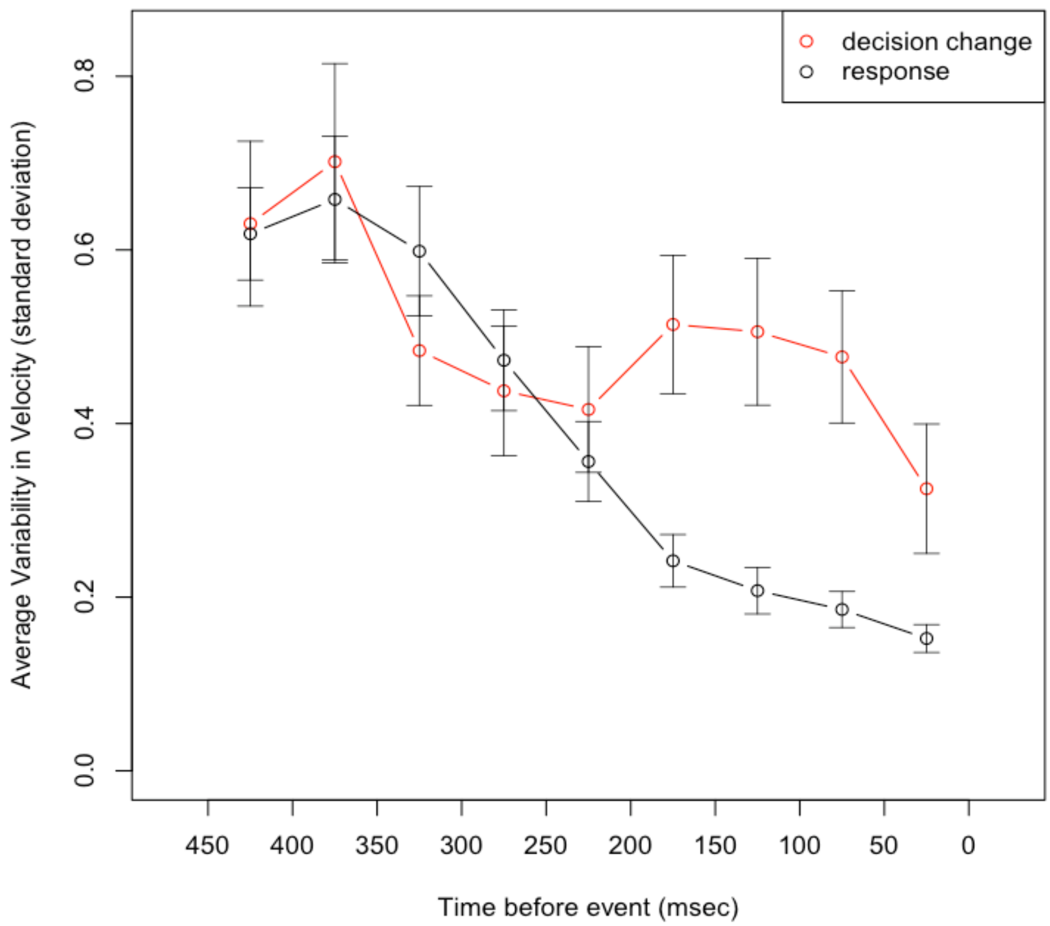

Figure 5. Displayed are average standard deviations for velocity over nine successive 50msec windows prior to the onset of a decision change or a response. The onset of a decision change is anticipated by a relative increase in the variability of action 150-200msec prior to that change.

A within subjects repeated measures ANOVA was conducted on the variability data for the successive 50msec windows leading up to a decision change or a response. There was an effect for type of event, ($F(1, 314) = 12.36$; $p < 0.01$), an effect for time ($F(8, 314) = 13.19$; $p < 0.01$), and a reliable interaction of the two effects ($F(8, 314) = 4.16$; $p < 0.01$). Post-hoc comparisons were made between the two response types at each of the nine time windows, with a Bonferroni alpha correction applied. Of these, only the post-hoc comparisons in the ranges of 199-150msec, 149-100msec, 99-50msec, and 49-0msec prior to one of the two events are statistically reliable (each $p < 0.001$).

