COGNITIVE SCIENCE
A Multidisciplinary Journal

Cognitive Science 35 (2011) 983–996

ISSN: 0364-0213 print / 1551-6709 online
DOI: 10.1111/j.1551-6709.2010.01164.x

The Cognitive Dynamics of Negated Sentence Verification

Rick Dale, Nicholas D. Duran

Department of Psychology, The University of Memphis

Received 27 January 2010; received in revised form 7 September 2010; accepted 23 September 2010

Abstract

We explored the influence of negation on cognitive dynamics, measured using mouse-movement trajectories, to test the classic notion that negation acts as an operator on linguistic processing. In three experiments, participants verified the truth or falsity of simple statements, and we tracked the computer-mouse trajectories of their responses. Sentences expressing these facts sometimes contained a negation. Such negated statements could be true (e.g., ‘‘elephants are not small’’) or false (e.g., ‘‘elephants are not large’’). In the first experiment, as predicted by the classic notion of negation, we found that negation caused more discreteness in the mouse trajectory of a response. The second experiment induced a simple context for these statements, yet negation still increased discreteness in trajectories. A third experiment enhanced the pragmatic context of sentences, and the discreteness was substantially diminished, with one primary measure no longer significantly showing increased discreteness at all. Traditional linguistic theories predict rapid shifts in cognitive dynamics occur due to the nature of negation: It is an operator that reverses the truth or falsity of an interpretation. We argue that these results support both propositional and contextual accounts of negation present in the literature, suggesting that contextual factors are crucial for determining the kind of cognitive dynamics displayed. We conclude by drawing broader lessons about theories of cognition from the case of negation.

Keywords: Negation; Discrete and continuous processing; Sentence verification; Cognitive dynamics; Action; Pluralism

1. Introduction

In Wason and Johnson-Laird’s (1972) now-classic study of reasoning, the influence of negation on semantic processing is described as taking ‘‘an extra step, or mental operation’’ (p. 39). In almost all cases, this operation is inferred by reaction-time studies, as in their original work. In this paper, we offer an analysis of a semi-continuous behavioral signal that

Correspondence should be sent to Rick Dale, Department of Psychology, University of Memphis, Memphis, TN 38152. E-mail: radale@memphis.edu

can directly detect the existence of extra ''steps,'' thus investigating whether the simple notion of negation as inducing an ''operation'' during unfolding cognitive processing may have continued explanatory value. More recent work has followed up on Wason's attempts at showing that this ''extra step'' in negation processing can be mitigated by context (Wason, 1965), showing that in a given context the extra processing can be diminished in reaction-time studies (Glenberg, Robertson, Jansen, & Johnson-Glenberg, 1999) and in N400 signatures that can also index negation processing (Fischler, Bloom, Childers, Roucos, & Perry, 1983; Nieuwland & Kuperberg, 2008).

Since Wason and Johnson-Laird (1972), two theoretical perspectives on negation have produced their own empirical literatures investigating it. The first may be termed the ''propositional'' account of negation, exemplified in studies of thinking and reasoning that explicitly take into account the discrete influences negation has on processing, such as the construction of mental models (e.g., Barres & Johnson-Laird, 2002; Khemlani & Johnson-Laird, 2009). The second perspective may be termed ''contextual'' and includes a range of investigations into the constraints on negation processing, from ''pragmatic licensing'' (Glenberg et al., 1999; Nieuwland & Kuperberg, 2008) to situational or perceptual simulation elicited during processing (Anderson, Huette, Matlock, & Spivey, 2010; Kaup, 2001; Kaup, Zwaan, & Lüdtke, 2007).

In the current paper, we investigate negation by tracking the time-course of cognitive processing as participants verify simple statements using their computer mouse. Previous work on negation has never employed an online, semi-continuous measure to tap into the *cognitive dynamics* of negation integration, and computer-mouse trajectories are uniquely poised as a method to do so (Song & Nakayama, 2009; Spivey & Dale, 2006). We have two goals. The first is to show that, in simple ''classic'' sentence verification, negation induces discrete shifts in processing, akin to the application of an operator, as one would predict from a propositional account. A second goal is to show, in follow-up experiments, that contextual factors may mitigate these discrete shifts by facilitating the integration of negation in unfolding linguistic processing.

In the next section, we briefly review other papers that have used the computer-mouse tracking technique we employ here. Following this, we recapitulate the goals of the studies and present three experiments on sentence verification that included negated statements. We end with theoretical discussion of negation, and the potential implications for cognitive theories generally.

