# IS SEMANTICS ACTIVATED AUTOMATICALLY? EVIDENCE FROM THE PRP PARDIGM.

A Thesis Submitted to the Committee on Graduate Studies in Partial Fulfillment of the Requirements for the Degree of Master of Science in the Faculty of Arts and Science

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**Abstract**

Is semantics activated automatically? Evidence from the PRP paradigm.

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Three experiments examined whether semantics is activated automatically by testing whether Arabic digits (e.g., 4), number words (e.g., four), and non-number words (e.g., rat) activate semantics in the absence of central attention within the Psychological Refractory Period (PRP) paradigm. In all three experiments, subjects performed colour discriminations as Task 1. In Task 2, subjects performed magnitude comparisons on digits (Experiment 1) and number words (Experiment 2) and size comparisons on animal words (Experiment 3). Task overlap was controlled by varying stimulus onset asynchrony (SOA). A distance effect arose in Task 2 and yielded underadditive effects with decreasing SOA for both digits and number words, consistent with these notations activating semantics in the absence of central attention, or automatically. A distance effect also arose for animal words, but it was additive with SOA, inconsistent with non-number words activating semantics automatically.

*Keywords:* Automaticity; Semantics; Numerical Cognition; Word Recognition; Central Attention; Dual Task; Magnitude Comparison; Distance Effect

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# Is semantics activated automatically? Evidence from the PRP paradigm.

Automaticity is a concept that is ubiquitous in cognitive psychology. In particular, two domains in which automaticity plays an important theoretical role are numerical cognition (e.g., Cohen Kadosh, 2008; Ford & Reynolds, 2016) and visual word recognition (e.g., Augustinova & Ferrand, 2014; Besner & Reynolds, 2017). Critically, these domains are thought to use at least some of the same processing structures (e.g., Dehaene, 1992; McCloskey, 1992), and automatic activation of semantics has previously been argued in both the numerical cognition and visual word recognition literatures (e.g., Augustinova & Ferrand, 2014; Dehaene, Bossini, & Giraux, 1993). Testing the claim that semantic activation is automatic is complicated by the fact that multiple features have been attributed to automatic processes. For instance, automatic processes have been described as occurring unintentionally, as well as efficiently, or in the absence of attentional resources (Moors & De Houwer, 2006). Further, comparing the automaticity of semantic activation across the numerical cognition and visual word recognition domains is complicated by the use of different tasks, methodologies, and measures of semantic activation. The goal of the present set of experiments, then, was to test the claim that semantic activation occurs automatically in the sense that it is efficient. The semantic activation of Arabic digits (e.g., 4), number words (e.g., four), and non-number words (e.g., rat) was examined using the same task, methodology, and measure of semantic activation in order to allow for a clear comparison across the numerical cognition and visual word recognition domains.

I begin by considering Arabic digits. The most widely received view is that digits activate magnitude representations (i.e., semantics) automatically (e.g., Cohen Kadosh, Henik, & Rubinsten, 2008; Dehaene & Akhavein, 1995; Dehaene et al., 1993; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; Fischer, Castel, Dodd, & Pratt, 2003; Ganor-Stern & Tzelgov, 2008; Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006; Nuerk, Wood, & Willmes, 2005; Tzelgov & Ganor-Stern, 2005; Tzelgov, Meyer, & Henik, 1992). Considerable support for this claim comes from studies showing that digits activate magnitude when this information is unnecessary for correct task performance (i.e., unintentionally). For instance, an effect that is frequently reported for digits in the numerical cognition literature is the spatial-numerical association of response codes (SNARC) effect, which refers to faster left- than right-hand responses executed in response to small numbers and faster right- than left-hand responses executed in response to large numbers (e.g., Dehaene et al., 1993; Fias et al., 1996; Fischer et al., 2003; Gevers et al., 2006; Nuerk et al., 2005). This effect is thought to arise from the unintentional activation of an internal, analogue number line on which small numbers are located on the left side and large numbers are located on the right side (but see van Dijck & Fias, 2011; van Dijck, Abrahamse, Acar, Ketels, & Fias, 2014). Responses are faster on trials where a number's position on the number line (i.e., magnitude) and response side are congruent compared to trials where these dimensions are incongruent. Critically, the SNARC effect is typically observed in the parity judgment task, where the goal is to indicate whether a number is odd or even. Magnitude has also been found to affect the time taken to name digits (e.g., Brysbaert, 1995; Reynvoet, Brysbaert, & Fias, 2002) and make physical size comparisons (e.g., Cohen Kadosh et al., 2008; Dehaene & Akhavein, 1995), phoneme detections (Fias et al., 1996), and orientation discriminations (Fias, Lauwereyns, & Lammertyn, 2001), all tasks where magnitude is activated unintentionally.

Although the observation that a process occurs unintentionally is consistent with this process occurring automatically, many characteristics besides unintentional have been attributed to automatic processes. For instance, they have also been argued to (1) occur in the absence of processing resources (e.g., Pashler, 1994), (2) proceed in parallel with other processes (e.g., Treisman, Vieira, & Hayes, 1992), and (3) not use attention (e.g., LaBerge & Samuels, 1974). In other words, they are argued to be efficient, or occur in the absence of attentional resources. In a comprehensive examination of the concept of automaticity, Moors and De Houwer (2006) argued that the characteristics attributed to automaticity could be organized into four broad conceptual features: (1) unintentional, (2) efficient, (3) unconscious, and (4) fast. Thus, assessing whether a process occurs unintentionally is not an exhaustive test of the claim that a process is automatic, despite unintentional being an important characteristic of automaticity. Consequently, assessing whether digits activate magnitude in the absence of attentional resources (i.e., efficiently) provides a valuable test of the claim that digits activate semantics automatically. In order to better understand whether semantics is activated automatically, the present set of experiments examined whether semantic activation is efficient.

Assessing whether a process requires attentional resources is complicated by the fact that research on attention points to the existence of at least two separable attentional systems: (1) input attention, which arises at an early stage of processing and is involved in the parallel perceptual processing of multiple stimuli (e.g., finding the largest of several simultaneously presented stimuli), and (2) central attention, which arises at a later stage of processing and is involved in response selection (e.g., deciding how to respond to the largest stimulus; Johnston, McCann, & Remington, 1995; Lavie, Hirst, de Fockert, & Viding, 2004; Reimer, Strobach, Frensch, & Shubert, 2015; Wickens, 2002). Critically, assessing whether a process requires input attention assesses whether it requires domain-specific perceptual resources, whereas assessing whether a process requires central attention assesses whether it requires more general central processing resources involved in response selection (Johnston et al., 1995; Pashler, 1994; Lavie et al., 2004; Wickens, 2002).

The research to date indicates that digits do not require input attention in order to activate magnitude. Utilizing Shiffrin and Gardener's (1972) time delimitation procedure, Blanc-Goldhammer and Cohen (2014) and Pashler and Badgio (1987) had subjects indicate which digit in a set of four was the largest numerically. These digits were presented either two at a time (successive trials) or all at once (simultaneous trials). The authors hypothesized that if digits require input attention in order to activate magnitude, better performance should be observed on successive trials (where the magnitude of only two digits had to be encoded at a given time) than on simultaneous trials (where the magnitude of all four digits had to be encoded at once). Neither Blanc-Goldhammer and Cohen (2014) nor Pashler and Badgio (1987) observed better performance on successive trials than on simultaneous trials, a finding they interpreted as evidence that multiple digits can activate magnitude in parallel. This result is further consistent with digits not requiring input attention in order to activate magnitude.

## Psychological Refractory Period (PRP) Paradigm

Evidence that digits do not require input attention in order to activate semantics is consistent with digits activating magnitude efficiently. But in order to further test the efficiency criterion, the present set of experiments investigated whether digits require *central* attention in order to activate magnitude. This was accomplished using the psychological refractory period (PRP) paradigm (e.g., Pashler 1984; 1994; Welford, 1952). Within this paradigm, subjects perform two speeded tasks (Task 1 and Task 2) with priority given to Task 1. Task overlap is controlled by varying the stimulus onset asynchrony (SOA) separating the Task 1 and Task 2 stimuli (see Figure 1). At short SOAs (e.g., 50 ms), processing for the two tasks largely overlaps, whereas at long SOAs (e.g., 2000 ms), processing for the two tasks does not overlap at all. The standard finding is that Task 2 response time (RT) increases as SOA decreases. The most widely held interpretation of this finding is that both tasks use the same limited capacity processor that acts as an all-or-none central processing bottleneck located at response selection (e.g., Pashler, 1984; 1994; Welford, 1952). However, there is some evidence that the bottleneck can affect processes as early as stimulus categorization (Johnston & McCann, 2006). According to the all-or-none bottleneck account, Task 2 slowing with decreasing SOA occurs because Task 2 central processing (i.e., response selection) is delayed until the limited capacity processor is freed by Task 1 central processing. Meanwhile, Task 2 processes that occur before or after the bottleneck do not use the limited capacity processor (i.e., central attention), and can therefore proceed in parallel with Task 1 central processes.[1]

Insight into whether a process uses central attention can be gained by examining how the effect of a Task 2 factor is affected by increasing task overlap (see Figure 1). According to locus of slack logic (Pashler & Johnston, 1989; Schweickert, 1978), the delay of Task 2 central processing at short SOAs creates a period of cognitive slack during which Task 2 central processing waits for the processing bottleneck to be freed by Task 1 (see Figure 1, panel A). This period of cognitive slack (depicted as the box with dashed lines) can absorb the effect of a Task 2 factor that affects processing prior to the central processing bottleneck. Thus, the effect of a pre-bottleneck factor (i.e., one that does not require central attention) will be reduced or eliminated at short SOAs (see the absence of a Task 2 effect in Figure 1, panel A). However, if the effect of a Task 2 factor arises at the bottleneck (i.e., requires central attention) or after, the effect of this factor will arise after the period of cognitive slack and consequently be of the same magnitude across SOAs (see the Task 2 effect in Figure 1, panels B and C). Because cognitive slack logic clearly predicts how the effect of a factor that uses central attention will behave when two tasks overlap, the PRP paradigm has been used in both the numerical cognition and visual word recognition literatures to investigate whether processes arise automatically (e.g., Besner & Reynolds, 2017; Ford & Reynolds, 2016; McCann, Remington, & Van Selst, 2000; Reynolds & Besner, 2006; Sigman & Dehaene, 2005; 2006).