Standard deviation is a coarse measure of instability. Trial data were additionally submitted to recurrence quantification analysis. We computed two measures of instability, %DET and MAXLINE for trials with and without decision changes (RQA, and both measures are detailed in the methods section). Results were collapsed by participant. On decision change trials, only the portions of a trial preceding the locus of a decision change, not following it, were used. We are primarily interested in instability that anticipates decision changes. The presence of a decision change is instability at a different scale, and we did not want this to influence results.

Trajectories preceding responses had a higher %DET than trajectories preceding decision changes. Values were 0.88 ($SE = 0.01$) and 0.80 ($SE = 0.02$), respectively. This difference was reliable (paired $t(19) = 4.68$; $p < 0.01$). Trajectories preceding a response had a higher MAXLINE than trajectories preceding a decision change. Values were 17.43 ($SE = 1.64$) and 12.94 ($SE = 1.46$), respectively. This difference was also reliable (paired $t(19) = 4.51$; $p < 0.01$). Both of these results suggest trajectories preceding a decision change are less stable than trajectories preceding a response.

No reliable differences were found in the line length entropy analysis. Values were 1.86 (*SE* = 0.15) for decision changes and 1.98 (*SE* = 0.09) for non-change responses, with $t(19) < 1$. No difference in entropy may simply be due to the difficulty in calculating line length entropies over short time series (mean observations/series = 57.11). Notably, this non-reliable difference is also in the opposite direction as expected.

In these analyses, the likelihood of decision change was 21% on correct 'no' homophone trials. Surprisingly, it was equally high for correct responses to spelling controls, exemplars, and nonexemplars (21%, 22%, and 20%, respectively; see Table 1.1 for a breakdown of response mode likelihoods). This result was unexpected and led to post-hoc analyses which are reviewed next.

Post-hoc response latency analyses

Post-hoc analyses were performed on the latencies of correct 'no' homophone and control responses, broken down by trials with and without decision changes. Bar plots of the RT distributions are displayed in Figure 6.

When RTs within only one response mode (decision change or no change) are examined, there are no differences between correct responses to homophones and controls, despite the widely observed finding that correct semantic categorizations to homophones take longer than spelling controls (Van Orden, 1987). However, when both types of responses are pooled, this classic finding is recovered with correct homophone responses having a mean latency of 2280 msec (*SE* = 145) and controls having one of 2023 (*SE* = 109). This difference is statistically reliable (paired $t(19) = 2.33$; $p < 0.05$).