2. Mouse-tracking reveals cognitive dynamics

Using such devices as a computer-mouse or Nintendo Wii remote as semi-continuous measures of behavioral activity, several studies have demonstrated a more graded flow of information from cognition into action (e.g., Dale, Kehoe, & Spivey, 2007; Dale, Roche, Snyder, & McCall, 2008; Farmer, Cargill, Hindy, Dale, & Spivey, 2007; Spivey, Grosjean, & Knoblich, 2005). In this body of research, computer-mouse cursors are tracked, producing trajectories of *x*,*y*-pixel coordinates. Fine-grained characteristics of these trajectories, such as curvature (e.g., Farmer et al., 2007; Spivey et al., 2005) or complexity (e.g., Dale et al., 2007; McKinstry, Dale, & Spivey, 2008), co-vary with cognitive processes, such as word recognition, categorization, social cognition (e.g., Freeman, Ambady, Rule, & Johnson, 2008; Wojnowicz, Ferguson, Dale, & Spivey, 2009), and even deception (Duran, Dale, & McNamara, 2010). These data suggest a more graded connection between cognition and action than commonly assumed, as a number of neurophysiological studies have also shown in the flow of information from higher-level associative into premotor cortices (e.g., Cisek & Kalaska, 2005). In short, the dynamics of action have become a valuable signature of ongoing cognitive activity, revealing finer-grained characteristics of these processes (Spivey & Dale, 2006; see Freeman & Ambady, 2010, for a recent review).

With respect to the goals of this paper, mouse tracking may also reveal discreteness during processing. During computer-mouse movement, these events could appear as abrupt changes in course. In everyday decision-making, in which changes of mind can be of great significance (Gardner, 2006), such discrete shifts are present in arm movements that accompany decisions (Walsh & Anderson, 2009). Just as there may be systematic granularity in the smooth dynamics of an arm movement, there may be systematic shifts in arm movements under other task and processing contexts. These shifts in action could serve as a signature of shifts in the dynamics of thought, rapidly converging at the body's effectors (see also Resulaj, Kiani, Wolpert, & Shadlen, 2009).

As described at the outset of the paper, classic notions of negation predict that it induces a rapid shift during verification, as language processing eventually ''flips'' the truth-value of an interpreted kernel statement into its denial (e.g., ''elephants are not large,'' falsified by applying ''not'' to the truthful ''elephants are large''). In the methods below, we detail how we measure this discreteness in mouse-movement trajectories. In the first experiment, we demonstrate that in the simplest version of sentence verification, these abrupt shifts indeed occur under negation.

3. Experiment 1: Simple negated sentence verification

Establishing the truth or falsity of a sentence has been a long-studied activity in experimental psychology (see Wason & Johnson-Laird, 1972, Ch. 1–4, for an early review). General findings include a main effect of truth versus falsity. Numerous studies demonstrate that affirming a true basic declarative sentence (i.e., without negation) proceeds more quickly than disaffirming a false one (Wason, 1959). In addition, there is a main effect of negation: The presence of negation in a sentence overall slows readers down during verification (Wason, 1959). Finally, there has been a consistently observed interaction between these two factors. True sentences tend to take longer to process when they contain a negation (Wason & Jones, 1963). These basic patterns have been identified consistently since they were first discovered.

Debate continues regarding the best way to capture the characteristics of negation (see Giora, 2006), and recent work has shown that negation is not always processed as a simple propositional operator, but its function could depend upon perceptuo-motor simulation and situational representations and expectancies (Glenberg et al., 1999; Kaup & Zwaan, 2003), akin to other embodied theories of language processing (Glenberg & Kaschak, 2003; Zwaan & Radvansky, 1998).

We revisit the ''classic'' decontextualized task, as it is here that even these contextual theories allow that negation works as an operator on ongoing language processing that may induce a ''flip'' from true to false when integrated. Yet, to date, there has been no available means to demonstrate that a discrete ''shift'' indeed takes place during cognitive processing. Latency measures simply tell researchers how long it takes to go from stimulus to response, but they do not reveal the *kind of change* that is unfolding. As described above, the action-dynamics method may show such discreteness in the standard verification task. We draw from the elegantly simple design of Just and Carpenter (1976), in which participants verified statements involving simple facts. We concocted a small set of simple sentences, describing basic facts, that could be turned into true/false or negated/nonnegated sentences experimentally.

3.1. Method

3.1.1. Participants

Sixty participants were recruited online through Amazon's Mechanical Turk (http://www.mturk.com). This system has been demonstrated to produce reliable respondents in other studies, including data-intensive work such as corpus annotation (e.g., Snow, O'Connor, Jurafsky, & Ng, 2008; Sorokin & Forsyth, 2008). In the three experiments presented here, participants had an error rate under 5%. They were compensated with a small amount of money for their participation, which required approximately 5–10 min.

3.1.2. Interface and materials

The interface was programmed using Adobe Flash, permitting extraction of *x*,*y*-pixel coordinates at a sampling rate of approximately 40 Hz (see Fig. 1). The software filled the window of the participant's browser. We created 12 sentences to serve as a basis for true/false statements. Each of these sentences could be a true or false statement in both negated and nonnegated forms.[1] As examples, ''elephants are not small'' is an example of a negated true statement, made false by changing the adjective: ''elephants are not large'' (a false, negated statement). Another example stimulus was ''cars have wings,'' a false statement without negation, but true when negated: ''cars have no wings.'' Importantly, each subject saw an equal number of these four types, but with each sentence randomly assigned to one type.