In the present set of experiments, I used the PRP paradigm and cognitive slack logic to assess whether digits (Experiment 1), number words (Experiment 2), and non-number words (Experiment 3) activate semantics automatically. If semantics is activated in the absence of central attention, a semantic effect would go underadditive with decreasing SOA. In contrast, if semantics is not activated in the absence of central attention, a semantic effect would be additive with SOA.

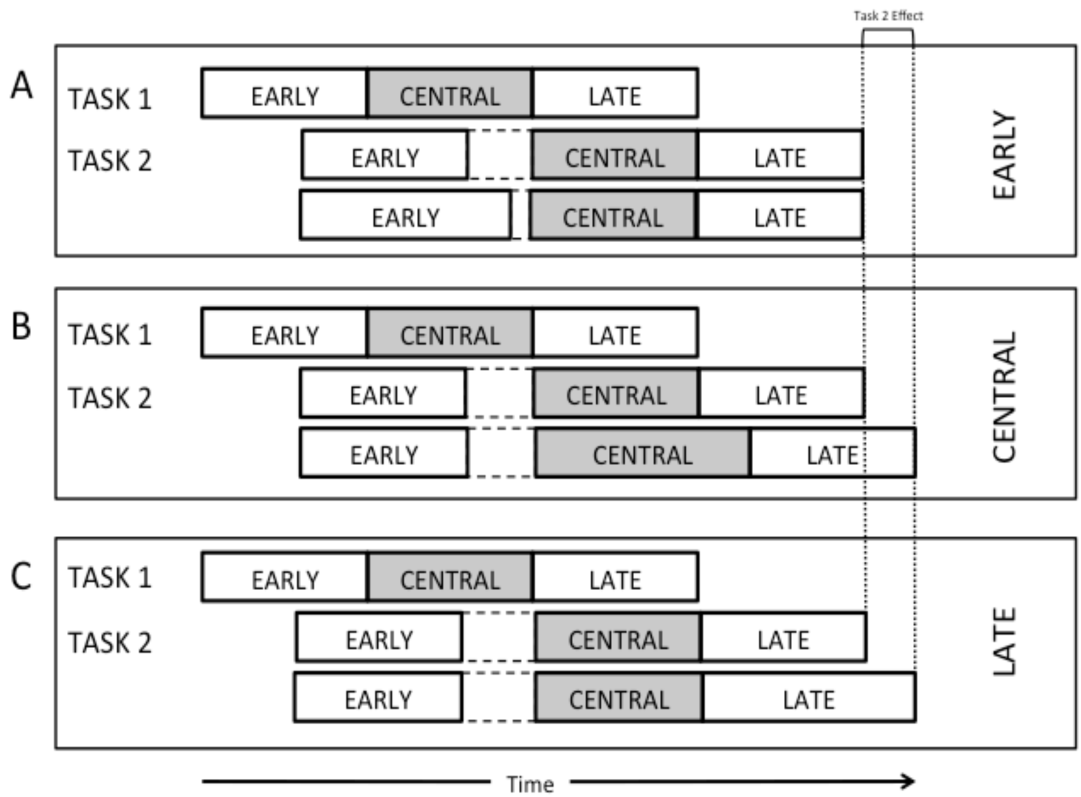



Figure 1: An illustration of cognitive slack logic in the context of the psychological refractory period (PRP) paradigm. The length of each box indicates the duration of each processing stage. The distance between the leftmost edge of the *early* square and the rightmost edge of the *late* square indicates overall response time (RT). The boxes with the dashed lines depict cognitive slack. The vertical dotted lines depict the size of the Task 2 effect in RT. Panel A illustrates absorption of an early Task 2 effect into cognitive slack. Panels B and C illustrate how central and late effects in Task 2 are unaffected by task overlap.

## EXPERIMENT 1

I am aware of five previous studies that have used the PRP paradigm to examine whether digits can activate magnitude in the absence of central attention. In two of these studies, magnitude was activated *unintentionally*, and the researchers investigated whether the SNARC effect went underadditive with decreasing SOA when parity judgment was Task 2 (Ford & Reynolds, 2016; Müller and Schwarz, 2007). Müller and Schwarz (2007) reported that the SNARC effect was additive with SOA, inconsistent with digits unintentionally activating magnitude in the absence of central attention. This result is further inconsistent with digits activating magnitude automatically. However, interpretation of their data is complicated by the fact that their long SOA condition was only 400 ms, which means that Task 2 was likely still delayed by Task 1 central processing in their long SOA condition. More recently, Ford and Reynolds (2016) used SOAs of 50, 150, and 2000 ms and reported a SNARC effect that went underadditive with decreasing SOA, consistent with digits unintentionally activating magnitude in the absence of central attention. This result is further consistent with the claim that digits activate magnitude automatically (e.g., Cohen Kadosh et al., 2008; Dehaene & Akhavein, 1995; Dehaene et al., 1993).

Oriet et al. (2005) used the PRP paradigm to examine whether digits can activate magnitude in the absence of central attention when magnitude is activated *intentionally*. In this study, the researchers assessed whether the distance effect went underadditive with decreasing SOA when magnitude comparison was performed as Task 2 (Oriet et al., 2005). The distance effect refers to faster magnitude comparisons for numbers that are numerically distant (e.g., 1  9) than for numbers that are numerically close (e.g., 1  2; e.g., Dehaene & Akhavein, 1995; Moyer & Landauer, 1967; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Schwarz & Ischebeck, 2003; Tzelgov et al., 1992). The distance effect is widely thought to arise because numbers that are close numerically have overlapping internal representations on the number line, which makes discriminating between these numbers more difficult than discriminating between numbers that are distant numerically (and therefore do not have overlapping internal representations; Dehaene, 1992; Moyer & Laundauer, 1967; Rubinsten et al., 2002; Tzelgov et al., 1992). Critically, Oriet et al. (2005) found that the distance effect went underadditive with decreasing SOA, an outcome that is consistent with digits intentionally activating magnitude in the absence of central attention.

Two other studies have examined whether the distance effect is affected by SOA within Task 2 of the PRP paradigm (Sigman & Dehaene, 2005; 2006). Unfortunately, although these studies used both digits and number words, the distance effect was not examined separately for each notation. Therefore, specific claims about how digits and number words activate semantics cannot be made based on these studies. Also problematic is the fact that Sigman and Dehaene reported both additivity (2005) and underadditivity (2006) of the distance effect with SOA. A post hoc examination suggests that these studies may have been underpowered (the power to detect the effect reported by Oriet et al. [2005] was .26 in Sigman & Dehaene [2005] and .23 in Sigman & Dehaene [2006]). Power may have been affected by their use of a large number of SOAs (i.e., random, continuous SOAs in Sigman & Dehaene (2005) and 15 different SOAs in Sigman & Dehaene (2006). Finally, unlike traditional PRP experiments, task order was varied between subjects in Sigman and Dehaene (2005) and on a trial-by-trial basis in Sigman and Dehaene (2006). Therefore, these studies only increase uncertainty about how numbers activate semantics.

Resolving whether digits intentionally activate magnitude in the absence of central attention is important for at least two reasons. First, there is evidence that different magnitude representations may be activated in intentional and unintentional contexts. This leaves open the possibility that intentionally and unintentionally activated magnitude representations place different demands on attentional resources. Second, as will be discussed in the introduction to Experiment 2, there is little evidence to support the claim that number words activate magnitude unintentionally. Therefore, if the automaticity (operationalized here as the central attentional requirements) of semantic activation is to be assessed in such a way that permits direct comparisons across the numerical cognition and visual word recognition domains, it must be clear whether digits activate magnitude intentionally in the absence of central attention.