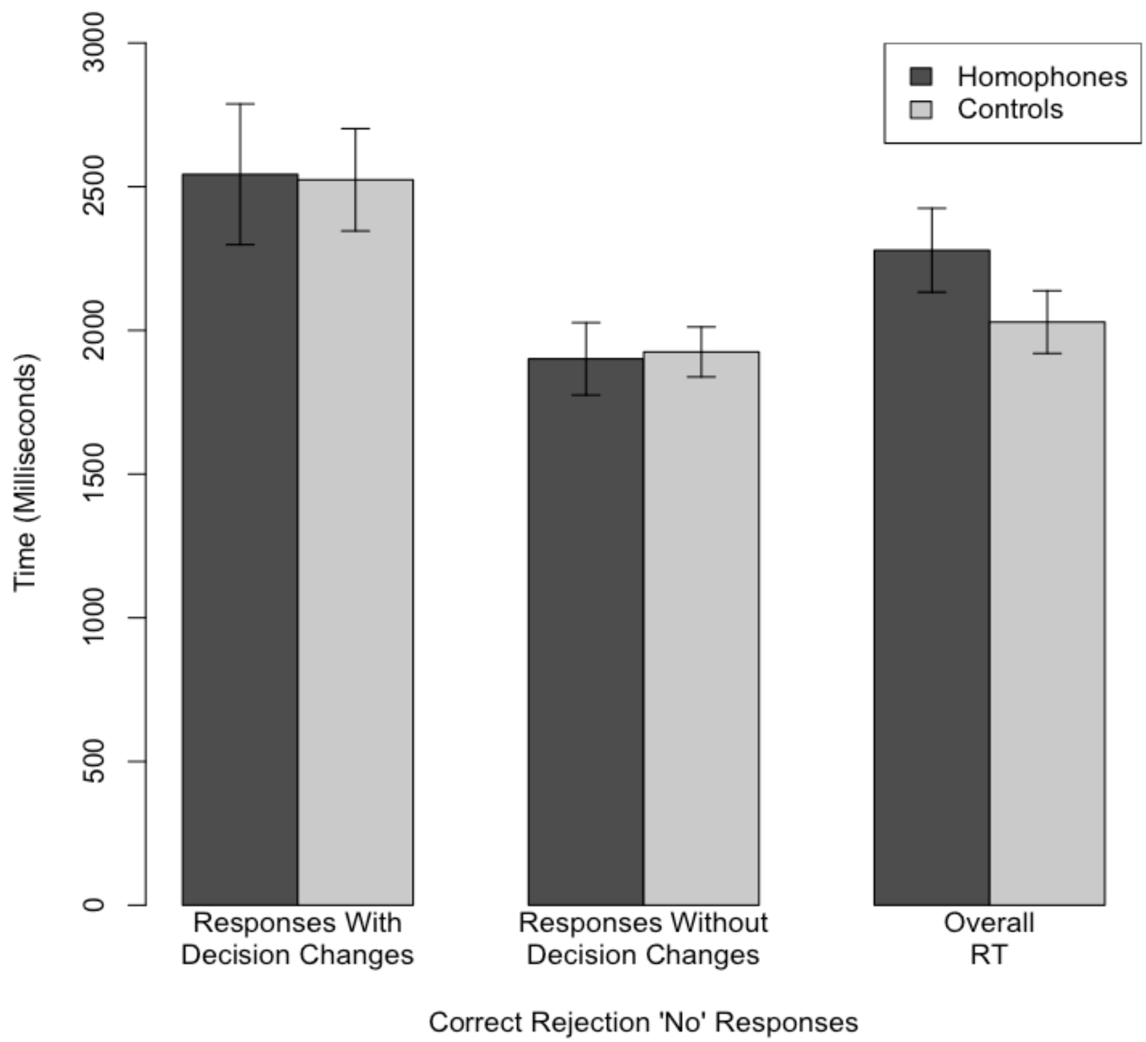

Figure 6. Correct ‘no’ homophone response latencies are slower than correct ‘no’ control response latencies. However, when only responses with or without decision changes are analyzed, differences between homophone and control response latencies are not evident. This implies that slower homophone responses arise from proportional differences in response modes between homophones and controls.

Approximately 20% of both homophone and control responses are correct ‘no’ responses with decision changes. However, 72% of control responses are correct *without* decision changes, whereas only 47% of homophone responses are correct without decision changes (see Table 1). Since responses with decision changes are slower than responses without decision changes, the weighted average of correct response latencies to homophones is higher. This suggests that the ubiquitous slower response times when categorizing homophones may not be an overall processing disadvantage but, rather, differences in the proportions of response modes.

	Correct Response		Incorrect Response	
	With Change	Without	With Change	Without
homophone	0.21	0.47	0.10	0.22
control	0.21	0.72	0.04	0.04
exemplar	0.22	0.66	0.06	0.07
nonexemplar	0.20	0.77	0.02	0.02

Table 1. The likelihood of responses being correct or incorrect, and containing decision changes or not. All types of words have the same likelihood of responses being correct and with decision changes. The largest discrepancy between word types is that some homophone responses without decision changes are incorrect instead of correct.

Given these results, there is every reason to think that an analysis of means is not the correct method for comparing overall response latencies. The response latencies for homophones are not all being shifted upward, which is when a comparison of means would be useful. Instead, proportionally fewer fast responses are contributing to the overall distribution of correct ‘no’ homophones, relative to correct ‘no’ control responses. A measure of median performance more accurately reflects central tendency in this case. When overall correct ‘no’ homophone and control responses are presented as box plots with median performance, instead of barplots with mean performance, it is evident that the distribution of homophone responses has less mass in the fast tail, and more mass in the slow tail, with only a marginal impact on the median response time (Figure 7).