3.1.3. Procedure

Sentences were presented one word at a time in a self-paced reading format. After initial instructions, participants saw TRUE and FALSE boxes at the top-left or top-right of the interface (placement was randomized across participants, but consistent within). They then clicked a circle at the bottom center of the interface, revealing a word immediately above this circle. They clicked until the final word appeared, at which point the circle disappeared,

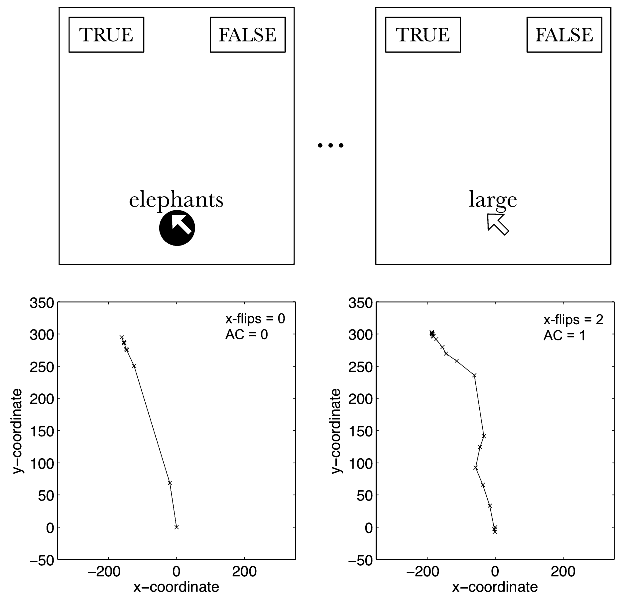

Fig. 1. The top two panels portray the experimental interface. Subjects clicked on a central, bottom circle to reveal words in a self-paced manner. The final word had the circle disappear, and it required a response. Response boxes were on the top-left or top-right (randomized for each subject). Arrows simply represent the mouse cursor for illustration. The bottom two panels show two example trajectories, along with *x*-flip and AC values.

and a response was made to either TRUE or FALSE as appropriate. Participants saw all 12 sentences, with each sentence randomly assigned to negated/not negated and true/false, counterbalanced to ensure participants saw an equal number of each kind. The *x*,*y*-pixel trajectory was saved, and it consisted of their movement from their last word click (from the bottom center) to their TRUE/FALSE click (to the top-left or top-right). Importantly, the negation in these sentences appears several words before a response is made. This ensured that any results we obtained were not purely stimulus-induced, because the negating element (most often ''not'') always occurred 1–2 words before the end of a sentence.

3.1.4. Measures, predictions, and analyses

We chose two trajectory measures that imply more discrete changes in the mouse-movement trajectory, both exemplified in Fig. 1. First, we calculated *x*-flips (Dale et al., 2008), which is a count-based score of the number of times the mouse cursor goes back and forth along the *x*-axis (i.e., the axis of decision):

$$x\text{-flips} = \sum H[-(\Delta x_t - \Delta x_{t-1})(\Delta x_{t-1} - \Delta x_{t-2})]$$

x_t represents the *x*-axis pixel coordinate at time *t*. *H* represents the Heaviside function, a threshold function that will return 1 when there is a flip of directionality by taking the product of −1 and three-step comparisons of directional change along the *x*-axis. If *x* is increasing from $t-1$ to *t* (+ change), and decreasing from $t-2$ to $t-1$ (− change), the product of these differences will always be −1, thus the negative sign produces a positive product, and H functions to produce an output of 1. By conducting this three-window analysis across the trajectory (indicated by the summation sign), we obtain a count of the number of switches.

Second, we used what we will here term ''acceleration components'' (AC). Similar measures have been used in studies on error correction in low-level motor control (Fishbach, Roy, Bastianen, Miller, & Houk, 2005), and it reflects the number of times the trajectory accelerates/decelerates during the response:

$$\mathrm{AC} = \left(\sum H[-(a_t - a_{t-1})(a_{t-1} - a_{t-2})]\right) - 1$$

AC is defined in the same way as x-flips, but a_t above reflects the acceleration at time t.[2] When acceleration changes direction (going from positive acceleration to negative acceleration) there is more complexity in the programmed movement (Fishbach et al., 2005; also see Wojnowicz et al., 2009 for analysis of acceleration complexity). The subtraction of 1 is to factor out the standard change in acceleration that is seen in a basic movement (even the simplest, straight movement will have one instance of positive to negative acceleration). The measure of x-flips reflects a complexity in the direction of movement—a spatial shift occurring during action dynamics. AC complements x-flips as discreteness may be present in the unfolding movement without necessarily a change in direction. For example, a participant may indicate a temporal fluctuation in their movement but not shift direction. Images exemplifying both measures are shown in Fig. 1. Thus, the two measures offer complementary ways of detecting abrupt changes in unfolding cognitive dynamics.

The above review of the sentence verification literature suggests two straightforward predictions from these measures. If negation changes cognitive processing in ways that go beyond just the time required for a decision to be made (reaction time), we should see increased discreteness or complexity of unfolding action execution. Specifically, if negation produces abrupt shifts in cognitive dynamics, then x-flips should increase in count for sentences with negation. This should also occur for AC, because the integration may require a temporary break from the smooth dynamics of a previous interpretation, indexed by the arm's movement.

