One, 2, Thrie: Effects of Surface Format on the Intentional

and Unintentional Activation of Quantity

by

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Abstract

I examined intentional and unintentional activation of quantity information when numbers were presented as digits, words, and pseudohomophones (e.g., 1, one, wun). Undergraduates completed numerical (intentional activation of quantity) and physical (unintentional activation of quantity) comparison tasks. The size congruity and distance effects were used as indices that quantity information was activated. In the number comparison task all formats elicited a distance effect. In contrast, in the physical comparison task, digits but not words activated quantity information. The results of Experiment 1 also showed pseudohomophones unintentionally activated quantity information. Examination of the stimuli indicated that the physical length of pseudohomophones and congruity were confounded. Experiment 2 resolved this by forcing words and pseudohomophones to fit into a specified area. The results concerning digits and words were replicated. However, there was no evidence pseudohomophones unintentionally activated quantity information. Results are discussed in terms of theories on the representation of quantity information.

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People encounter numbers in various contexts and formats every day. Consider the example of reading a book. Arabic digits indicate the pages in the book (e.g., 4, 5), different sections of the book are sequenced in the table of contents as Roman numerals (e.g., IV, V), and numbers presented in the text are in word format (e.g., four, five). Even though the stimuli in the book are presented in different surface formats—compare *5* and *five*—and thus look quite different, they all may signify quantity information. In this thesis, I explored the question of how people process numerical information when the surface format varies.

Humans' remarkable flexibility with handling numbers in different notations has led researchers to propose that the representation of numbers in semantic memory is independent of surface format. For example, in theories such as the abstract-code and triple-code models, the representation of numbers is assumed to be independent of notation (e.g., Dehaene, 1992; Dehaene & Cohen, 1995; McCloskey, 1992; McCloskey & Macaruso, 1995). In contrast, other theories of numerical cognition, such as the encoding-complex theory, posit that the representation of magnitude information is dependent on the format (e.g., Campbell, 1994; Campbell & Clark, 1988; Campbell & Epp, 2004). According to the encoding-complex theory, when numbers are presented in different surface formats (e.g., 5, five) they activate format-specific representations. To determine which of these two broad theoretical views is valid, researchers have examined if numbers in different surface formats activate numerical information in similar ways.

When adults complete a task that involves activation of quantity information, such as deciding that 5 is larger than 4, one indication that numerical information has been activated is the distance effect (Moyer & Landauer, 1967). The distance effect refers to the finding that it takes longer to compare numbers that are closer in magnitude (e.g., 5 vs. 6) than to compare two numbers that are farther apart in magnitude (e.g., 5 vs. 9; Dehaene & Akhavein, 1995; Duncan & McFarland, 1980; Henik & Tzelgov, 1982; Schwarz & Ischebeck, 2003). The distance effect is hypothesized to occur because numbers are spatially represented in semantic memory with small numbers to the left and large numbers to the right along a metaphorical number line (for a review, see Fias & Fischer, 2005). Researchers have shown that when two numbers activate quantity information the activation for both numbers is more similar than when the two numbers are farther apart (e.g., Dehaene & Changeux, 1993; Fias & Fischer, 2005; Rubinsten, Henik, Berger, & Shahar-Shaleu, 2002). As a result, it takes people longer to distinguish between two numbers that are close together than far apart which indicates quantity information has been activated. In summary, the distance effect has been observed when adults complete numerical comparisons and is interpreted as evidence that quantity information has been activated.

The other effect observed in comparison tasks is called *size congruity*. This effect is observed when pairs of numbers are presented for comparison that simultaneously varies along two dimensions; numerical and physical (see Table 1 for examples). When the numerical and physical information match, such that the numerically larger number is also physically larger (e.g., 4 3), the pair is congruent. When the numerical and physical information do not match, such that the numerically larger number is physically smaller (e.g., 4 3) the pair is incongruent. When participants complete a numerical comparison, the incongruent pair takes longer to compare than the congruent pair. This difference between congruent and incongruent pairs is called the size congruity effect (Paivio, 1975). When digit stimuli are used, the size congruity effect occurs both for numerical comparisons, suggesting that physical information has been intentionally processed, and for physical comparisons (i.e., choose which number is physically larger), suggesting that numerical information has been unintentionally activated (e.g., Girelli, Lucangeli, & Butterworth, 2000; Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992). Participants' performance on neutral number pairs (e.g., 2 3 is physically neutral and 2 2 is numerically neutral) can indicate if the size congruity effect is due to interference (i.e., slowed processing) from incongruent pairs or facilitation (i.e., speeded processing) from congruent pairs. Effects of size congruity are well established when numbers are presented as digits (Tzelgov & Ganor-Stern, 2005). However, the question addressed in

Table 1

Examples of number pairs that are congruent, incongruent, and neutral for the numerical and physical comparison tasks. The correct selection for each task is underlined.

	Pair Type		
Task	Congruent	Incongruent	Neutral
Numerical Comparison	8 3	8 3	8 3
(Choose Numerically Larger)	8 7	8 7	8 7
Physical Comparison	3 8	3 8	8 8
(Choose Physically Larger)	2 3	2 3	2 2

Note: The example in each box has a distance of five (top) and one (bottom).

the present research is whether activation of numerical information occurs when numbers are presented in different surface formats.