In order to help resolve this ambiguity, Experiment 1 provided an additional test of the claim that the distance effect for digits in the magnitude comparison task goes underadditive with decreasing SOA. A number of steps were taken in the present experiment to maximize the power to detect an interaction between SOA and distance. First, I utilized a traditional PRP design with a finite number of SOAs (50, 150, and 2000 ms; identical to Ford and Reynolds, 2016) and a fixed task order (Oriet et al., 2005; see also Ford & Reynolds, 2016). This stands in contrast to Sigman and Dehaene (2005), who used random continuous SOAs, and Sigman and Dehaene (2006), who varied the task order randomly on a trial-by-trial basis. Second, only a single notation was used in this experiment, unlike Sigman and Dehaene (2005; 2006), who randomly intermixed digits and number words. Third, the present Task 1 was a colour discrimination task that did not require subjects to make any sort of high versus low comparison, a requirement that could potentially interfere with subsequent judgments of numerical value (Cohen Kadosh, Brodsky, Levin, & Henik, 2008; Cohen Kadosh, Lammertyn, & Izard, 2008; Hommel, 1998). This stands in contrast to the PRP experiments described above (Oriet et al., 2005; Sigman & Dehaene, 2005; 2006), all of which used a tone discrimination task where the goal was to indicate whether a tone was high or low. Fourth, I had more observations per cell for each subject than previous experiments. Lastly, more subjects were used here than in Sigman and Dehaene (2005; 2006). Thirty subjects participated in the present Experiment 1 in order to be comparable with Ford and Reynolds (2016), whereas 16 of Sigman and Dehaene's (2005; 2006) subjects performed magnitude comparison as Task 2.

## Method

*Participants.* Thirty undergraduate Trent University students participated in the experiment in return for credit in an eligible psychology course. This sample size was chosen a priori so as to be identical to Ford and Reynolds (2016). They reported a large effect size ($r = .5$). With an N of 30, this should yield .80 power to detect the presence of an interaction. All participants had normal or corrected-to-normal vision, and reported normal colour vision.

*Stimuli.* The stimulus for Task 1, a colour discrimination task, was a rectangle that subtended 1.6° visual angle vertically and 3.2° visual angle horizontally. The border of this rectangle was three pixels thick and alternated unpredictably across trials between red and blue. The stimuli for Task 2, a magnitude comparison task, were two Arabic digits presented side-by-side that ranged in value from 1 to 9. The digits were presented in a white 18-pt Courier New font against a black background and each subtended .6° by .6° visual angle and were separated by 1.4°.

*Apparatus.* The experiment was conducted on a Dell Vostro 420 computer running Microsoft Windows XP operating system with Service Pack 3. Stimulus presentation and data collection were controlled using E-Prime 2.0 software. Task 1 vocal responses were collected using a PST response box and voice-key assembly. Task 2 manual responses were collected using a standard USB keyboard.

*Procedure.* The experiment consisted of one block of 48 practice trials and six blocks of 72 experimental trials. Subjects were given the opportunity to take breaks between blocks. Subjects responded to Task 1 by saying the colour of the rectangle into a microphone and to Task 2 by pressing the X and M keys on a computer keyboard. Subjects were instructed to press the key on the side of the numerically larger number. They were also instructed to respond to both tasks as quickly and accurately as possible, but with priority given to Task 1.

At the beginning of each trial, a white rectangle appeared in the center of the screen. After 500 ms, the border of the rectangle changed to either red or blue. Two digits then appeared in the center of the rectangle after an SOA of 50, 150, or 2000 ms. When a vocal response was registered, the border of the rectangle returned to white. In order to encourage subjects to give priority to Task 1, they received feedback (a reminder to give priority to Task 1) on trials where Task 1 RTs were longer than 1500 ms, where they responded to Task 2 before Task 1, or an interval of less than 100 ms separated the two responses. Feedback remained on the screen for 3500 ms. On trials where feedback was not given, a blank screen was presented for 100 ms. Accuracy of the vocal response (correct, incorrect, or a voice-key failure) was coded via key press by the researcher after the feedback screen, but before the beginning of the next trial.

Subjects were seated approximately 50 cm from the computer screen. The experiment took approximately 40 minutes to complete.

**Results**

Separate repeated measures ANOVAs were run on the RT and error data for Task 1 and Task 2, with SOA (50 ms vs. 150 ms vs. 2000 ms) and numerical distance (near vs. far) as factors. Trials were labelled "near" when the digits differed in magnitude from one to four (e.g., 1 2) and "far" when the digits differed in magnitude from five to eight (e.g., 1 9). The distance effect was derived by calculating the difference in mean RT for near and far trials. The size of the distance effect was compared across SOAs. Only the linear effects of SOA were examined in order to maximize power (see Reynolds & Besner, 2006). T-tests were used to examine simple effects. Mean RTs and percentage errors for both tasks can be seen in Figure 2.

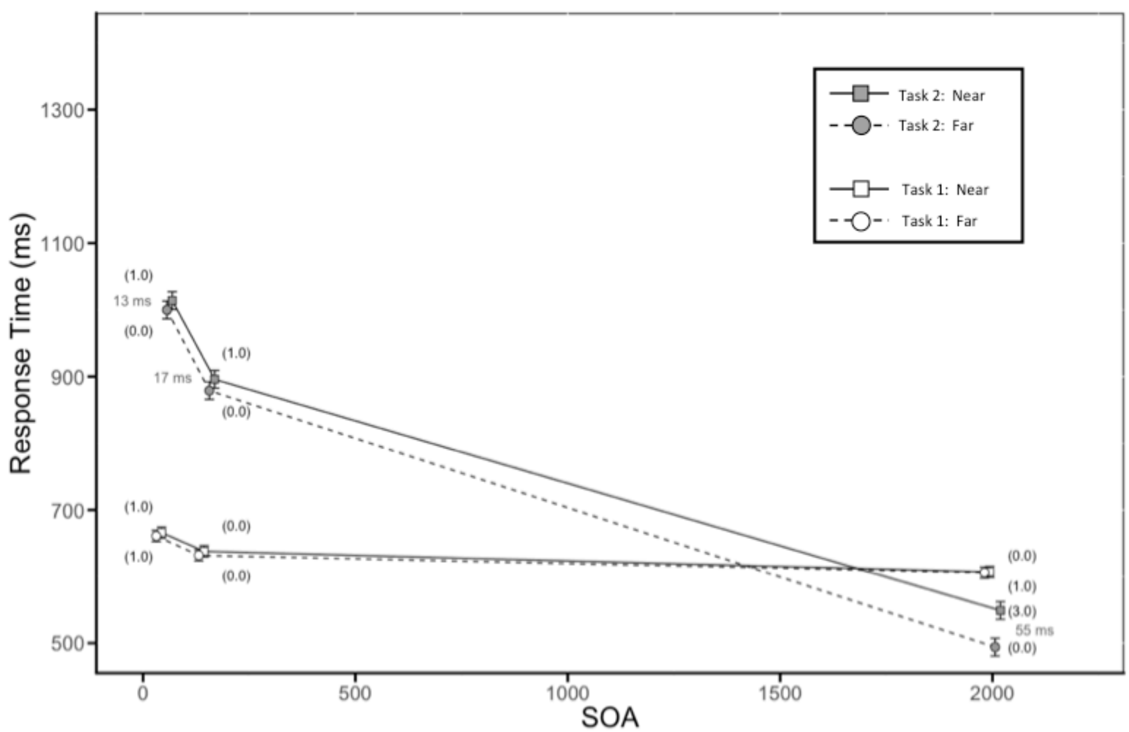



Figure 2: Mean response time (ms) and percentage error in Experiment 1 as a function of task (colour discrimination vs. magnitude comparison), stimulus onset asynchrony (SOA; 50 vs.150 vs. 2000 ms), and distance (near vs. far). 95% confidence intervals were calculated separately for each task using Loftus and Masson (1994).

**Response Time (RT)**

Trials where an error was made in Task 1 (0.548%) or Task 2 (1.09%) were removed prior to analyzing the RT data, as were any trials where a voice-key failure occurred in Task 1 (1.62%). The remaining RT data were subjected to a recursive outlier trimming procedure where the criterion cut-off for removal is determined by the sample size in that cell for each subject (Van Selst & Jolicoeur, 1994). This resulted in the removal of 1.38% of the remaining Task 1 RT data and 1.01% of the remaining Task 2 RT data.

*Task 1: Colour Discrimination.* There was a main effect of SOA, whereby the time taken to name colours increased as SOA decreased, $F(1, 29) = 50.23$, $p < .001$, $\eta_p^2 = .634$. However, there was no main effect of Task 2 numerical distance, $F(1, 29) = 1.92$, $p = .176$, $\eta_p^2 = .062$, nor was there an interaction between SOA and distance, $F(1, 29) = 0.349$, $p = .559$, $\eta_p^2 = .012$, consistent with subjects giving priority to Task 1, and inconsistent with response grouping or capacity sharing.

*Task 2: Magnitude Comparison.* There was a main effect of SOA, whereby the time taken to respond increased as SOA decreased, $F(1, 29) = 363.75$ $p < .001$, $\eta_p^2 = .926$. There was also a main effect of distance, whereby responses were on average 28 ms slower on near trials than on far trials, $F(1, 29) = 42.33$, $p < .001$, $\eta_p^2 = .593$. Consistent with digits not requiring central attention in order to activate magnitude, there was an interaction between SOA and distance, whereby the size of the distance effect decreased with decreasing SOA, $F(1, 29) = 17.54$, $p < .001$, $\eta_p^2 = .175$. There was a 55 ms distance effect at the 2000 ms SOA, $t(29) = 8.78$, $p < .001$, an attenuated but still significant 17 ms distance effect at the 150 ms SOA, $t(29) = 3.20$, $p = .003$, and an unreliable 13 ms distance effect at the 50 ms SOA, $t(29) = 1.55$, $p = .131$.