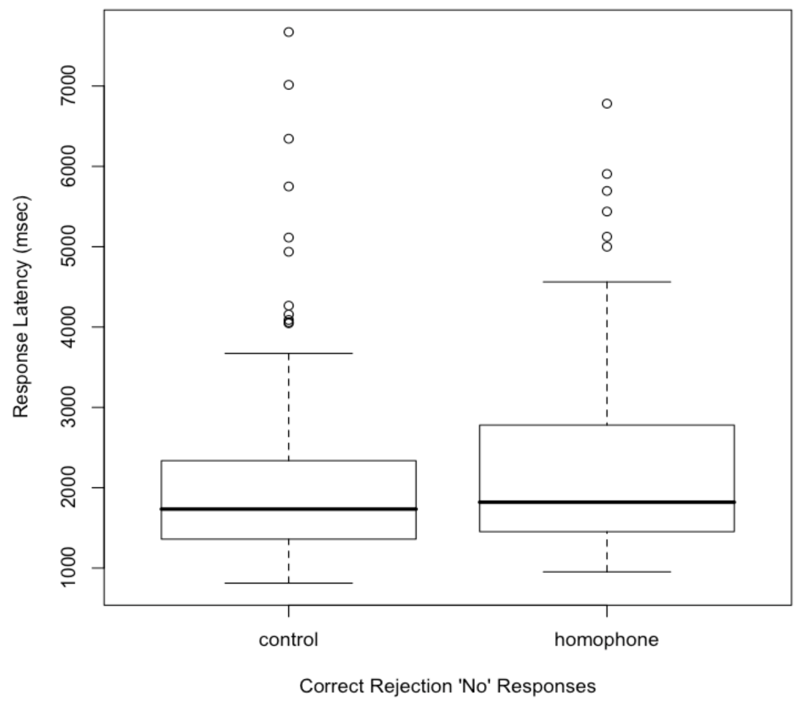

Figure 7. When the overall distribution of correct ‘no’ responses to homophones and controls is displayed as a box plot, it is apparent that the effect of slower mean ‘no’ response latencies to homophones is not an overall shift of the distribution but, rather, less of the distribution’s mass being in the ‘fast’ tail and more being in the ‘slow’ tail.

Discussion

Stephen et al. (2008) demonstrated that inter-trial changes in cognitive strategy are anticipated online by increased instability of motor behavior. This has been taken as evidence for the interdependence of cognition and action. We have demonstrated a similar finding for intra-trial changes in cognition; response changes are anticipated online by increased instability of motor behavior. From this, we draw a similar conclusion as Stephen et al., at the level of individual responses instead of collective strategy. This is a surprising result; it is typically assumed that cognition feeds unidirectionally into action during a trial response.

Our results also demonstrate that slower average correct response times to homophones are conflated with how response modes are distributed. The homophone disadvantage in correct response times may have nothing to do with difficulty of responding to homophones but, rather, how responses without decision changes are distributed. One corollary to this conclusion is that averaged incorrect latencies to homophones should be faster than those to controls, because they include proportionally more responses without decision changes.

Indeed, this is the case. The mean latency for incorrect 'yes' homophone responses is 1776 msec, whereas for controls the average latency is 2562 msec. This large difference is not statistically reliable, however, due to the small number of incorrect responses to spelling controls. A second corollary is that when correct and incorrect responses are pooled, this should eliminate any difference between latencies for homophones and controls, because this balances the proportions of responses with and without decision changes. This is seen in our results. The overall latency for both 'yes' and 'no' responses is 2092 msec for homophones, and 2069 msec for controls, with $t(19) < 1$.

All these results are consistent with the idea that cognition and action share a mutual interdependence. This interdependence is typical of dynamic, self-organizing systems (Stephen et al., 2008; Van Orden, Holden, & Turvey, 2003; Van Orden, Holden, & Turvey, 2005). In addition to the various theoretical questions this assertion raises, it also reveals practical concerns. Most poignantly, *what do measures taken exclusively at response outcomes reveal about cognition?* The vast majority of laboratory tasks measure behavior only at the outcome of the response. However, if cognition and action are interdependent, such methods are necessarily overlooking informative dynamics prior to the response outcome.

Relevant to this concern, our most surprising result was that spelling controls, exemplars, and nonexemplars each had the same likelihood as homophones of eliciting decision changes on the way to a correct response – in the order of 20% of trials. The crux of word ambiguity effects is typically thought to be a competition between, or instability of, multiple response options that originates in the ambiguity of the stimulus, as the homophone ROWS is ambiguous for instance (Abrams & Balota, 1991; Gottlob, Goldinger, Stone, & Van Orden, 1997; Plaut, McClellend, Seidenberg, & Patterson, 1996; Rubenstein, Garfield, & Millikan, 1970; Siakaluk, Pexman, Sears, & Owen, 2007). This perspective predicts more decision changes on homophone trials, compared to other words, but not what we found. All categories of word trials were equally likely to include decision changes to correct responses. Moreover, a decision change versus no decision change coincides with a very large difference in response time as Figure 6 illustrates.