To gain a better understanding of the issues, a review of several key topics follows. First, I review theories on the architecture of how quantity information is processed and represented in semantic memory. Second, I examine the differences between intentional and unintentional activation of quantity information. Third, I outline previous research on the intentional and unintentional activation of quantity information in different surface formats. Fourth, I present a brief review on previous research in the language and reading literature concerning the semantic processing characteristics of digits, words, and pseudohomophones. Finally, I discuss the results two experiments that investigated the intentional and unintentional activation of numerical information in digit, number word, and pseudohomophone formats.

Theories of Quantity Representation and Processing

Notation-independent quantity representation. According to the triple-code model, there are three primary mental codes that are invoked during numerical processing (Dehaene, 1992; Dehaene & Cohen, 1995). These codes include (a) an auditory verbal word frame, (b) a visual Arabic number form, and (c) an analogue magnitude representation. Each of these codes is hypothesized to subsume different numerical tasks. The auditory verbal word frame is used to represent addition and multiplication facts, is phonological, and is involved in encoding number words. The visual Arabic number form is involved in the representation of multi-digit arithmetic (e.g., 23 + 14) and encoding Arabic digits. Of particular importance to the current review is the analogue magnitude representation, which is believed to be an abstract representation of quantity, involved in numerical comparison, estimation, and subitizing tasks. Each of the systems listed above has input-output processes that are format specific and allow numerical information to enter and exit the three systems. Further, because each system subsumes a certain task, the information can be transferred from different systems by direct asemantic links. Thus, activation of the magnitude code can occur when either a visual or auditory stimulus activates the visual number form or auditory word frame, respectively.

The triple-code model predicts that digits and number words will enter the numerical cognition system through different systems (Dehaene, 1992; Dehaene & Cohen, 1995). Specifically, digits are encoded into the numerical system by the visual Arabic number form but number words are encoded into the numerical system by the auditory verbal word frame. For a numerical comparison to occur the information contained in either the auditory verbal word frame or visual Arabic number form must activate the analogue magnitude representation. As numerical comparisons are conducted on the same code, response characteristics (e.g., distance effect and size congruity effect) that reflect activation of quantity information will be independent of surface format. The triple-code model predicts that there will be differences in the amount of time it takes to make this comparison between formats, but only at the encoding level. Specifically, it can take longer for number words to activate the analogue magnitude representation than digits, but once in the analogue magnitude representation, the format of the number should have no effect on the numerical comparison and activation of quantity information.

Another commonly cited theory of numerical cognition, the abstract-code model (McCloskey, 1992), also proposes that the representation of quantity is independent of notation. There are two primary comprehension systems, one that encodes number words and the other that encodes Arabic digits. Both of these systems input numbers into an abstract semantic representation of quantity. Numerical comparisons are believed to occur within this abstract representation and response systems allow an adult to produce a response. Similar to the triple-code model the abstract-code model also predicts that digits and number words are encoded by different systems but are translated to an abstract representation of quantity before a numerical comparison can occur. The abstract-code model has other components but they are not relevant to the current study.

Both of the models describe how numbers are unintentionally processed. As described above, when numbers are intentionally processed the numbers activate an abstract magnitude representation (Dehaene & Akhavein, 1995; McCloskey, 1992; 1995). Both models assume that when a task does not require numerical judgments quantity information is still unintentionally activated. Therefore, the predictions concerning the presence or absence of effects that indicate quantity information has been activated are straightforward. If quantity information is required to perform the task (i.e., intentional activation), then both distance and size congruity effects are expected across all formats. When quantity information is not required, distance and size congruity effects should also be elicited as the models assume quantity information is processed unintentionally. The effects should not differ across formats, as the quantity representation is abstract.

Notation-dependent representation of numbers. In contrast to the models described above, the encoding-complex hypothesis posits that numbers are not abstracted away from their surface format when a numerical comparison is performed (Campbell & Clark, 1988; 1992; Campbell & Epp, 2004). Specifically, the more practiced and familiar a number format is the more efficient and fast retrieval of quantity information will be (Campbell, 1994; Campbell & Epp, 2004). For example, when a participant compares the digits "2" and "3" they access numerical information faster than if the numbers had been presented as "two" and "three". As digits are more practiced and familiar than number words, the pattern of responses that indicate quantity information has been activated differ between the two formats. Importantly, the differences are not completely due to encoding processes but also implicate number access and comparison processes. On this view the encoding-complex model hypothesizes that numbers are not abstracted away from their original format and number format affects cognitive processing.

The encoding-complex hypothesis also assumes that when a task does not require numerical judgments quantity information is unintentionally activated. As is the case for tasks where numerical judgments are required the strength of activation of quantity information is contingent on how familiar and practiced a participant is with that particular number format (Campbell, 1994; Campbell & Epp, 2004). Therefore, when quantity information is unintentionally activated the response characteristics that indicate quantity information has been activated will differ across formats.

In summary, although these theories of numerical cognition differ in their details they can be grouped into two broad categories in terms of their predictions for the number comparison task across formats. McCloskey's (1992) abstract-code model and Dehaene's (1992) triple-code model both predict that the representation of quantity is abstract. Hence, the surface format of the number presented should have no effect on the comparison process even if it does affect encoding. In contrast, Campbell and Epp's (2004) encoding-complex hypothesis predicts that the representation of quantity is not abstract and thus a number's surface format will affect whether or how much quantity information is activated. Researchers have used various methodologies, primarily those that involve the intentional processing of quantity information, to determine if numbers in different surface formats activate quantity information. In general, if the patterns of activation are similar, particularly if surface format doesn't interact with other factors, then the representation of numbers is assumed to be independent of notation. In contrast, if the patterns of quantity activation are not similar across formats (i.e., if surface format interacts with factors such as magnitude), then these results would be consistent with the view that the representation of quantity is notation dependent.