**Percentage Error**

*Task 1: Colour Discrimination.* Because there were too few errors (< 1%), the error data from Task 1 were not analyzed.

*Task 2: Magnitude Comparison.* The error data mirrored the RT data. There was a main effect of SOA, whereby fewer errors were made as SOA decreased, $F(1, 29) = 11.82$, $p = .002$, $\eta_p^2 = .290$. There was also a main effect of distance, whereby more errors were made on near trials than on far trials, $F(1, 29) = 27.98$, $p < .001$, $\eta_p^2 = .491$. The decrease in errors with decreasing SOA can be attributed to an interaction between SOA and distance, whereby the distance effect decreased in size with decreasing SOA, $F(1, 29) = 22.75$, $p < .001$, $\eta_p^2 = .440$.

## Discussion

The goal of Experiment 1 was to assess whether digits activate magnitude in the absence of central attention. This was accomplished by testing whether the distance effect for digits goes underadditive with decreasing SOA when a magnitude comparison task was performed as Task 2 within the PRP paradigm. The distance effect went underadditive with decreasing SOA, consistent with digits activating magnitude in the absence of central attention. This result replicates the findings of Oriet et al. (2005). Further, this result is consistent with digits activating magnitude automatically, as efficient is a key feature of automaticity (Moors & De Houwer, 2006).

Underadditivity has now been observed for both the SNARC effect in the parity judgment task and the distance effect in the magnitude comparison task. This pattern of results suggests that activating magnitude intentionally or unintentionally does not change the capacity demands of semantic activation for digits. Thus, I have provided evidence for the independence of the intentionality and efficiency criteria of automaticity, as suggested by Moors and De Hower (2006). Further, research suggests that different magnitude representations are activated in intentional and unintentional contexts (e.g., Cohen Kadosh & Walsh, 2009). If so, then the present work suggests that these representations have similar capacity demands.

## EXPERIMENT 2

Although digits are widely assumed to activate magnitude representations automatically, there is little evidence that this is the case for number words. With regards to the unintentional processing criterion of automaticity, previous research suggests that number words are less likely to activate magnitude unintentionally than digits (Cohen Kadosh et al., 2008; Dehaene et al., 1993; Fias, 2001; but see Dehaene & Akhavein, 1995; Nuerk et al., 2005). Namely, magnitude effects are typically smaller for number words than for digits or entirely absent in tasks where magnitude is activated unintentionally, such as parity judgment (Dehaene et al., 1993), phoneme detection (Fias, 2001), and physical size comparison (Cohen Kadosh et al., 2008). Consequently, some researchers have claimed that number words do not activate magnitude unintentionally (e.g., Fias, 2001). This stands in contrast with evidence from the visual word recognition literature that non-number words activate semantic representations unintentionally (e.g., Brown, Gore, and Carr, 2001; Dark, Johnston, Myles-Worsley, & Farah, 1985; Dudschig, Souman, Lachmair, Vega, Kaup, 2013; Estes, Verges, & Barsalou, 2008; Henik, Friedrich, & Kellogg, 1983; McKenna & Sharma, 1995; Neely, 1976; 1977, Reynolds &

Langerak, 2015). Specifically, word meaning has been found to affect performance across a variety of non-semantic tasks, such as naming and spatial orientation.

With regards to the efficiency criterion of automaticity, I am unaware of any studies that have investigated whether number words require *input attention* in order to activate magnitude. In contrast, there is substantial evidence that non-number words require input attention in order to activate semantics (e.g., Besner & Stolz, 1999; Besner, Risko, & Sklair, 2005; Harris & Pashler, 2004; Harris, Pashler, & Coburn, 2004; Risko, Stolz, & Besner, 2005; Scharff, Palmer, & Moore, 2011). For instance, Scharff et al. (2011) employed Shiffrin and Gardner's (1972) time delimitation paradigm and found better performance when subjects semantically categorized words in the successive condition compared to the simultaneous condition (see the introduction for a description of this paradigm; see also Harris et al., 2004). Similarly, Stroop interference is reduced when a neutral (non-colour) word is presented in the display along with the colour word (e.g., Brown et al., 2002; Kahneman & Chajczky, 1983), and when attention is focused on another location within a display (e.g., Besner et al., 2005; Dark et al., 1985) or on a single letter within the colour word (e.g., Besner & Stolz, 1999).

As noted earlier, previous work by Sigman and Dehaene (2005; 2006) examined the distance effect within the PRP paradigm, but did not directly examine how the distance effect for number words was affected by SOA. Related evidence from studies using non-number words as stimuli suggests that central attention is required in order to activate semantics (Besner & Reynolds, 2017; Fagot & Pashler, 1992). These studies found that Stroop interference from task-irrelevant colour words (e.g., green; Fagot &

Pashler, 1992) and colour-related words (Besner & Reynolds, 2017; e.g., frog) was additive with SOA in a colour naming task.

In order to (1) further test semantic activation within the domain of numerical cognition and (2) clarify the attentional requirements of semantic activation by number words, Experiment 2 tested whether number words, like digits, activate magnitude in the absence of central attention. Identical to Experiment 1, this was accomplished by looking for evidence that the distance effect for number words goes underadditive with decreasing SOA within the PRP paradigm. Given previous evidence that (1) number words are less likely to activate magnitude unintentionally than digits (e.g., Dehaene et al., 1993) and (2) non-number words require both input attention (e.g., Harris et al., 2004) and central attention (Besner & Reynolds, 2017) in order to activate semantics, as well as the claim that number words use at least some of the same processing structures as other types of words (Cipolotti & Butterworth, 1995; Dehaene, 1992; McCloskey, 1992), it appears likely that number words will require central attention in order to activate magnitude.

## Method

*Participants.* A new group of thirty undergraduate Trent University students participated in the experiment in return for credit in an eligible psychology course. All participants had normal or corrected-to-normal vision, and reported normal colour vision.

*Stimuli.* The stimulus for Task 1 was identical to that used in Experiment 1, except that the rectangle now subtended 1.6° visual angle vertically and 4.9° to 5.8° visual angle horizontally. The digits that were used for Task 2 in Experiment 1 were replaced with number words that encompassed the same numerical range. The number words were presented in lower case letters in a white 18-pt Courier New font against a black background. They subtended .6° visual angle vertically and 1.1° to 2.1° visual angle horizontally, and were separated by 1.4°.

*Apparatus.* The apparatus was identical to Experiment 1.

*Procedure.* The procedure was identical to Experiment 1, except that subjects compared the magnitude of number words.

## Results

The RT and error data were analyzed in the same way as in Experiment 1. Mean RTs and percentage errors for both tasks can be seen in Figure 3A.

### Response Time (RT)

Trials where an error was made in Task 1 (0.641%) or Task 2 (2.86%) were removed prior to analyzing the RT data, as were any trials where a voice-key failure occurred in Task 1 (1.20%). Outlier trimming (Van Selst & Jolicoeur, 1994) resulted in the removal of 1.60% of the remaining Task 1 RT data and 0.765% of the remaining Task 2 RT data.