If these results generalize they bring into question all previous findings concerning word categories and response times. That is, response time effects based on word properties must be reinterpreted to agree with a probability of decision change explanation. However, prior to such a drastic step there remain other options to explain the present outcome. For instance, the presence of homophones in the task may exaggerate participants' expectancies of ambiguity, and induce an eccentric response strategy to all stimuli. This is what we test in Experiment 2.

CHAPTER 3:

Experiment 2 – The Source of Decision Changes in Trial Responses

Results from Experiment 1 suggest that observed latency differences of homophones and other words are due to a difference in the distribution of non- decision change trials. However, the rate of decision change was surprisingly high for non-homophones. This experiment is designed to test whether the presence of homophones is inducing a task-wide exaggeration of participants' expectancies of ambiguity, and propensity to change responses.

In this experiment, participants will perform the same task as Experiment 1, without homophones present. We find that participants still make the same amount of decision changes when responding, and conclude that it is not the presence of homophones that is driving the overall propensity to make a decision change.

Method

Apparatus and Procedure

The same apparatus, procedure, and stimuli from Experiment 1 are used, with the exception that the 10 homophones appearing in Experiment 1 are replaced with 10 new category exemplars.

Participants

10 undergraduates from the University of Cincinnati participated for course credit.

Trial filtering

Responses longer than 8 seconds were dropped from the analysis, as in Experiment 1.

Results

The likelihood of decision change

The likelihood of decision change was calculated across all classes of words. The presence of a decision change was calculated the same way as in Experiment 1. Results are displayed in Table 2.

	Correct Response		Incorrect Response	
	With Change	Without	With Change	Without
homophone	---	---	---	---
control	0.34	0.63	0.00	0.03
exemplar	0.26	0.60	0.06	0.08
nonexemplar	0.23	0.71	0.03	0.02

Table 2. The likelihood of responses being correct or incorrect, and containing decision changes or not. Homophones are not present in this experiment. Despite this, the likelihood of decision changes being present is comparable to Experiment 1. This suggests that decision changes are being brought about by the inherent uncertainty of making a forced-choice response, and not a exaggerated perception of ambiguity brought about by the presence of homophones.

Even without homophones present, participants are still making an equally high number of decision changes. When the likelihood of making decision changes to controls, exemplars, and nonexemplars in this experiment are compared to their counterpart values from Experiment 1, there are no reliable differences (all $p > 0.05$). Decision changes appear to be the result of the uncertainty inherent in forced choice tasks, not the ambiguity of homophones.

Discussion

We believe that decision change is a product of having to make a forced choice response. The presence of a decision change is observable, even when ambiguous stimuli are not. The previous literature on homophone categorization takes for granted the notion that averaged outcome measures are transparent to the cumulative events leading up to those outcomes. We suggest this is not the case. Longer latencies do not mean longer processing time for homophone responses. Longer latencies are reflecting a difference in the distribution of response modes for homophones, over other words.

It is interesting to note that these results were foreshadowed as early as the first experiment to definitively establish the role of phonology in reading (Van Orden, 1987). Van Orden found that when the long tails of correct response RT distributions were truncated, the homophone effect disappeared. Effectively, this was rebalancing the proportions of the two response modes within homophones, by selectively removing trials with decision changes.

Our data suggest the fundamental difference between responding to homophones and controls in a forced choice categorization task is that *more errors are made to homophones, but only when the participant is certain their error is a correct response.* This is at odds with what we conceptually associate with ambiguity. Ingrained in this notion are the ideas of competition, uncertainty, and fuzziness, from the scale of reading individual words, to making decisions about college or finding a job. At this point, it is worth revisiting the 0.6% of trials (n = 10; n = 5 of which were homophones) that were filtered from analyses in experiment 1. All of these were trials longer than eight seconds, and characterized by a cycling back and forth of the mouse between the two response options. Cycling back and forth is congruent with what we typically understand ambiguity to mean. Perhaps it is these very extreme, very few, qualitatively different cases that are picking up on what we mean by ambiguity in homophone experiments. It would be interesting to revisit these extreme trials, and understand what is happening, on a case-by-case basis. However, for the remaining 99.5% of responses, the homophone effect seen in laboratory experiments appears to be one of only making errors when those errors appear to be correct responses.