Intentional and Unintentional Processing of Quantity Information

It is crucial in studies that examine the nature of the representation of quantity information in semantic memory to consider whether the quantity information is activated intentionally or unintentionally. Intentional processing of quantity information means that the processing of the numbers was necessary to accomplish the task (Cohen Kadosh, Henik, & Rubinsten, 2008). In contrast, unintentional activation of quantity information occurs when it is not necessary to process quantity information to do the task, and yet there is evidence of quantity activation. For example, quantity information has been activated when distance effects (Moyer & Landauer, 1967), size congruity effects (Henik & Tzelgov, 1982), and / or spatial numerical association of response codes effects (SNARC; Dehaene, Bossini, & Giraux, 1993) occur. In the current study, intentional and unintentional activation of quantity information was examined using numerical (e.g., 2, 3; 3 is numerically larger) and physical (e.g., 2, 3; 3 is physically larger) comparison tasks, respectively.

There are several reasons that contrasting intentional and unintentional processing of numerical information is important to understand how numbers in different surface formats are processed and represented. First, activation of quantity information in intentional processing tasks will occur no matter the format of the number and thus cannot be used to indicate whether the activation of quantity information is obligatory. For example, when an adult completes a numerical comparison task, quantity information is necessarily activated because otherwise the task can not be completed – thus, it is not surprising that distance and size congruity effects are observed across different surface formats in numerical comparisons (Cohen Kadosh et al., 2008; Tzelgov & Ganor-Stern, 2005). Second, researchers have argued that when people intentionally process quantity information the semantic representations suggested by the data, such as the distance effect and SNARC effect (described below), can change due to differences between tasks and stimuli (Tzelgov & Ganor-Stern, 2005). Finally, in a review of the literature, Barsalou (2003) concluded that *intentional* processing of any type of information in semantic memory could lead to a temporary representation optimal for the current task. Hence, the best way to understand the nature of semantic representations and examine processing differences is to focus on the *unintentional* activation of information in semantic memory.

Activation of Quantity Information in Different Surface Formats

Considerable research supports the conclusion that digits activate quantity information in tasks where quantity information is necessary for task completion (e.g., Barth, Kanwisher, & Spelke, 2003; Naccache & Dehaene, 2001; Tzelgov et al., 1992). For example, the distance effect is reliably found when digits are used in numerical comparison tasks (Duncan & McFarland, 1980; Pavese & Umiltà, 1998). The classic SNARC effect, where small numbers are responded to faster with the left hand than the right hand and vice versa for large numbers, has also been taken as evidence that digits intentionally activate numerical information (e.g., Dehaene et al., 1993). From imaging data, there is converging evidence to indicate that an area in both parietal lobes, the horizontal segment of the intraparietal sulcus (HIPS), is consistently activated by numbers presented in digit format when they are intentionally processed (reviewed by Dehaene, Piazza, Pinel, & Cohen 2003). For example, when adults completed number comparison, naming, and single-digit arithmetic with digits, the HIPS was consistently activated across all tasks (Chochon, Cohen, van de Moortele, & Dehaene 1999). Thus, both behavioural and neurological research supports the conclusion that digits activate quantity information when that information is necessary for task completion.

In contrast, there is little consensus on the question of whether numbers in other formats, such as words, elicit the same markers of quantity activation when they are used in tasks were quantity is necessary for task completion. Foltz, Poltrock, and Potts (1984) examined the activation of quantity information in digit and number word formats. Participants completed the standard numerical comparison task with congruent and incongruent number pairs (see Table 1 for examples) in both digit and word format. Foltz et al. (1984) found that both formats exhibited a significant distance effect although participants responded to number words more slowly than to digits. This research was the first evidence that number words could activate quantity information in intentional processing tasks. However, one criticism of Foltz' et al.'s experiment is that number format was manipulated between participants. This manipulation could have led to strategic changes in how participants responded to digits and number words, as they never saw the other format. Nonetheless the results of Foltz et al. suggest that when numbers are intentionally processed in either digit or word format they activate quantity information that results in format-independent distance effects.

The effect of format has also been examined using other markers of semantic activation. Dehaene et al. (1993) explored the SNARC effect using a parity task. The SNARC effect is the finding that participants respond faster to small numbers on the left and larger numbers on the right. The SNARC effect is taken as evidence that quantity information has been activated. In two experiments, participants completed a parity task (i.e., is the number even or odd) with numbers in both digit and number word formats. Number words were responded to significantly more slowly than digits, but this difference can be accounted for by the longer time necessary to encode words versus digits. More importantly, a SNARC effect emerged for numbers in both digit and word formats, although the size of the effect was modest. In summary, when numbers are intentionally processed in number comparison and in parity tasks, both digits and number words activated quantity information as reflected in distance and SNARC effects (Dehaene et al., 1993; Foltz et al., 1984).