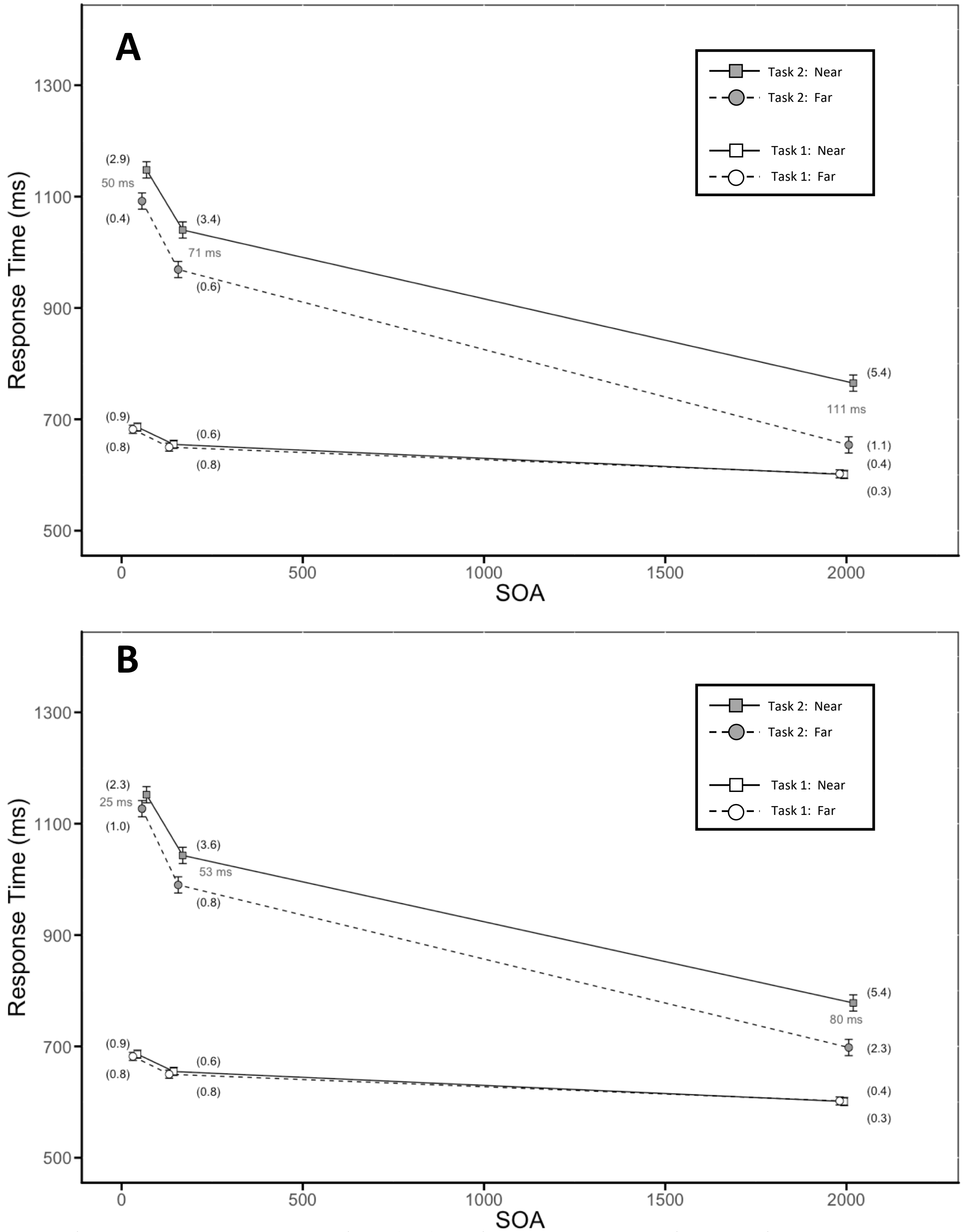



Figure 3: Mean response time (ms) and percentage error in Experiment 2 as a function of task (colour discrimination vs. magnitude comparison), stimulus onset asynchrony (SOA; 50 vs. 150 vs. 2000 ms), and distance (near vs. far). Panel A shows the original trimmed data. Panel B shows the data once the effect of word length had been removed. 95% confidence intervals were calculated separately for each task using Loftus and Masson (1994).

*Task 1: Colour Discrimination.* There was a main effect of SOA, whereby the time taken to name colours increased as SOA decreased, $F(1, 29) = 102.34$, $p < .001$, $\eta_p^2 = .779$. However, there was no main effect of distance, $F(1, 29) = 0.941$, $p = .340$, $\eta_p^2 = .031$, nor was there an interaction between SOA and distance, $F(1, 29) = 0.436$, $p = .514$, $\eta_p^2 = .015$. These results are consistent with subjects giving priority to Task 1.

*Task 2: Magnitude Comparison.* There was a main effect of SOA, whereby the time taken to respond increased as SOA decreased, $F(1, 29) = 258.19$, $p < .001$, $\eta_p^2 = .899$. There was also a main effect of distance, whereby responses were on average 79 ms slower on near trials than on far trials, $F(1, 29) = 161.75$, $p < .001$, $\eta_p^2 = .848$. Consistent with number words not requiring central attention in order to activate magnitude, there was an interaction between SOA and distance, whereby the distance effect decreased in size with decreasing SOA, $F(1, 29) = 32.33$, $p < .001$, $\eta_p^2 = .527$. There was a 111 ms distance effect at the 2000 ms SOA, $t(29) = 13.74$, $p < .001$, and attenuated but still highly significant distance effects of 71 ms at the 150 ms SOA, $t(29) = 6.50$, $p < .001$, and 57 ms at the 50 ms SOA, $t(29) = 7.71$ $p < .001$.

**Percentage Error**

*Task 1: Colour Discrimination.* Because there were too few errors (< 1%), the error data from Task 1 were not analyzed.

*Task 2: Magnitude Comparison.* The error data mirrored the RT data. There was a main effect of SOA, whereby fewer errors were made as SOA decreased, $F(1, 29) = 21.27$, $p < .001$, $\eta_p^2 = .423$. There was also a main effect of distance, whereby more errors were made on near trials than on far trials, $F(1, 29) = 63.41$, $p < .001$, $\eta_p^2 = .686$. Similar to Experiment 1, the decrease in errors with decreasing SOA can be explained by an interaction between SOA and distance, whereby the distance effect became smaller as SOA decreased, $F(1, 29) = 7.96$, $p = .009$, $\eta_p^2 = .215$.

**Controlling for Word Length**

One potential problem with comparing the magnitude of number words is that magnitude is correlated with word length, as there is a general trend for words denoting larger magnitudes to have more letters. For instance, the words “one” and “two” contain three letters, whereas the words “eight” and “nine” contain five and four letters, respectively. It is well established that the physical size of the numbers being compared affects the time taken to make magnitude comparisons (e.g., Cohen Kadosh et al., 2008). Therefore, I was concerned that subjects may have compared word length in addition to magnitude, and that it may have been this comparison process that went underadditive with decreasing SOA. In order to provide more compelling evidence of underadditivity of the distance effect, the previous analyses were re-run with all of the variability due to differences in physical size, or word length inequality, removed. Word length inequality was defined here as the difference in word length between the left and right stimuli on each trial. For this analysis, I calculated the slopes relating word length inequality with RT and percentage error separately for each cell and then re-calculated the scores in each cell with word length inequality set to 0. The previous analyses were then re-run on the adjusted raw data. Outlier trimming resulted in the removal of 1.60% of the Task 1 data and 0.71% of the Task 2 data. The data for both tasks can be seen in Figure 3B. Only the analyses of Task 2 are discussed below.

Again, there was a main effect of SOA, $F(1, 29) = 228.28$, $p < .001$, $\eta_p^2 = .887$, and there was a 53 ms main effect of distance, $F(1, 29) = 73.42$, $p < .001$, $\eta_p^2 = .717$.

Lastly, the interaction between SOA and distance was again significant, $F(1, 29) = 16.11$, $p <.001$, $\eta_p^2 = .357$. There was an 80 ms distance effect at the 2000 ms SOA, $t(29) = 7.86$, $p < .001$, a 53 ms distance effect at the 150 ms SOA, $t(29) = 5.52$, $p < .001$, and a 25 ms distance effect at the 50 ms SOA, $t(29) = 2.31$, $p = .028$.

The error data yielded a main effect of SOA, $F(1, 29) = 9.25$, $p = .005$, $\eta_p^2 = .242$, no main effect of distance, $F(1, 29) = 0.041$, $p = .842$, $\eta_p^2 = .002$, and no interaction between these factors, $F(1, 29) = 0.058$, $p = .812$, $\eta_p^2 = .002$.[2]

## Discussion

The goal of Experiment 2 was to assess whether number words activate magnitude in the absence of central attention. This issue was addressed by testing whether the distance effect for number words went underadditive with decreasing SOA when a magnitude comparison task was performed as Task 2 within the PRP paradigm. The distance effect went underadditive with decreasing SOA, consistent with number words activating magnitude in the absence of central attention. Because it was possible that subjects were comparing word length in addition to magnitude, the RT and error analyses were re-run once I had controlled for word length. Again, the distance effect went underadditive with decreasing SOA, consistent with number words activating magnitude in the absence of central attention. The observation of underadditivity of the distance effect for number words is inconsistent with the observation of additivity of both standard (Fagot & Pashler, 1992) and semantic (Besner & Reynolds, 2017) Stroop interference.

Regarding claims about automaticity, the observation that number words activate magnitude in the absence of central attention is inconsistent with previous claims based on the unintentionality criterion that number words *do not* activate magnitude automatically (Fias, 2001). The observation that number words activate magnitude efficiently (i.e., in the absence of central attention), but not unintentionally, is consistent with Moors and De Houwer's (2006) suggestion that intentionality and efficiency are independent features of automaticity.

It must be noted that although the distance effect in Experiment 2 went underadditive, consistent with automatic semantic activation, it was still statistically significant at the shortest SOA. This partial underadditivity is consistent with part of the distance effect arising before the central processing bottleneck (i.e., not requiring central attention) and another part of the distance effect arising at the central processing bottleneck (i.e., requiring central attention). I will return to this issue in the General Discussion.

## EXPERIMENT 3

The conclusion that number words can activate magnitude representations in the absence of central attention is consistent with the widely held belief that words activate semantics automatically (e.g., Augustinova & Ferrand, 2014; Neely & Kahan, 2001). However, this result is somewhat surprising given (1) the previous finding that non-number words require central attention in order to activate semantics (e.g., Besner & Reynolds, 2017), and (2) the claim that the same structures are used to process number words and non-number words (Cipolotti & Butterworth, 1995; Dehaene, 1992; McCloskey, 1992).