To analyze these measures, we used a linear mixed-effects analysis in the way described by Baayen, Davidson, and Bates (2008), using a 2 (negation vs. no negation) by 2 (true vs. false) full factorial, repeated-measures model. Subject and sentence topic were used as random factors. This simultaneously controls for subject- and item-derived effects.

3.2. Results and discussion

The data from two participants were discarded for responding correctly less than 80% of the time. Trials with extremely long total motion times, from sentence-final word to final TRUE/FALSE choice, were removed before analysis. This was defined as 3 standard deviations away from the mean total movement time and amounted to less than 2% of all the trials for remaining subjects.

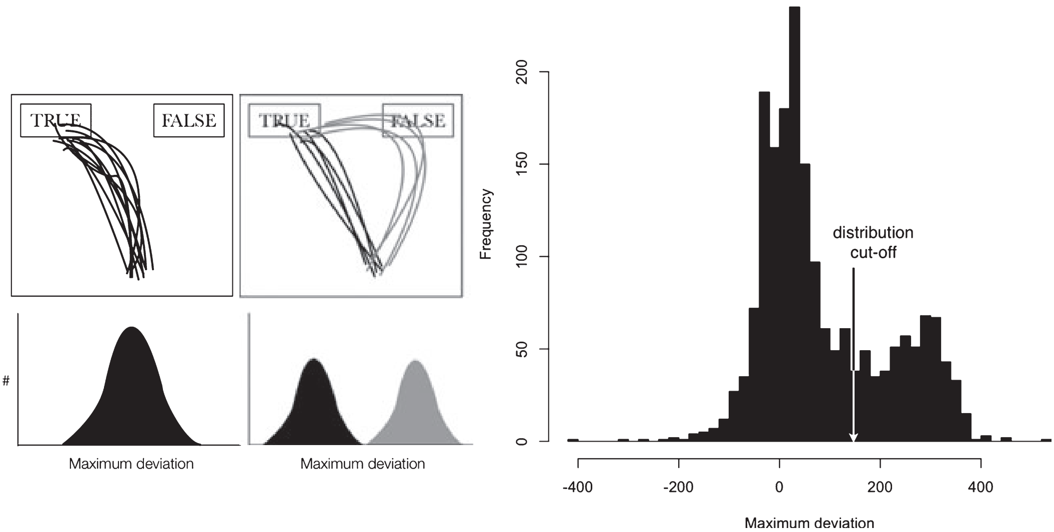

Fig. 2. On the left, a simplified representation of two kinds of trajectory distributions, one unimodal, normal distribution, and a second with abrupt shifts along the *x*-axis. On the far right, a histogram of the maximum deviation values across all trials of the experiments from the paper. The trials in the rightmost distribution (high maximum deviation trials) are predicted to occur significantly when negation is present in a sentence.

For *x*-flips, the model revealed a main effect of negation, showing that negation significantly increases *x*-flips by 0.35, $F(1,655) = 14.5$, $p < .0005$, and a significant interaction between negation and truth, $F(1,655) = 6.9$, $p < .01$. Given the pattern of means in Table 1, this interaction was produced by a greater increase in *x*-flips when true sentences have negation compared to false sentences, though false sentences still exhibit an increase in *x*-flips under negation. There was no main effect of truth/falsity, $F(1,655) = 1.9$, $p = .2$.

Results were similar for AC. Negation increases of the number of acceleration/deceleration events by approximately 0.70, $F(1,655) = 19.1$, $p < .0001$, and its interaction with veracity is significant, $F(1,655) = 13.3$, $p < .0005$. This was again due to negation in true sentences producing relatively higher AC than when false sentences contain negation. There was no significant effect of veracity, $F(1,655) = 0.1$, $p = .8$.

Table 1
Experiment 1: Means and effect estimates

Condition	*x*-flips (#)	AC (#)
T/no negation	1.13	1.56
T/negation	1.71	2.86
F/no negation	1.24	2.16
F/negation	1.34	2.27
$\text{Estimate}_{\text{negation}}$	0.35***	0.70***
$\text{Estimate}_{\text{T/F}}$	0.13	0.31
$\text{Estimate}_{\text{N} \times \text{T/F}}$	0.47**	1.16***

Note: $^{**}p < .01$, $^{***}p < .001$.