Dehaene and Akhavein (1995) compared the intentional and unintentional processing of quantity information in digit and number word formats. In Experiment 1, participants decided if two numbers that were either both digits, both number words, or a mixed pair were numerically the same or different (i.e., standard numerical comparison task). As expected, a distance effect was observed for both the pure and mixed pairs of numbers. In Experiment 2, a different group of participants decided if two numbers were physically identical (e.g., 2, 2; two, two) or not (e.g., 2, two). There was no significant distance effect for mixed pairs (e.g., 2, FOUR) but a distance effect did emerge for pure digit (e.g., 2, 4) and number word pairs (e.g., TWO, FOUR). Dehaene and Akhavein (1995) concluded that both digits and number words unintentionally activated quantity information. An issue with this conclusion concerns the mixed pair results. If both digits and number words unintentionally activated quantity information one would expect there to be a distance effect for the mixed pairs. Furthermore, the finding that number word pairs activated quantity information may have been a spurious effect. Consider that participants would only respond ‘same’ when the two numbers were physically identical and had a distance of zero. Because number words vary in length (e.g., one vs. seven), participants may have used a strategy of quickly comparing the lengths of the pairs to determine a same/different judgment. Thus, the distance effect for pure number word pairs may have been a product of differing word length and not of numerical size. These results call into question whether number words unintentionally activate quantity information.

Ganor-Stern and Tzelgov (2008) performed two experiments to explore unintentional activation of quantity information with Arabic speakers. In the first experiment, participants completed a physical comparison using pairs of digits, Indian numbers, or mixed pairs. Indian numbers are the Arabic characters used to denote numbers. Indian number words are different from English number words (e.g., 1, 2; ١, ٢; one, two) in that they are single characters. Therefore, Indian number words are not analogous to English number words and resemble digits more than words. For all pair types, a size-congruity effect was observed which indicated that some quantity information was unintentionally activated. However, the distance effect was not significant for pure Indian word pairs or mixed pairs. These results are inconclusive in that Indian words did produce size congruity but not distance effects.

In Experiment 2, participants completed the physical same or different task used by Dehaene and Akhavein (1995). Participants determined if two numbers were the same or different rather than which one was physically larger (as in Experiment 1). In this comparison task, both digits and Indian number words elicited a distance effect (Ganor-Stern & Tzelgov, 2008). Hence, with the exception of the lack of a distance effect in Experiment 1, the results suggest that Indian number words unintentionally activated quantity information. However, these results must be interpreted cautiously as digits and Indian number words are more similar to each other than digits and English number words.

Cohen Kadosh et al. (2008) had adults complete several numerical and physical comparison tasks with digits and words. This was the first research that examined both intentional and unintentional processing of quantity information completely within participants. Cohen Kadosh et al. conducted several experiments to determine if factors such as word length and variability in physical size differences influenced activation of quantity information. They manipulated size congruity and the numerical distance between the pairs. In contrast to the findings reported by Ganor-Stern and Tzelgov (2008) and Dehaene and Akhavein (1995), Cohen Kadosh et al. found evidence of unintentional activation of quantity information only for digits and not for number words – for the latter, neither the size congruity nor the distance effect was significant. They also examined mixed number pairs and found no size congruity effect for a physical comparison task with number words when they were paired with digits. Overall, after controlling for several factors that have been shown to affect the size congruity effect and distance effect in the three other experiments, they concluded that number words do not unintentionally activate quantity information. In contrast to previous research, Cohen Kadosh et al. had the same participants perform both the numerical and physical comparison and checked to ensure that the effects found were not due to stimuli artifacts that may have compromised the interpretation of the results of previous research reviewed above. Thus, their findings provide a comprehensive and convincing argument against the view that number words elicit quantity activation in unintentional processing tasks.

Activation of quantity information has also been explored using priming. Priming, in the context of the activation of quantity information, occurs when a prime stimulus (e.g., 2) facilitates the response to a probe stimulus (e.g., 3; Dehaene, Naccache, Le Clec'H, Koechlin, & Mueller, 1998; den Heyer & Briand, 1986). A priming distance effect occurs when the numerically closer the prime and the probe are to each other the faster the response to the probe. Thus, participants respond more quickly to 4 when it is primed by 5 than when it is primed by 9. If the priming distance effect occurs when the prime and probe differ in notation this would provide evidence that they both address an abstract representation of quantity information. Koechlin, Naccache, Block, and Dehaene (1999) used primes in digit and number word format and participants determined if the target was greater or less than five. They found priming within digit and word formats but no evidence of quantity information activation across formats; both when primes were masked and when there were not masked. The masked priming condition was used to produce unintentional processing of quantity information because participants could not see the prime in the masked condition. The finding that there was within-format distance effects indicated that number words may unintentionally activate quantity information. However, as with the results of Dehaene and Akhavein (1995) the interpretation of the meaning of the within-notation priming is difficult due to the lack of between-format priming. If number words and digits activated the same type of quantity information between and within-format priming would be expected.

In contrast to the findings reported by Koechlin et al. (1999), Naccache and Dehaene (2001) observed masked priming both within and between notation when adults determined if the probe was greater or less than five. These results indicated that number words and digits unintentionally activated quantity information. The discrepancy in results may be due to the sensitivity of masked priming to minor experimental details. The crucial interaction in Koechlin et al. (1999), which would have indicated across-format priming had occurred, was almost significant (i.e., $p = .05$). Therefore, across notation priming may have occurred but the study had insufficient power. In summary, the two priming studies appear to indicate that digits are processed unintentionally but words are not.

In summary, all of the research reviewed supports the conclusion that when numbers are presented as digits they activate quantity information in both intentional and unintentional processing conditions. For number words, the results indicate that they activate quantity information when they are intentionally processed. However, the results are mixed as to whether words activate quantity information in unintentional tasks. To further explore this issue, several researchers have used neuroimaging techniques to determine if number words unintentionally activate quantity information.