One hypothesis of attempting to generalize our results is that homophone effects should only exist when there are multiple, plausible response options. In fact, Siakaluk et al. (2007) have looked at this. When yes/no semantic categorization is performed to homophones and only one response is plausible, e.g., rows::an animal?, opposed to rows::a flower? as we performed, homophone effects disappear. Curiously, however, when a no-go/go response is employed instead of a yes/no response, homophone effects resurface even when only a single response option is plausible. That is, it takes longer to correctly reject rows::an animal? with a 'go' response than a spelling control like robs. Our results do not speak to this, and it is interesting that they do not.

Another curious finding is that there is an *ambiguity advantage* in lexical decision (Kawamoto, Farrar, & Kello, 1994; Kellas, Ferraro, & Simpson, 1988; Millis & Button, 1989). Words with multiple senses (e.g., *bank*, *fool*, *bond*) are correctly recognized faster than other words with similar frequencies, but only one sense. Our data suggest that the crux of homophone ambiguity effects, at least in semantic categorization, is an issue of responses without decision change being split between correct and incorrect choices. Generalizing this idea, ambiguity advantages should not be possible in lexical decision tasks, because both senses would result in the same response (i.e., it is a word). Obviously, the linkage between homophone ambiguity and ambiguity in general, semantic categorization and lexical decision, or no-go/go and yes/no responses for that matter, is disjointed. Why this is, is a curious question.

The answer may be as simple as all Psychological effects are, in part, a function of actually making a response (action feeding into cognition), and that different tasks necessitate different types of responses. In these two experiments, we see that what is traditionally referred to as the homophone disadvantage is actually a confluence of the task effect of being able to change one's response, and the fact that participants only make homophone errors when they are certain their error response is a correct response (i.e., when they do not have a decision change). Committing to- and later uncommitting to- a response is possible with a yes/no response paradigm, and an option differentially taken advantage of by homophones and spelling controls. However, the problem of whether or not to commit to a response in the first place is the issue posed in a no-go/go task. They necessitate fundamentally different ways of responding, which is changing how action and cognition can interact.

The result of Siakaluk et al. (2007) these data do not speak to – that when neither interpretation of a homophone is incongruent with a category context (e.g., hoarse::a type of flower), no homophone effect is visible with yes/no responding, but is with no-go/go responding – may be because action and cognition are interacting in different ways for yes/no tasks and no-go/go tasks. Our experiments demonstrate that the homophone effect for yes/no responding is a propensity to commit to a response when it is incorrect. When both interpretations of a homophone lead to the same response (such as with hoarse::a type of flower), this is an inconsequential point, and why Siakaluk et al. (2007) do not see a homophone effect in this situation. However, if the crux of a no-go/go task is whether or not to commit to a response in the first place, it is plausible that an effect would still be seen even when both interpretations of the homophone entail the same response. This is because homophones have more interpretations to incorrectly commit with, compared to spelling controls. As the window for making a ‘go’ response approaches its end, the cumulative probability of false alarming to a homophone rises steeper than a spelling control, because there are more interpretations to false alarm to.

CHAPTER 4:

General Discussion

We began these experiments with a discussion of three hypotheses about the relation between cognition and action – the planning-control hypothesis, the continuity hypothesis, and one of cognition-action interdependence. The planning-control hypothesis suggests a strict boundary between action and cognition, where the cognitive system tells the motor system to carry out specific goals, and then the motor system fulfills those goals with ballistic movement. The continuity hypothesis suggests more closely coupled cognitive and motor systems, with cognition constantly monitoring and updating actions as plans, goals, and thoughts resolve in real time. The cognition-action interdependence hypothesis suggests a fundamental integration of the two entities, where cognition is not only informing action, but action is in turn feeding back to reinform cognition.