Previously, Besner and Reynolds (2017) and Fagot and Pashler (1992) reported additivity of a semantic effect for non-number words. Namely, they found that Stroop interference from task-irrelevant colour words (e.g., green; Fagot & Pashler, 1992) and colour-related words (e.g., frog; Besner & Reynolds, 2017) was additive with SOA in a colour naming task, where a word's meaning was activated unintentionally. In contrast, semantics was activated intentionally in the present Experiment 2. It is therefore possible that underadditivity of a semantic effect was observed for number words (Experiment 2) while additivity of a semantic effect was observed for non-number words (Besner & Reynolds, 2017) because of task-related processing differences. Therefore, the goal of Experiment 3 was to examine whether non-number words can activate semantics in the absence of central attention in a task as similar as possible to the magnitude comparison task that was used in Experiments 1 and 2, where underadditivity was observed. In order to compare the attentional requirements of numbers and non-number words, the same task, methodology, and measure of semantic activation was used here as in Experiments 1 and 2. This was possible because a distance effect consistently appears when subjects compare the physical size of the referent denoted by words (hereafter referred to as size comparison; e.g., Banks & Flora, 1977; Foltz, Poltrock, & Potts, 1984; Moyer, 1973; Paivio, 1975; Rubinsten & Henik, 2002). For instance, it takes less time to compare "whale" and "ant" than "bee" and "ant."

More specifically, Experiment 3 examined whether the distance effect for animal words goes underadditive with decreasing SOA within the PRP paradigm. A distance effect that went underadditive with decreasing SOA would be consistent with non-number words activating semantics in the absence of central attention. In contrast, a distance effect that was additive with SOA would be consistent with non-number words requiring central attention in order to activate semantics (Besner & Reynolds, 2017).

## Method

*Participants.* A new group of thirty undergraduate Trent University students participated in the experiment in return for credit in an eligible psychology course. All participants had normal or corrected-to-normal vision, and reported normal colour vision.

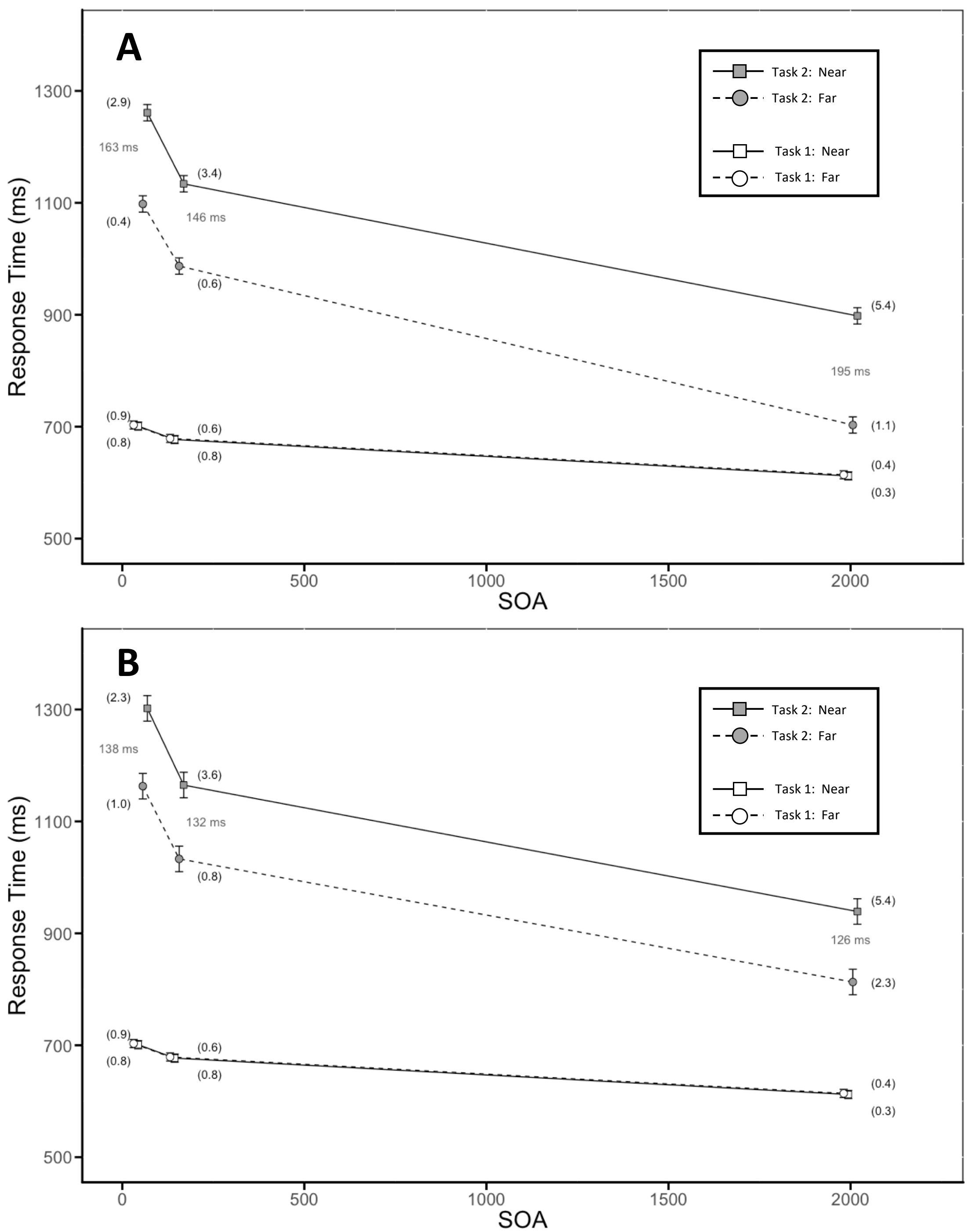
*Stimuli.* The stimulus for Task 1 was identical to that used in Experiments 1 and 2, and the rectangle again subtended 1.6° visual angle vertically and 4.9° to 5.8° visual angle horizontally. The stimuli for Task 2 were nine animal words selected from a list of stimuli used by Moyer (1973; see also Paivio, 1975): ant, bee, mouse, rat, duck, goat, tiger, rhino, and whale. The size of these animals increased in an approximately linear function (see Paivio, 1975). Word length ranged from three to five letters and these stimuli subtended .6° visual angle vertically and 1.1° to 2.1° visual angle horizontally, and were separated by 1.4°, consistent with the number words that were used in Experiment 2.

*Apparatus.* The apparatus was identical to Experiments 1 and 2.

*Procedure.* The procedure was identical to Experiments 1 and 2, except that subjects compared the conceptual size of animal words.

## Results

The RT and error data were analyzed in the same way as in Experiments 1 and 2. Trials were labelled "near" when the size of the animals were separated by a distance of one to four. For instance, the words "ant" and "bee" corresponded to the smallest and second smallest animals on the list, respectively, meaning they were separated by a distance of one.  Trials were labelled “far” when the animals were separated in size by a distance of five to eight.  For instance, the word “ant” corresponded to the smallest animal on the list and the word “whale” corresponded to the largest animal on the list, meaning they were separated by a distance of eight.  Mean RTs and percentage errors for both tasks can be seen in Figure 4A.




<u>Figure 4:</u> Mean response time (ms) and percentage error in Experiment 3 as a function of task (colour discrimination vs. size comparison), stimulus onset asynchrony (SOA; 50 vs. 150 vs. 2000 ms), and distance (near vs. far). Panel A shows the original trimmed data. Panel B shows the data once the effect of word length had been removed. 95% confidence intervals were calculated separately for each task using Loftus and Masson (1994).

**Response Time (RT)**

Trials where an error was made in Task 1 (0.787%) or Task 2 (3.77%) were removed prior to analyzing the RT data, as were any trials where a voice-key failure occurred in Task 1 (1.70%). Outlier trimming (Van Selst & Jolicoeur, 1994) resulted in the removal of 1.52% of the remaining Task 1 data and 1.10% of the remaining Task 2 data.

*Task 1: Colour Discrimination.* There was a main effect of SOA, whereby the time taken to name colours increased as SOA decreased, $F(1, 29) = 52.70$, $p < .001$, $\eta_p^2 = .645$. However, neither the main effect of distance, $F(1, 29) = 0.483$, $p = .492$, $\eta_p^2 = .016$, nor the interaction between SOA and distance, $F(1, 29) = 0.024$, $p = .855$, $\eta_p^2 = .001$, approached significance. These results are consistent with subjects giving priority to Task 1.

*Task 2: Size Comparison.* There was a main effect of SOA, whereby the time taken to make size comparisons increased as SOA decreased, $F(1, 29) = 196.37$, $p < .001$, $\eta_p^2 = .871$. There was also a main effect of distance, $F(1, 29) = 171.15$, $p < .001$, $\eta_p^2 = .855$, whereby responses were on average 169 ms slower on near trials than on far trials. Consistent with non-number words activating semantics in the absence of central attention, there was an interaction between SOA and distance, $F(1, 29) = 4.89$, $p = .035$, $\eta_p^2 = .144$. There was a 195 ms distance effect at the 2000 ms SOA, $t(29) = 15.22$, $p < .001$, and somewhat attenuated but still highly significant distance effects of 146 ms at the 150 ms SOA, $t(29) = 10.10$, $p < .001$, and 163 ms at the 50 ms SOA $t(29) = 9.04$, $p < .001$.