Neuroimaging research. Neuroimaging techniques such as fMRI and ERP have been used to evaluate the neural areas activated during both intentional and unintentional processing of quantity information. Dehaene et al. (2003) reviewed the extant neuroimaging literature and concluded that the horizontal segment of the intraparietal sulcus (HIPS) is the neural area that subsumes the semantic representation of quantity. Therefore, if both digits and words activate quantity information, numbers in both formats should activate the HIPS. Naccache and Dehaene (2001) obtained fMRI and ERP measurements as participants completed the physical comparison task. Critically, both digits and number words activated the HIPS area in the parietal lobes indicating both formats unintentionally activated quantity information. In addition, the ERP waveform components did not significantly differ in the parietal regions when digits and number words were presented. In another study, similar results were obtained with a numerical comparison task (Pinel, Dehaene, Rivière, & LeBihan, 2001). Crucially, the HIPS were always active when comparing either digits or number words. However, Pinel et al.'s (2001) results only indicate that number words can intentionally activate the HIPS. Based on the two studies that examined these questions using basic fMRI and ERP both digits and words activate quantity information as indexed by the activation of the HIPS.

Advanced neuroimaging techniques that allow more refined pictures of neural activation, relative to basic fMRI and ERP techniques, has suggested that different neuronal populations within the HIPS may be recruited when numbers are presented in different formats (Cohen Kadosh & Walsh, 2009; Piazza, Pinel, LeBihan, & Dehaene, 2007). The adaptation paradigm has been used to determine changes in processing within fMRI voxels (Cohen Kadosh & Walsh, 2009). A participant is shown two numbers in either digit or number word format. If format has no effect on the activation of quantity information and the two numbers are the same it is expected that activity in the HIPS should decrease relative to when the two numbers are different. When adults viewed dots and digits, adaptation did not occur in the left intraparietal sulcus (IPS) but did occur in the right IPS (Piazza et al., 2007). These results indicated that, at least in the left hemisphere, the unintentional activation of quantity information elicited by digits and dots differed. Other studies that have used the adaptation paradigm have also found differences in the neuronal populations recruited within the HIPS when digits and number words have been unintentionally processed (Cohen Kadosh, Cohen Kadosh, Kaas, Henik, & Goebel, 2007; Cohen Kadosh, Muggleton, Silvanto, & Walsch, 2010). The adaptation paradigm allows for greater spatial resolution than is possible with basic fMRI and ERP techniques. Results from this paradigm have indicated that the neural regions activated within the HIPS differ for digits and words. These results suggest that digits and words both activate quantity information but in different ways.

Processing of Digits and Words

The triple-code, abstract-code, and encoding-complex models focus on the nature of the representation of quantity in semantic memory. They do not consider evidence from the reading literature that indicates the ways in which words and digits are encoded and processed differently. These differences in processing may contribute to differences in findings across experiments. To understand how the distinction between digits and number words may affect numerical processing we must consider the properties of each surface format. Digits are arbitrary logographic symbols whose smallest unit of meaning is the digit itself. The symbols are linked directly to the magnitude through arbitrary learned associations (Fias, 2001). In contrast, number words for the numbers from one to ten, in English and most European languages, are composed of letters that represent the sounds that form words. A single letter on its own is not directly connected to the concept being conveyed. Only a certain combination of letters in the correct order conveys meaning. This difference in the information contained in the stimuli (e.g., 5 vs. five) can potentially lead to activation of very different processing pathways. None of the current major models of numerical cognition take into account differences in the links among orthography, phonology, and semantics for digits and number words.

One way to capture the differences between digits and words is to use the analogy of pictures. A digit is more like a picture of an object whereas a number word is like a word. Fias, Reynvoet, and Brysbaert (2001) tested the hypothesis that digits are processed like pictures and number words as words in a Stroop-like number naming task. Participants were shown a digit and word that was either the same (i.e., congruent pairs such as 2 and TWO) or different (i.e., incongruent pairs such as 2 and ONE). Half of the participants were required to name the digit whereas the other half named the number word. Fias et al. found that digit naming was disrupted when an incongruent number word was present whereas number word naming was not affected by the presence of an incongruent digit. This pattern suggests that, when participants read a number word they could do so without accessing semantic memory and thus the irrelevant digit had no effect on naming. In contrast, naming the digit required access to semantic memory that was disrupted by the obligatory activation of the meaning of the number word. These results parallel those commonly found in the reading literature that words can be named without semantic mediation (e.g., Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) but pictures cannot (e.g., Glaser, 1992; Humphreys, Price, & Riddoch, 1999).

In a follow-up study, Fias (2001) found that when participants had to access numerical information in a parity task, number words activated numerical information and a SNARC effect occurred. However, when participants completed a phoneme-monitoring task, which did not require access to numerical information, no SNARC effect occurred for number words. Other researchers have also found evidence that when the task does not require access to meaning number words are processed along an asemantic route in English (Damian, 2004) and Japanese (Ito & Hatta, 2003). Taken together these results indicate that the different processing pathways of digits and words need to be taken into account when examining how surface format affects the activation of numerical information.

Consider when an adult sees a number in digit or word format where the quantity information is unintentionally processed. According to the triple-code model (Dehaene, 1992) and abstract-code model (McCloskey, 1992), digits and number words are initially processed by separate input systems whether the task involves intentional or unintentionally processing of quantity information. Once into the numerical system the quantities represented by the digits and words are transformed into abstract codes and activate the quantity representation. However, the research reviewed above (Damian, 2004; Fias, 2001; Fias et al., 2001; Ito & Hatta, 2003) indicates that when number words are unintentionally processed, as in a naming task, they are directly linked to the phonology and can be named without the need to access semantic information. On the other hand, processing of digits does require access to semantic memory and thus they obligatorily invoke access to a representation of quantity. None of the current theories of quantity representation take these findings into account. If it is true that number words do not activate quantity information then the lack of distance or size congruity effects are not surprising. Yet, reading and language researchers have found that non-numerical words and by extension number words can be named (and thus encoded to a certain level) without requiring access to semantic memory.