These findings reveal the predicted patterns for simple sentence verification with negation. Negation overall produced more ''discrete-like'' trajectories as participants responded, both in the changes in direction (*x*-flips) and in the movement components that made up their trajectories (AC).[3]

4. Experiment 2: Including a simple preamble context

As previous research has shown, the integration of negation, in its time-course (Glenberg et al., 1999) or ERP signature (e.g., N400, Nieuwland & Kuperberg, 2008), can be modified by including contextual material. If this is the case, then adding contextual material to Experiment 1's items should reduce the discreteness in trajectories, as participants may come to anticipate and rapidly integrate negation during self-paced reading. One general property of context that has been theorized to govern the use of negation is one of ''plausible denial'' (Glenberg et al., 1999; Wason, 1965) that may make the negative statement pragmatically licensed (Nieuwland & Kuperberg, 2008). We therefore ran exactly the same experiment, but this time introduced a short preamble to each sentence. For example, for the ''cars have {no} {wings/wheels}'' item, the preamble material was ''Flying cars!?,...'' In the ''elephants are {not} {small/large}'' item, the context given was ''You want to lift an elephant?'' Each preamble was intended to set up anticipation of plausible denial, where the appropriate response for elephant could be ''elephants are not small,'' indicating it is unlikely that the contextual material is possible. Besides this added contextual material, Experiment 2 ($N = 61$) was exactly the same as Experiment 1, except for one additional change. The sentence to be verified was presented in all caps, and participants were instructed to verify that sentence. This change to the text was to ensure that the attention of participants was drawn to the same sentential unit verified in Experiment 1.

4.1. Results and discussion

The same criteria were used for discarding data. Three subjects performed under 80% and their data were not included, and trials with high motion times were removed, which again included only approximately 2% of the data. We ran the same model as described in the previous experiment. For *x*-flips, the model again revealed an effect of negation, showing that negation significantly increases *x*-flips by 0.34, $F(1,650) = 12.6$, $p < .0005$, and a marginally significant interaction between negation and truth, $F(1,650) = 3.3$, $p = .07$. As in the previous experiment, truth/falsity had no effect, $F(1,650) = 0.14$, $p = .7$. For AC, the model predicted an increase of approximately 0.63 through negation, $F(1,650) = 11.3$, $p < .005$, and also a significant interaction between negation and veracity, $F(1,650) = 5.3$, $p < .05$. The interaction terms had a similar pattern to the previous experiment (see Table 2), in that negated true statements were especially influenced by negation compared to false statements.

We were surprised that the same effects were induced as in the previous experiment, apparently in contrast to previous work showing contextual modification of negation

Table 2
Experiment 2: Means and effect estimates

Condition	*x*-flips (#)	AC (#)
T/no negation	1.11	2.12
T/negation	1.63	3.16
F/no negation	1.33	2.57
F/negation	1.49	2.73
$\text{Estimate}_{\text{negation}}$	0.34***	0.63**
$\text{Estimate}_{\text{T/F}}$	−0.03	−0.02
$\text{Estimate}_{\text{N} \times \text{T/F}}$	0.35	0.87*

Note: *$p < .05$, **$p < .01$, ***$p < .001$.

Table 3
Experiment 3: Means and effect estimates

Condition	*x*-flips (#)	AC (#)
T/no negation	1.41	2.30
T/negation	1.60	2.66
F/no negation	1.34	2.07
F/negation	1.38	2.51
$\text{Estimate}_{\text{negation}}$	0.10	0.40*
$\text{Estimate}_{\text{T/F}}$	0.15	0.21
$\text{Estimate}_{\text{N} \times \text{T/F}}$	0.16	−0.07

Note: *$p < .05$.

processing. When comparing the materials used by Glenberg et al. (1999) and Nieuwland and Kuperberg (2008), one important difference in their contextual setup is that they tended to be more pragmatically embedded through a longer setup than what we used in Experiment 2. Experiment 3 was intended to enhance these contextual effects.

5. Experiment 3: Enhancing pragmatic context

Experiment 3 ($N = 57$) used the same contextual material as Experiment 2 but embedded it in an enhanced pragmatic context, which was designed as a statement from an adult to a child. For example, ''You want to lift an elephant?'' is a statement that may set up anticipation for plausible denial from an adult who is correcting a child, next stating, ''but elephants are not small.'' The items were then converted into a quote, such as: '''You want to lift an elephant?' the mother said to her child, 'but elephants are not small'.'' This was done for each item, and participants were told to judge whether the statements by adults were sensible or nonsense. This experiment thus embeds the items in a strong pragmatic context and changed the nature of the response: Participants now judged the sensibility of adult statements to the child. This increased the pragmatic license of negation, and participants were instructed to focus on the whole statement and judge it for sensibility. Crucially, negation occurred at exactly the same distance from the final word cuing a participant's response.

5.1. Results and discussion

Four subjects were discarded for under 80% performance, and only 2% of the data were discarded due to high movement times. The same model as the previous two experiments was used. For *x*-flips, this model revealed no effect of negation, $F(1,585) = 1.0$, $p = .3$, and also no significant interaction, $F(1,585) = 0.7$, $p = .4$. There was again no effect of veracity, $F(1,585) = 2.2$, $p = .13$. For AC, the model did reveal a weaker but significant increase of approximately 0.40 for negation, $F(1,585) = 4.6$, $p < .05$, but no significant interaction between negation and veracity, $F(1,585) = 0.04$, $p = .8$, nor, again, a significant effect of veracity, $F(1,585) = 1.4$, $p = .2$ (see Table 3). As predicted by contextual accounts of negation, with sufficiently rich pragmatic licensing, the discreteness of trajectories is no longer significantly increased by negation as measured through *x*-flips, and the AC measure is substantially diminished.