**Percentage Error**

*Task 1: Colour Discrimination.* Because there were too few errors (< 1%), the error data from Task 1 were not analyzed.

*Task 2: Magnitude Comparison.* The error data mirrored the RT data. There was a main effect of SOA, whereby fewer errors were made as SOA decreased, $F(1, 29) = 8.62$, $p = .006$, $\eta_p^2 = .229$. There was also a main effect of distance, with more errors being made on near trials than on far trials, $F(1, 29) = 60.87$, $p < .001$, $\eta_p^2 = .677$. Similar to Experiments 1 and 2, the decrease in errors with decreasing SOA can be explained by an interaction between SOA and distance, whereby the distance effect became smaller as SOA decreased, $F(1, 29) = 5.66$, $p = .024$, $\eta_p^2 = .163$.

**Controlling for Word Length**

Similar to the number words that were used in Experiment 2, word length in the present experiment was correlated with animal size. For instance, the two smallest words, “ant” and “bee”, both have three letters, whereas the two largest words, “rhino” and “whale”, both have five letters. Because of this relationship between animal size and word length, and because it is well established that the physical size of the stimuli being compared affects the time taken to make magnitude comparisons (e.g., Cohen Kadosh et al., 2008), it was anticipated that subjects may have compared word length in addition to animal size. Therefore, the previous analyses were re-run on the Task 2 data with all of the variability due to word length inequality removed (see the Experiment 2 Results section). Outlier trimming resulted in the removal of 1.51% of the Task 1 data and 1.03% of the adjusted Task 2 data. The data from both tasks can be seen in Figure 4B. Only the analyses on Task 2 are discussed below.

Again, there was a main effect of SOA, $F(1, 29) = 135.25$, $p < .001$, $\eta_p^2 = .823$, and there was a 132 ms main effect of distance, $F(1, 29) = 90.03$, $p < .001$, $\eta_p^2 = .756$. Lastly, the interaction between SOA and distance was no longer significant, $F(1, 29) = 0.349$, $p = .559$, $\eta_p^2 = .012$. There was a 126 ms distance effect at the 2000 ms SOA, $t(29) = 7.02$, $p < .001$, a 132 ms distance effect at the 150 ms SOA, $t(29) = 6.15$, $p < .001$, and a 138 ms distance effect at the 50 ms SOA, $t(29) = 8.03$, $p < .001$.

The error data yielded no main effect of SOA, $F(1,29) = 1.02$, $p = .322$, $\eta_p^2 = .034$, no main effect of distance, $F(1,29) = 1.45$, $p = .238$, $\eta_p^2 = .048$, and no interaction, $F(1,29) = 1.00$, $p = .325$, $\eta_p^2 = .033$.[3]

**Discussion**

The goal of Experiment 3 was to test whether non-number words require central attention in order to activate semantics. Here, subjects performed a size comparison task on animal words and the size of the distance effect was compared across SOAs. An initial analysis suggested that the distance effect went underadditive with decreasing SOA, consistent with animal words activating semantics in the absence of central attention. However, when the analyses were re-run after controlling for word length, the distance effect was additive with SOA. The results of the second analyses converge on previous demonstrations that words require central attention in order to activate semantics (Besner & Reynolds, 2017). Given the observation of underadditivity of the distance effect for number words in Experiment 2, the present results suggest that number words and non-number words differ in the efficiency with which they activate semantics. Regarding automaticity, the observation that number words but not non-number words activate semantics automatically according to the efficiency criterion, while non-number words but not number words activate semantics automatically according to the intentionally criterion, the present set of experiments provides strong evidence for the independence of efficient and unintentional as features of automaticity.

## GENERAL DISCUSSION

The present set of experiments examined whether semantic activation by digits, number words, and non-number words is automatic in the sense that it is efficient, and therefore does not require central attention. The use of central attention was assessed by examining how the effect of a semantic factor manipulated in Task 2 of the PRP paradigm was affected by SOA. In the present set of experiments, subjects performed magnitude comparisons on digits (Experiment 1) and number words (Experiment 2) and size comparisons on animal words (Experiment 3) as Task 2 within the PRP paradigm. The size of the distance effect was then compared across SOAs. Thus, semantic activation was compared across the numerical cognition and visual word recognition domains using the same task, methodology, and measure of semantic activation.

The distance effect for both digits and number words went underadditive with decreasing SOA, consistent with these notations activating magnitude in the absence of central attention (Dehaene & Akhavein, 1995). In contrast, the distance effect for animal words was additive with SOA, inconsistent with non-number words activating their semantic representations in the absence of central attention (e.g., Besner & Reynolds, 2017). Taken together, the present results suggest that semantics is activated automatically by digits and number words, but not by non-number words.

**Relating to Other Automatic Properties**

A comprehensive review of automaticity by Moors and De Houwer (2006) highlighted the importance of studying the different characteristics of automaticity separately due to their conceptual separability. The current section discusses whether different characteristics of automaticity are independent. Here, I consider the two criteria discussed in the introduction: (1) unintentional and (2) efficient (input and central).

A large body of previous evidence from the parity judgment, physical size comparison, naming, and orientation discrimination tasks indicates that digits can activate magnitude unintentionally (e.g., Cohen Kadosh et al., 2008; Dehaene et al., 1993; Fias et al., 1996; Fias et al., 2001; Ganor-Stern & Tzelgov, 2008; Tzelgov et al., 1992). It has also been demonstrated using Shiffrin and Gardener's (1972) time delimitation paradigm that digits can activate magnitude in the absence of input attention. Finally, it has been demonstrated using the PRP paradigm that digits can activate magnitude in the absence of central attention in the parity judgment task, where magnitude is activated unintentionally (Ford & Reynolds, 2016), and in the magnitude comparison task, where magnitude is activated intentionally (the present Experiment 1; Oriet et al., 2005). Thus, the activation of magnitude by digits is both efficient and can be unintentional. It may be appropriate, then, to say that digits activate magnitude in a "purely automatic" fashion (to borrow a phrase from Bargh, 1994).

Less research has examined whether number words activate magnitude automatically. Previous evidence from the parity judgment, physical size comparison, and naming tasks indicates that number words are unlikely to activate magnitude unintentionally (e.g., Dehaene et al., 1993; Fias, 2001). With regards to the efficiency criteria, we are unaware of any previous research assessing whether number words require input attention in order to activate magnitude. Lastly, I have provided one demonstration using the PRP paradigm that number words, like digits, can activate magnitude in the absence of central attention in the magnitude comparison task (Experiment 2). Therefore, although the present results are consistent with claims that number words activate magnitude automatically, it cannot be claimed that number words activate magnitude in a "purely automatic" fashion, as there is only support for one criterion of automatic processing: (central) efficient, but not unintentional.

Similar to digits, a substantial body of research has examined whether non-number words activate semantics automatically. A great deal of previous evidence from reading, colour naming, and location discrimination tasks indicates that non-number words can activate semantics unintentionally (e.g., Brown et al., 2002; Dark et al., 1985; Dudschig et al., 2013; Neely, 1977). However, previous evidence from the Stroop and time delimitation procedures (Shiffrin & Gardener, 1972) indicates that words, even those that are highly salient (such as one's own name and negatively valenced emotional words) require input attention in order to activate semantics (e.g., Besner et al., 2005; Harris & Pashler, 2004; Reynolds & Langerak, 2015). Further, three demonstrations using the PRP paradigm (Besner & Reynolds, 2017; Fagot & Pashler, 1992; the present Experiment 3) indicate that non-number words also require central attention in order to activate semantics. Thus, there is only support for one of the two criteria of automatic processing discussed here, as words appear able to activate semantics unintentionally but not efficiently (neither input nor central). Consequently, it may not be appropriate to claim that non-number words activate semantics in a “purely automatic” fashion (Bargh, 1994).

The present results indicate that different characteristics of automaticity are independent. This conclusion is consistent with the conclusion drawn by Moors and De Houwer (2006) that the different characteristics of automaticity are conceptually separable and should therefore be studied separately. The present results also indicate that digits, number words, and non-number words differ in the number of automatic processing criteria they meet when activating semantics. The observation that both criteria of automatic processing were met by digits and not by words (number or animal) suggests that it may be beneficial to reserve the term “automatic” for processes that meet all of the criteria of automatic processing (e.g., digits activating magnitude), and refrain from applying this term to processes that only meet one criterion (e.g., words activating semantics).

**Locus of the Distance Effect**

The observation of either additivity or underadditivity of the distance effect with SOA within the PRP paradigm has implications for the stage of processing at which this effect arises. Central attention is considered synonymous with response selection (e.g., Pashler, 1984; 1990; 1994; but see De Jong, 1993). Therefore, additivity of the distance effect would be consistent with this effect arising at response selection, whereas underadditivity would be consistent with this effect arising before response selection (i.e., at encoding). Many investigators have placed the distance effect solely at response selection (e.g., Dehaene, 1996; Schwarz & Ischebeck, 2000). The observation of additivity of the distance effect for animal words (Experiment 3) is consistent with this claim. However, the results of Experiments 1 and 2 do not support this claim for numbers. Rather, the observation that the distance effect went at least partially underadditive with decreasing SOA for digits and number words suggests that part of the distance effect for symbolic numbers arises at the encoding stage of processing, meaning it does not have an entirely late locus.