The most common theories on the processing of words are dual-route models (e.g., Coltheart et al., 2001). Most dual-route models postulate that when a word is seen there are two processing pathways, a lexical route and a grapheme-phoneme route. If the task requires access to semantic memory, such as in a lexical decision task, the word undergoes an orthographic analysis and accesses the semantic system. In contrast, if the task does not require access to the meaning of the word, such as in a physical size judgment or a reading task, only the grapheme-phoneme route is activated, bypassing semantic memory. The lexical route also has a non-semantic component that is activated when the task requires a word to be pronounced. Because participants will not complete a naming task in the current study the non-semantic lexical route is not considered further. There is some evidence that the phonological information attached to words can be unintentionally activated and activate some information in semantic memory (Carr & Pollatsek, 1985; Luo, 1996; Luo, Johnson, & Gallo, 1998). However, under normal reading with words the phonological activation of semantic information is overridden by the orthographic route (Coltheart et al., 2001). With the exception of the encoding-complex hypothesis (Campbell & Clark, 1992), no theory of numerical representation has taken this evidence into account.

Based on these findings and theory I hypothesized that, when number words are not intentionally processed as numbers, they do not directly activate semantic memory. In contrast, when number words are processed intentionally as numbers, semantic memory must be activated and thus quantity information is available to influence processing. To test this hypothesis, it would be useful to have an alternative number format that is processed differently from words to determine if quantity information is accessed intentionally and unintentionally. The results from this alternative format could help us determine how (or whether) quantity information is activated.

Pseudohomophones and the Activation of Quantity Information

Pseudohomophones provide a word-like format that meets the requirements above. These stimuli are strings of letters that sound like real words but are not words (e.g., ziro, wun, tue, thrie, fowr, fyve, siks, sevin, eit, nyne). They are unique in that they convey the same phonological information as real words but the orthographic information does not match the real word representation (Briesemeister et al., 2009; Yates, Locker, & Simpson, 2003). Activation of a pseudohomophone cannot go directly from orthography to phonology. Instead, they are presumably processed along a computational route (spelling-to-sound translation) that is much slower than the direct route from orthography to phonology. This translation may be obligatory and may activate semantics, at least under some conditions (Briesemeister et al., 2009; Yates et al., 2003). Thus, pseudohomophones provide a stimulus format that shares some, but not all, of the processing complexities of normal words.

Pseudohomophones have been used in the reading literature to examine the degree to which phonology but not orthography can activate semantic information. Of particular relevance to the current study is the pseudohomophone effect (e.g., Briesemeister et al., 2009; Seidenberg, Petersen, MacDonald, & Plaut, 1996; Yates et al., 2003). The pseudohomophone effect is the finding that, in lexical decision tasks, pseudohomophones take longer to categorize as nonwords than orthographically comparable stimuli – for example, phocks versus snocks. The effect appears to indicate that phonological information can activate some semantic information related to the base word that the pseudohomophone is derived from. For example, the phonological information contained in the pseudohomophone "brane" activates the semantic representation of the base word "brain" (Yates et al., 2003). The pseudohomophone effect in the context of the lexical decision task indicates that when they are intentionally processed as words, pseudohomophones can activate semantic information.

Researchers have turned their attention to whether pseudohomophones can unintentionally activate semantic information. The primary method that has been used for this investigation is the masked priming effect (e.g., Lukatela, Frost, & Turvey, 1998). Essentially, participants are very briefly shown a normal word, pseudohomophone, or a control non-word that is masked. Lukatela and Turvey (1994) found that participants named words faster when preceded by a semantically-related masked pseudohomophone (e.g., tode – frog) than by a control non-word (e.g., tore –frog). Simos et al. (2002) found that when adults were instructed to read either a word or pseudohomophone, the neural regions activated were similar. Furthermore, the neural areas activated have been associated with areas that subsume semantic memory. Preliminary results such as these provide some evidence that pseudohomophones may unintentionally activate semantic representations due to the phonological links between them and their corresponding real words (e.g., tode-toad).

Pseudohomophones provide an interesting way to examine the effect of surface format on the intentional and unintentional activation of numerical information. First, pseudohomophones are made up of the same basic components, letters, as words are. Second, there is evidence that under unintentional processing conditions pseudohomophones may activate semantic memory (Lukatela & Turvey, 1994; Simos et al., 2002). In that regard, they may be treated more like digits than number words when they are processed into the numerical system. If pseudohomophones can access the quantity representation in unintentional processing tasks, using them as stimuli could remove a confound in research that examines the effect of surface format on the unintentional processing of numbers. Specifically, words may be processed along specific asemantic pathways (Coltheart et al., 2001; Fias, 2001; Fias et al., 2001). In contrast, no specific processing pathway exists for pseudohomophones. Thus, they could reveal how quantity information is activated independent of highly trained processing pathways associated with digits and number words.