Our data suggest that the type of relation between cognition and action is one of reciprocal interdependence. Cognition is informing action, but action is also informing cognition. Changes in cognition are reflected as overt shifts from one response to another. However, these changes are in turn anticipated by instabilities in motor performance. Results from each of these three veins of research are largely congruent, simply interpreted in different ways. When testing the planning-control hypothesis, one of the major findings reported by Glover and Dixon is a propensity for rapid recorrections of grasping motions in the presence of optical illusions (2001a, 2001b, 2001c, 2002a). This bears resemblance to our result that response changes in yes/no semantic categorization tasks are characterized as overt directional changes, as opposed to graded corrections from one response to another. We suspect that, were their experiments to be replicated and grasping motions continuously measured, an increase in the variability of grasp aperture would be apparent just prior to their observed, rapid recorrections.

A common result of work in the vein of the continuity hypothesis is that participants spend more time moving in the space between response options when responding to ambiguous and atypical stimuli. While we do point out that their measures are confounded by an inability to differentiate between qualitative and quantitative changes, the research is still valid insofar as it makes salient the importance of understanding motor variability in response data, not simply response outcomes. Our finding that the variability in trajectories is higher prior to a decision change than a response can be seen as a reaffirmation of this point.

Both the planning-control and continuity hypotheses put cognition at the root of all observed change. Perhaps this is simply because research in each framework only identifies one type of change (qualitative or quantitative, respectively); since there is only one type of change, why posit the existence of multiple sources for that change? The relevance of cognition-action interdependence only becomes apparent when one has to reconcile the fact that our behavior is characterized both by overt changes and continuous fluctuations in performance. This means it is simply not enough to measure response outcomes. To understand behavior, one must measure changes in cognition and action from the onset of that behavior to its completion.

At the end of Experiment 2, we mention two findings that are unanticipated by our current results: a reported homophone disadvantage during semantic categorization by no-go/go responses, despite homophones not conflicting with the category to respond to, and an ambiguity advantage in lexical decision for words with multiple senses. Both of these findings are at odds with our conclusions from Experiments 1 and 2.

However, this may not be unexpected if one considers that different task environments can specify different action possibilities. The acceptable actions of a yes/no response are different from the acceptable actions of a no-go/no response. How action can feed back to cognition depends on what actions are possible in the first place. If possible actions are specified by experimental context, and cognition is dependent on feedback from action, cognition becomes a context-sensitive entity whose effects may not necessarily generalize from one situation to another (Van Orden, Holden, & Turvey, 2003; 2005).

Note, however, that we are able to replicate the classic homophone disadvantage, despite using a mouse-driven response paradigm instead of a button pressing response paradigm. There is even a consistency in the magnitude of the effect; Van Orden (1987) report a difference of around 150msec between homophone and control latencies. We report a difference of around 250msec. Van Orden's mean response latency is in the order of a second, whereas ours is in the order of two seconds. The ratios of differences and the ratios of means are roughly the same. It seems as if all we have done is changed the task to unfold on a slower timescale, not the dynamics of what participants are doing.

Similar effects are also generated in conceptually different tasks, when the dynamics of the response are the same. For instance, Bub, Masson, and Bukach (2003) have participants reach for handles when the type of grasp they need to use is ambiguous. How participants respond bears a striking resemblance to what participants are doing with forced-choice yes/no responses during semantic categorization; they must select between one of multiple plausible grasps and apply it to make a response. Bub et al. report qualitatively similar results in their task to a forced-choice yes/no semantic categorization task, despite the task having the conceptual goal of forming hand grasps instead of categorizing meanings.

Cognition is content-dependent, but it is not without general principles. The feature that binds our results, those of the original Van Orden (1987) study, and those of Bub et al.'s (2003) grasping task is that responding involves making *a single selection out of multiple opposing but plausible options, once each trial*. Comparatively, no-go/go tasks require participants to make *one pre-specified response on some, but not all, trials*. Lexical decision to words with multiple senses requires participants to *select any of multiple complimentary options, once each trial.* The constraints for how action and cognition can relate differs from situation to situation. When the same, abstracted constraints are at play – as in the case of these experiments, Van Orden (1987), and Bub et al. (2003), similar patterns of results are seen. When the constraints differ, even if the point of the task stays the same (semantic categorization), how action and cognition can relate necessarily changes, and thus so do the results. Understanding what possibilities for action are available, and how this relates to deciding on a response, is at least as important as understanding the object of study itself, whether it be grasping and reaching, problem solving, or semantic categorization. Understanding the issue of context dependence in Psychology may simply be an issue of understanding what constraints are in place for how action and cognition can interact within a response.

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