Instead, the data are more consistent with the two-stage model of the distance effect for numbers proposed by Oriet et al. (2005). According to their account, there is a rough small / large classification process that occurs at encoding (i.e., early) and an accuracy checking procedure that occurs at response selection (i.e., late). The observation that the distance effect went underadditive with decreasing SOA in Experiments 1 and 2 provides support for the early classification process. The observation that the distance effect was only partially underadditive for number words in Experiment 2 provides support for a late stage. The persistence of the distance effect at the 50 ms SOA is consistent with some of the distance effect for number words occurring at response selection.

However, the observation that the distance effect was not significant at the 50 ms SOA for digits in the present Experiment 1, but it was in Oriet et al. (2005), creates ambiguity. It could be that the present Experiment 1 did not have sufficient power to detect the late effect at the short SOA, or it could mean that the distance effect arose entirely at the encoding stage of processing in the present Experiment 1. If the latter is the case, there are two differences between the procedure utilized here and the procedure utilized by Oriet et al. (2005) that may explain the partial underadditivity observed in their study compared with the full underadditivity observed in the present Experiment 1.

First, Oriet et al. (2005) had subjects compare a single visually presented number to a fixed standard held in memory, whereas in the present set of experiments, subjects compared two visually presented stimuli. Second, Oriet et al.'s (2005) Task 1 was a tone discrimination task that required high versus low comparisons to be made and may have interfered with subsequent magnitude comparisons (Cohen Kadosh, Brodsky, Levin, & Henik, 2008; Cohen Kadosh, Lammertyn, & Izard, 2008; Hommel, 1998). In contrast, Task 1 in the present set of experiments was a colour discrimination task.

The observation that digits, number words, and non-number words each yielded a different interaction with SOA in the present set of experiments (underadditive, partially underadditive, and additive, respectively) suggests that the processing underlying the distance effect has different attentional requirements for all three notations. This pattern of results can be explained by assuming that each of these notations activates a different semantic system, and that each of these semantic systems has a different attentional requirement. Consistent with this explanation, previous evidence from brain-imaging studies suggests that separate, notation-dependent magnitude representations are activated by digits and number words in the intraparietal sulcus (e.g., Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007; Cohen Kadosh & Walsh, 2009; Cohen Kadosh, Muggleton, Silvanto, & Walsh, 2010), and the semantic representations of non-number words are stored in a diverse range of other areas, including the superior frontal gyrus (Price, 2012).

However, there are two issues with attributing notational differences in attentional requirements to the use of different semantic systems. First, it is unclear why these separate semantic systems would have different attentional requirements. Second, there is evidence that digits and number words activate shared, notation-independent magnitude representations in the intraparietal sulcus (e.g., Pinel, Dehaene, Rivère, & LeBihan, 2001) in addition to the notation-dependent magnitude representations mentioned above. Critically, previous research suggests that notation-independent magnitude representations are activated when magnitude is activated intentionally (e.g., Cohen Kadosh et al., 2008; Cohen Kadosh & Walsh, 2009), like in the present set of experiments. If it were the case that digits and number words were activating representations in the same semantic system in Experiments 1 and 2, this would suggest that the attentional requirements of this system are dependent on the characteristics of the stimulus activating the system. Here, I speculate that differences in the attentional requirements of semantic activation by digits, number words, and non-number words stem from the amount of semantic interference that arises when these three notations are processed. Indeed, previous evidence suggests that resolving semantic interference requires central attention (Piai, Roelofs, & Schriefers, 2014).

Here, I propose that the underadditivity of the distance effect for numbers and additivity of the distance effect for animal words may have been due to the richness of the semantic representations activated by these notations. There are two influential ways that semantic richness has been measured: (1) the number of features that are linked to a concept and (2) the number of ways in which a word is used (e.g., Pexman, Hargreaves, Siakaluk, Bodner, & Pope, 2008; Pexman, Holyk, & Monfils, 2003; Pexman, Lupker, & Hino, 2002; Yap, Tan, & Pexman, 2011). Critically, the semantic richness of numbers is minimal, there being a close to one-to-one correspondence between stimulus and meaning for numbers. For instance, the digit "4" and the word "four" refer almost exclusively to the value four. Meanwhile, animal words are semantically richer. To use the word “rat” as an example, many properties besides size are attached to the word “rat”: rats are living organisms, animals, mammals, can be kept as pets, but can also be considered pests. In addition, the word “rat” can be used to refer to a wide variety of things, ranging from a common brown rat to a Gambian pouched rat. Here, I hypothesize that the richer semantic representations of the animal words pushed the distance effect to a later stage of processing (i.e., response selection), perhaps by interfering with the rough categorization process (Oriet et al., 2005). Correspondingly, the distance effect for digits (Experiment 1) and number words (Experiment 2) had an early locus, while the distance effect for animal words was entirely late (Experiment 3).

The late component of the distance effect for number words (and possibly for digits) could arise from a different source of semantic interference, more specifically, from semantic representations that are activated by visually similar words (i.e., orthographic neighbours). Evidence from the visual word recognition literature suggests that when a word is encountered, the semantic representations of orthographically similar words are also activated (e.g., Forster & Hector, 2002; Hino, Lupker, & Taylor, 2012; Rodd, 2004). For instance, the non-word “turple” and the word “hurtle” may both activate the semantic representation of the word “turtle”. Within this account, resolving the semantic interference from multiple activated semantic representations requires central attention, which results in a late locus of the distance effect for number words (and may contribute to the late locus of the distance effect for animal words). In contrast to words, it may be that digits do not activate the semantic representations of visually similar stimuli (e.g., the digit “1” may not activate semantic representations for the digit

"12"). This may explain our observation of full underadditivity of the distance effect for digits and not for number words.

**Future Directions**

A worthwhile future endeavour would be to assess whether there is a relationship between the efficiency of semantic activation for numbers and the cultural backgrounds of the participants. For instance, in the Chinese culture, the number 8 / eight is considered to be lucky. It seems likely that participants from cultures in which certain numbers have special meanings would have richer semantic representations for these stimuli. Consequently, these participants may not activate semantics efficiently for numbers.

Above, I have proposed that the efficiency of semantic activation is related to semantic interference. However, it is possible that changes in skill may also affect efficiency (LaBerge & Samuels, 1974; Samuels, LaBerge, & Bremer, 1978). Therefore, another worthwhile future endeavour would be to assess the relationship between the efficiency of semantic activation for numbers and math skill, in particular during the acquisition of basic math facts during early education.

In the present set of experiments, semantic activation for non-number words was inefficient when university students served as the participants. Although these participants did not disclose their age, the overwhelming majority appeared to be young adults. Therefore, it would be interesting to determine whether the activation of semantics by non-number words becomes efficient with more advanced age. Consistent with this possibility, there is some evidence from the PRP paradigm that lexical access is inefficient for younger participants (mean age = 25) and efficient for older participants (mean age = 71; Lien et al., 2006). As far as I am aware, there is not yet evidence that any other processes involved in word reading change in efficiency with increasing age.

**Conclusion**

The present set of experiments investigated whether semantic activation is automatic for digits, number words, and non-number words. This claim was tested by investigating whether these notations can activate semantics in the absence of central attention. The distance effect yielded underadditive effects with decreasing SOA for both digits and number words when subjects made magnitude comparisons as Task 2 within the PRP paradigm. These results are consistent with digits and number words activating magnitude in the absence of central attention, or automatically. However, the distance effect for animal words was additive with SOA. This result is inconsistent with non-number words activating semantics automatically.

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Foot Notes

1. For the present purposes, bottleneck theories that postulate capacity sharing between the two tasks (e.g., Tombu & Jolicoeur, 2003) make the same predictions as the all-or-none bottleneck account.
2. A third analysis was conducted, where repeated measures ANOVAs were run exclusively on trials where the words being compared were of the same length (e.g., one two). Critically, the distance effect in the RT data still went underadditive with decreasing SOA, $F(1,29) = 24.897$, $p < .001$, $\eta_p^2=.462$. There was a 85 ms distance effect at the 2000 ms SOA, $t(29) = 7.862$, $p < .001$, an attenuated but still significant 44 ms distance effect at the 150 ms SOA, $t(29) = 3.968$, $p < .001$, and an unreliable 9 ms distance effect at the 50 ms SOA, $t(29) = .658$, $p = .516$. These results provide additional evidence of underadditivity of the distance effect for number words.
3. Again, a third analysis was conducted, where repeated measures ANOVAs were run exclusively on trials where the words being compared were of the same length (e.g., one two). Critically, the distance effect in the RT data was additive with decreasing SOA, $F(1,29) = .283$, $p = .599$, $\eta_p^2=.001$. There was a 179 ms distance effect at the 2000 ms SOA, $t(29) = 7.491$, $p < .001$, a 176 ms distance effect at the 150 ms SOA, $t(29) = 6.850$, $p < .001$, and a 165 ms distance effect at the 50 ms SOA, $t(29) = 6.569$, $p < .001$. These results provide additional evidence of additivity of the distance effect for non-numbers words.