The Current Research

The goal of the present research was to examine how quantity information is activated when numbers are presented as digits, words, and pseudohomophones. This work is motivated by theories of numerical cognition and by findings in the reading literature that pseudohomophones could provide a crucial comparison group to digits and number words. A fundamental question that has eluded a simple answer is whether or not the surface format of a number affects the intentional and unintentional processing of its quantity information. The methodology of the current experiments is partially based on Cohen Kadosh et al.'s (2008) experiments. University students completed both a numerical and physical comparison task where number pairs were congruent, incongruent, or neutral (Table 1). The distance between the two numbers in a pair was either one (e.g., 2 3) or five (e.g., 2 7).

Two primary issues were addressed in Experiment 1. The first issue was that the majority of previous research on the activation of quantity information focused on tasks where the numerical information contained in the stimuli was intentionally processed. This choice of intentional tasks predisposes researchers to find that quantity information in different surface formats is processed in a similar way. To deal with this weakness in the literature, participants in Experiment 1 completed both numerical comparison and physical comparison tasks. The numerical comparison task required participants to intentionally process quantity information contained in the stimuli. In contrast, the physical comparison task did not require participants to intentionally process the numerical information contained in the stimuli. Thus, activation of quantity information was unintentional (i.e., obligatory). The second issue, (i.e., familiarity of digits and words) was addressed by using novel pseudohomophones as a third format.

Based on previous research certain hypotheses and predictions can be made. First, under intentional processing conditions it was expected that quantity information would be activated in all three formats. Therefore, size congruity and distance effects were expected for all three formats in the number comparison task because quantity information must be accessed to complete the task (Cohen Kadosh et al., 2007; Cohen

Kadosh et al., 2008; Dehaene & Akhavein, 1995; Fias, 2001; Ito & Hatta, 2003; Naccache & Dehaene, 2001). Second, participants were expected to process digits more quickly than words because words contain more characters than digits. Participants are also expected to process words more quickly than pseudohomophones because the latter are less familiar than words.

The hypotheses and predictions concerning the results of the physical comparison task are of greater interest. First, it was predicted that digits would activate quantity information unintentionally and thus strong size congruity and distance effects would emerge (Dehaene et al., 2003; Kohen Cadosh et al., 2008; Fias, 2001). In contrast, neither a size congruity nor distance effect was expected to occur for number words because words can bypass semantic memory when the task does not require semantic access (Cohen Kadosh et al., 2008; Fias, 2001; Fias et al., 2001; Ito & Hatta, 2003). Second, if pseudohomophones unintentionally activate quantity, as suggested by masked priming and neuroimaging research, a size congruity effect and a distance effect were predicted to occur. Third, digits are single characters whereas words and pseudohomophones consist of several characters. Therefore, it was expected that participants would be faster to compare digits than either or words and pseudohomophones. These word forms should take about the same amount of time to physically compare (e.g., wun vs. one). These hypotheses were tested in Experiment 1.

Experiment 1

Method

Participants. Thirty-two participants from the undergraduate research pool at Carleton University participated in the current experiment for course credit. Data from two students were not analyzed due to high error rates (> 10%). Data from two other students was lost due to technical failure. Therefore, all data analyses reported are based on a final sample of twenty-eight students (17 women and 11 men) whose ages ranged from 18 to 40 years (median = 22).

Materials. Stimuli were presented on a 14-inch CRT monitor controlled by an IBM compatible computer controlled by the E-Prime software package (Psychology Software Tools, 2010). Participants' responses were recorded with a serial reaction time box connected to the serial port of the computer. Examples of the stimuli used in the current study are provided in Table 1. Stimuli consisted of an equal number of pairs of numbers that differed by either one (e.g., 2 3) or five (e.g., 2 7). Each number pair was congruent, incongruent, or neutral. Note that neutral pairs were excluded in the current analysis because a neutral pair in the physical comparison (e.g., 6 6) always had a distance of zero. The numbers 1 through 9, excluding 5 and 0, were used to create the pairs and all digits appeared an equal number of times. Thus, there were four number pairs in the near condition (1 2; 3 4; 6 7; and 8 9) and four in the far condition (1 6; 2 7; 3 8; and 4 9). Each number pair was presented twice in both possible orders. The numbers were presented as Arabic digits (e.g., 3 4), number words (e.g., three four), or pseudohomophones (e.g., thrie fowr). All stimuli were presented in Courier font. The smaller member of a pair was presented in 18-point font and the larger member was presented in 22-point font. Number pairs in all three formats were randomly presented within a block.

Design. Participants completed four blocks of trials. The four blocks were created by crossing the instruction (choose larger vs. choose smaller) with the comparison task (numerical, physical). In each block, there were 144 number pairs (8 pairs x 2 distances x 3 congruencies x 3 formats = 144 number pairs) for a total of 576 trials. The order of the blocks was counterbalanced using a Latin square across participants. Thus, the study design can be summarized as a 2(task: physical, numerical) x 3(format: digits, words, pseudohomophones) x 3(congruency: congruent, incongruent, neutral) x 2(distance: small, large) completely within-subjects design.

Procedure. At the start of each block, participants were informed if they were to perform a numerical or physical comparison. They were also informed whether they should choose the smaller or larger number. They were instructed to press the button on the reaction time box that corresponded to the side of the screen the correct choice was on. Participants completed twelve practice trials at the beginning of each block that only included 0 and 5 because these numbers were not used in the experimental trials. At the start of each trial, a fixation cross appeared at the centre of the screen for 500 ms. Next, the fixation cross disappeared and there was a 300-ms inter stimulus interval (ISI) before the pair of numbers were displayed on the screen. Following the participants' response either the word "correct" or "incorrect" was displayed for 1000 ms. After a 1500ms break, the next trial began. These parameters were the same as those used by Cohen Kadosh et al. (2008). The procedure for the experimental trials was the same as those for the practice trials except that no feedback on performance was given. The entire experiment took approximately 45 minutes.