6. General discussion

Motivated by a growing application of trajectory tracking (Dale, Duran, & Roche, 2010; Song & Nakayama, 2009; Spivey & Dale, 2006), we used action dynamics to tap into the cognitive dynamics of sentence verification, revealing the kind of dynamic change that the cognitive system may be undergoing when negation is integrated during the task. We offered two primary findings across experiments. First, if insufficient context is present to produce appropriate anticipations, negation indeed seems to produce abrupt changes in unfolding thought processes. This is a direct demonstration of the classic notion of negation as an operator that the propositional account predicts (Wason & Johnson-Laird, 1972).[4] Second, when rich pragmatic licensing is established, anticipation may facilitate the integration of negation and thus diminish the abruptness displayed in arm trajectories (akin to modulating the N400 ERP signature, e.g., Nieuwland & Kuperberg, 2008). Context permits smooth integration of a linguistic operator that, without context, may induce discrete shifts in cognitive dynamics.

This paper therefore makes methodological and theoretical contributions to understanding comprehension processes involving negation. Though other studies have found that some sort of change in interpretation is occurring across an approximately 1,000-ms time scale (e.g., Kaup & Zwaan, 2003), the exact nature of this change within this time range is still a mystery. The current study demonstrates what Wason originally predicted, that negation is an operator on the dynamics of comprehension, inducing more abruptness of processing. Only a real-time methodology of the sort employed here can uncover this, and though previous reaction-time studies have obtained hints of it, these experiments are the first to show it with such a real-time measure.

Yet our results also reveal that negation is contextually malleable, as in numerous aspects of language processing (e.g., Spivey & Tanenhaus, 1998; Tanenhaus & Lucas, 1987). Previous work showing contextual modifications (such as Glenberg et al., 1999) take such findings to suggest that negation is by its nature contextual. But these contextual manipulations again beg the question whether the rapid integration of negation may still involve the Wason-predicted operator—just induced more quickly, with no resultant differences in reaction time compared to sentences without negation—or whether expectancies established by context permit smooth integration of the negating element. Our data suggest it is the latter. The abruptness is substantially diminished in action dynamics under pragmatic licensing. This means that negation processing has diverse cognitive dynamics in different contexts, and it is not just a matter of response speed.[5] From a broader perspective, discussed further below, these observations are nontrivial. Perennial rounds of debate erupt in the cognitive sciences about the nature of mental processing, and much recent debate is looking to the dynamic structure of processing in real-time in order to unveil that nature (e.g., Magnuson, 2005; Spivey, 2007).

So our data suggest that the *internal dynamic structure* of negation processing changes contextually. As mentioned, some accounts suggest this makes negation intrinsically contextual (Glenberg et al., 1999). But a problem with a blanket casting of negation as contextual is that, though context is undeniably ever-present for language and other cognitive processing, one cannot guarantee that the *right* context is present to facilitate negation. Put simply, the cognitive system must face negation occasionally in nonfacilitative contexts. Our results suggest that propositional accounts may still have explanatory value in such cases, where abruptly transitioning phases of processing unfold to integrate that negation. Other contexts, ones that may be facilitative, could produce smoothly integrative processes to handle negation. Both perspectives may be needed to capture cognitive dynamics relevant to negation in the ‘‘linguistic ecology.’’

Beyond negation, we take these results to have some broader implications. Many higher-level theories of sentence processing and semantics draw from (abstractly) discrete representations and processes. In our case here, negation can sometimes serve as an operator described in terms of logical operations, symbolic machinery, and so forth that may be more or less context-specific (e.g., Barres & Johnson-Laird, 2002; Giora, 2006; Glenberg et al., 1999). Indeed, our results could provide some justification for using traditional, symbolic accounts of simple negation, as these accounts easily accommodate discreteness in nonfacilitative contexts. This of course does not mean that the underlying neurophysiological time course is ‘‘discrete’’ the way an abstract (i.e., purely formal) symbol processor is discrete (but see Niessing & Friedrich, 2010).[6] Instead, it seems that the abrupt shifts are predicted by theories that typically draw from such symbolic notions. The broader conclusion from this is that task contexts can create behavioral signatures that could be valuably accounted for by using traditional symbolic notions. For anyone accepting the idea that a human being is a flexible and adaptive complex system (Van Orden, Holden, & Turvey, 2003), capable of displaying diverse emergent forms of processing under different contexts (Dale, 2008; Dale, Dietrich, & Chemero, 2009), this should not come as a surprise. In other words, some task constraints will bring the cognitive system to function at a level that has explanatory consonance with symbolic theories. Negation integration may skirt that line between discrete and continuous processing, governed by context.

Notes

1. We also replicated the basic effects reported here with a different set of stimuli.
2. Acceleration was calculated in the manner described in McKinstry et al. (2008).
3. In previous work employing trajectory measures, it has been important to show that the measures are normally distributed (see Fig. 2). Unimodal normality is required to argue that any mean measure obtained (e.g., maximum deviation, average trajectory shape, etc.) derives from a single distribution. Previous work has thus conducted separate analyses on the distribution of trajectory-based measures, such as maximum deviation (e.g., Dale et al., 2007; Farmer et al., 2007; Spivey et al., 2005). These analyses demonstrate that distributions of trajectory measures are indeed approximately normal (i.e., unimodal). In our case here, we predict the opposite. If different discrete shifts are occurring under negation, then we should get more than one mode in our maximum deviation distribution. A histogram of all maximum deviations across trials of all experiments is shown in Fig. 2. Clearly, there are shifts occurring in these trajectories producing a bimodal distribution (Hartigan's diptest for bimodality, $p < .0001$; Hartigan & Hartigan, 1985). See also Farmer, Anderson, and Spivey (2007).
4. We also conducted a follow-up analysis to underscore this interpretation. Trajectories with large deviation (>175 pixels), in the second, right mode in Fig. 2, indicate a ''shift'' is occurring during processing. We transformed this distribution into a dichotomous code (1 = shift, 0 = no shift) and conducted a logistic regression, predicting a shift from the full model including negation and veracity across the three experiments. This demonstrated a strong effect of negation, indicating that negation increases the chance of a shift by 39% (log-odds, 0.33, $z = 2.8$, $p < .005$).
5. We conducted further analyses to ensure that reaction time and total response time cannot by themselves account for the changes in our *x*-flips or AC measures. When controlling for latency and total response time, negation remains a significant predictor of *x*-flips and AC (all *p*'s < .05).
6. We have often used ''abrupt'' in place of ''discrete,'' because *pure* discreteness cannot be inferred from any behavioral data we know of; yet the abruptness may still be distributed systematically around symbolic notions and predicted by symbolic theories, which we argue here.

Acknowledgments

This research was supported in part by a National Science Foundation (NSF) Graduate Research Fellowship to the second author, and NSF grants BCS-0720322 and BCS-0826825 to the first author. Thanks to Mike Frank, Michael Spivey, Morten Christiansen, and Anne Warlaumont for valuable help.

References

Anderson, S., Huette, S., Matlock, T., & Spivey, M. J. (2010). On the temporal dynamics of negated perceptual simulations. In F. Parrill, V. Tobin, & M. Turner (Eds.), *Mind, form, and body* (pp. 1–20). Stanford, CA: CSLI Publications.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*(4), 390–412.

Barres, P., & Johnson-Laird, P. N. (2002). On imagining what is true (and what is false). *Thinking & Reasoning*, *9*(1), 1–42.

Cisek, P., & Kalaska, J. F. (2005). Neural correlates of reaching decisions in dorsal premotor cortex: Specification of multiple direction choices and final selection of action. *Neuron*, *45*(5), 801–814.

Dale, R. (2008). The possibility of a pluralist cognitive science. *Journal of Experimental and Theoretical Artificial Intelligence*, *20*, 155–179.

Dale, R., Dietrich, E., & Chemero, A. (2009). Explanatory pluralism in cognitive science. *Cognitive Science*, *33*, 739–742.

Dale, R., Duran, N. D., & Roche, J. (2010). The porous cognition-action interface, language processing, and pluralism. In R. K. Mishra & N. Srinivasan (Eds.), *Language-cognition interface: State of the art* (pp. 115–136). Munich, Germany: LINCOM Europa.

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

Dale, R., Roche, J., Snyder, K., & McCall, R. (2008). Exploring action dynamics as an index of paired-associate learning. *PLoS ONE*, *3*(3), e1728.

Duran, N. D., Dale, R., & McNamara, D. S. (2010). The action dynamics of overcoming the truth. *Psychonomic Bulletin & Review*, *17*, 486–491.

Farmer, T. A., Anderson, S. E., & Spivey, M. J. (2007). Gradiency and visual context in syntactic garden-paths. *Journal of Memory and Language*, *57*(4), 570–595.

Farmer, T. A., Cargill, S. A., Hindy, N. C., Dale, R., & Spivey, M. J. (2007). Tracking the continuity of language comprehension: Computer-mouse trajectories suggest parallel syntactic processing. *Cognitive Science*, *31*(5), 889–909.

Fischler, I., Bloom, P. A., Childers, D. G., Roucos, S. E., & Perry, N. (1983). Brain potentials related to stages of sentence verification. *Psychophysiology*, *20*(4), 400–409. doi: 10.1111/j.1469-8986.1983.tb00920

Fishbach, A., Roy, S. A., Bastianen, C., Miller, L. E., & Houk, J. C. (2005). Kinematic properties of on-line error corrections in the monkey. *Experimental Brain Research*, *164*(4), 442–457.

Freeman, J. B., & Ambady, N. (2010). MouseTracker: Software for studying real-time mental processing using a computer mouse-tracking method. *Behavior Research Methods*, *42*, 226–241.

Freeman, J. B., Ambady, N., Rule, N. O., & Johnson, K. L. (2008). Will a category cue attract you? Motor output reveals dynamic competition across person construal. *Journal of Experimental Psychology: General*, *137*(4), 673–690.

Gardner, H. (2006). *Changing minds: The art and science of changing our own and other people's minds*. Boston: Harvard Business School Press.

Giora, R. (2006). Is negation unique? On the processes and products of phrasal negation. *Journal of Pragmatics*, *38*(7), 979–980.

Glenberg, A. M., & Kaschak, M. P. (2003). The body's contribution to language. *Psychology of Learning and Motivation*, *43*, 93–126.

Glenberg, A. M., Robertson, D. A., Jansen, J. L., & Johnson-Glenberg, M. C. (1999). Not propositions. *Cognitive Systems Research*, *1*(1), 19–33.

Hartigan, J. A., & Hartigan, P. M. (1985). The dip test of unimodality. *The Annals of Statistics*, *13*(1), 70–84.

Just, M. A., & Carpenter, P. A. (1976). Relation between comprehending and remembering some complex sentences. *Memory and Cognition*, *4*, 318–322.

Kaup, B. (2001). Negation and its impact on the accessibility of text information. *Memory and Cognition*, *29*(7), 960–967.

Kaup, B., & Zwaan, R. A. (2003). Effects of negation and situational presence on the accessibility of text information. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *29*(3), 439–446.

Kaup, B., Zwaan, R. A., & Lüdtke, J. (2007). The experiential view of language comprehension: How is negation represented? In F. Schmalhofer & C. A. Perfetti (Eds.), *Higher level language processes in the brain: Inference and comprehension processes* (pp. 255–288). Mahwah, NJ: Erlbaum.

Khemlani, S., & Johnson-Laird, P. N. (2009). Disjunctive illusory inferences and how to eliminate them. *Memory & Cognition*, *37*(5), 615–623. doi: 10.3758/MC.37.5.615

Magnuson, J. S. (2005). Moving hand reveals dynamics of thought. *Proceedings of the National Academy of Sciences*, *102*(29), 9995–9996.

McKinstry, C., Dale, R., & Spivey, M. J. (2008). Action dynamics reveal parallel competition in decision-making. *Psychological Science*, *19*(1), 22–24.

Niessing, J., & Friedrich, R. W. (2010). Olfactory pattern classification by discrete neuronal network states. *Nature*, *465*(7294), 47–52. doi:10.1038/nature08961

Nieuwland, M. S., & Kuperberg, G. R. (2008). When the truth is not too hard to handle. *Psychological Science*, *19*(12), 1213–1217.

Resulaj, A., Kiani, R., Wolpert, D. M., & Shadlen, M. N. (2009). Changes of mind in decision-making. *Nature*, *461*(7261), 263–266.

Snow, R., O'Connor, B., Jurafsky, D., & Ng, A. Y. (2008). Cheap and fast – but is it good? Evaluating non-expert annotations for natural language tasks. Presented at the Proceedings of the Conference on Empirical Methods in Natural Language Processing (EMNLP 2008).

Song, J. H., & Nakayama, K. (2009). Hidden cognitive states revealed in choice reaching tasks. *Trends in Cognitive Sciences*, *13*(8), 360–366.

Sorokin, A., & Forsyth, D. (2008). Utility data annotation with Amazon Mechanical Turk (pp. 1–8). Presented at the Computer Vision and Pattern Recognition Workshops, 2008. CVPRW '08. IEEE Computer Society Conference on. doi: 10.1109/CVPRW.2008.4562953

Spivey, M. J. (2007). *The continuity of mind*. New York: Oxford University Press.

Spivey, M. J., & Dale, R. (2006). Continuous dynamics in real-time cognition. *Current Directions in Psychological Science*, *15*(5), 207–211.

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

Spivey, M. J., & Tanenhaus, M. K. (1998). Syntactic ambiguity resolution in discourse: Modeling the effects of referential context and lexical frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*, 1521–1543.

Tanenhaus, M. K., & Lucas, M. M. (1987). Context effects in lexical processing. *Cognition*, *25*(1–2), 213–234.

Van Orden, G. C., Holden, J. G., & Turvey, M. T. (2003). Self-organization of cognitive performance. *Journal of Experimental Psychology. General*, *132*(3), 331–350. doi: 10.1037/0096-3445.132.3.331

Walsh, M. M., & Anderson, J. R. (2009). The strategic nature of changing your mind. *Cognitive Psychology*, *58*(3), 416–440.

Wason, P. C. (1959). The processing of positive and negative information. *The Quarterly Journal of Experimental Psychology*, *11*(2), 92–107.

Wason, P. C. (1965). The contexts of plausible denial. *Journal of Verbal Learning & Verbal Behavior*, *4*(1), 7–11.

Wason, P. C., & Johnson-Laird, P. N. (1972). *Psychology of reasoning: Structure and content*. Cambridge, MA: Harvard University Press.

Wason, P. C., & Jones, S. (1963). Negatives: Denotation and connotation. *British Journal of Psychology (London, England: 1953)*, *54*, 299–307.

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

Zwaan, R. A., & Radvansky, G. A. (1998). Situation models in language comprehension and memory. *Psychological Bulletin*, *123*, 162–185.