Results

Participants completed 11,520 trials of which 357 (3.1%) were errors. Trials with errors were removed from the response time analyses. Trials where response times were greater than 2000 ms or less than 200 ms (0.7%) were also excluded from the analyses (outlier criteria adopted from Kohen Cadosh et al., 2008). Therefore, all response time analyses are based on a final sample of 11,081 trials. Mean response times and percentage of errors were analyzed in separate 2(Congruency: Congruent, Incongruent) x 3(Format: Digits, Words, Pseudohomophones) x 2(Distance: Small, Large) x 2(Task: Numerical Comparison, Physical Comparison) repeated-measures ANOVAs. In the analyses that follow, results from the error analysis should be interpreted cautiously because error rates were very low. When the assumption of sphericity was violated results were interpreted with a Greenhouse-Geisser adjustment. However, the degrees of freedom reported are those based on the design of the study. All effect sizes are reported as partial eta squared (η_p^2). All figures show 95% confidence intervals to facilitate interpretation (Jarmasz & Hollands, 2009). Significant effects were followed-up with Tukey HSD post-hoc tests.

All main effects were significant for latencies. As predicted, latencies and errors varied with format, $F(2, 54) = 234.30$, $p< .001$, $\eta_p^2 = .90$ and $F(2, 54) = 4.46$, $p = .02$, $\eta_p^2 = .14$. Participants responded more quickly to digits (574 ms) than to number words (741 ms) and more quickly to number words than to pseudohomophones (800 ms). Similarly, participants made fewer errors on digits (1.4%) than words (2.8%) or pseudohomophones

(3.3%) however, the difference in percentage error between words and pseudohomophones was not significant. Participants completed physical comparisons faster than the numerical comparisons (626 vs. 784 ms), $F(1, 27) = 81.62$, $p < .001$, $\eta_p^2 = .75$. Participants also made more errors on the numerical comparison (2.8%) than on the physical comparison (2.3%) but the difference did not reach statistical significance, $F(1, 27) = 2.30$, $p = .14$, $\eta_p^2 = .08$. Participants responded significantly faster to congruent than to incongruent pairs (683 vs. 727 ms), $F(1, 27) = 130.64$, $p < .001$, $\eta^2 = .83$, and with fewer errors (2.0% vs. 3.1%), $F(1, 27) = 8.31$, $p = .008$, $\eta_p^2 = .24$. Finally, participants were faster, $F(1, 27) = 28.78$, $p < .001$, $\eta_p^2 = .52$, and made fewer errors, $F(1, 27) = 6.10$, $p = .02$, $\eta_p^2 = .18$, to number pairs that were separated by five than those separated by one (692 vs. 718 ms; 2.2% vs. 2.9%). Thus, the stimuli and procedure used in the present experiment resulted in successful reproduction of the main findings from previous research. Overall, there was evidence for both size congruity and distance effects in these analyses.

Although many of the second and third order interactions were significant, in the remainder of the results section, I focus on breaking down the significant four-way interaction for reaction times shown in Figure 1, $F(2, 54) = 9.39$, $p < .001$, $\eta_p^2 = .26$. The four-way interaction was not statistically significant for errors, $F(2, 54) = .08$, $p = .92$, $\eta_p^2 = .003$. For reference purposes, the data were plotted (Appendix 1) and examined for evidence of speed-accuracy trade-offs. None were found. The lack of significance of the four-way interaction for mean percent error was due to the lack of an effect of distance on the congruity effect for digits in the physical comparison errors as the Congruency x Format x Task interaction was statistically significant, $F(2, 54) = 11.00$, $p < .001$, $\eta_p^2 =$

.29 (Figure 2). Recall, that the effect of distance on the congruity effect for digits in the physical comparison for the reaction time data was relatively small. Due to the large number of zero cells in the error analysis this small effect was not reflected in the error data. The pattern of percentage error reflected the primary effects observed in the reaction time data. Therefore, the error data did not compromise the interpretation of the reaction time results.

Numerical comparison. Consider the results for the numerical comparison, shown in Figure 1. The Congruency x Distance x Format interaction for the numerical comparison task w as not statistically significant, $F(2, 54) = 1.75$, $p = .183$, $\eta^2 = .06$. In contrast, the Congruency x Format interaction was statistically significant, $F(2, 54) = 18.04$, $p < .001$, $\eta^2 = .40$. Although all formats showed distance effects, the size congruity effect was only significant for digits. This finding will be addressed in the general discussion. The congruity effect for digits did not significantly differ over small and large distance number pairs (90 and 61 ms, respectively). The distance effect for digits (64 ms) was the same for number words (64 ms) and pseudohomophones (46 ms). Thus, the three-way reaction time interaction was not statistically significant for the number comparison task.

Physical comparison. In contrast, as shown in Figure 1, the Congruity x Distance x Format interaction for the physical comparison task was statistically significant, $F(2, 54) = 11.83$, $p < .001$, $\eta^2 = .31$. To further explore the congruity effects indicated by the significant three-way interaction for the physical comparison results from separate analyses on a per format basis are reported. Digits showed an interaction between distance and congruity, indicating (as in other research) that processing of digits resulted

Figure 1: Mean reaction times with 95% confidence intervals based on the four-way interaction for Experiment 1.

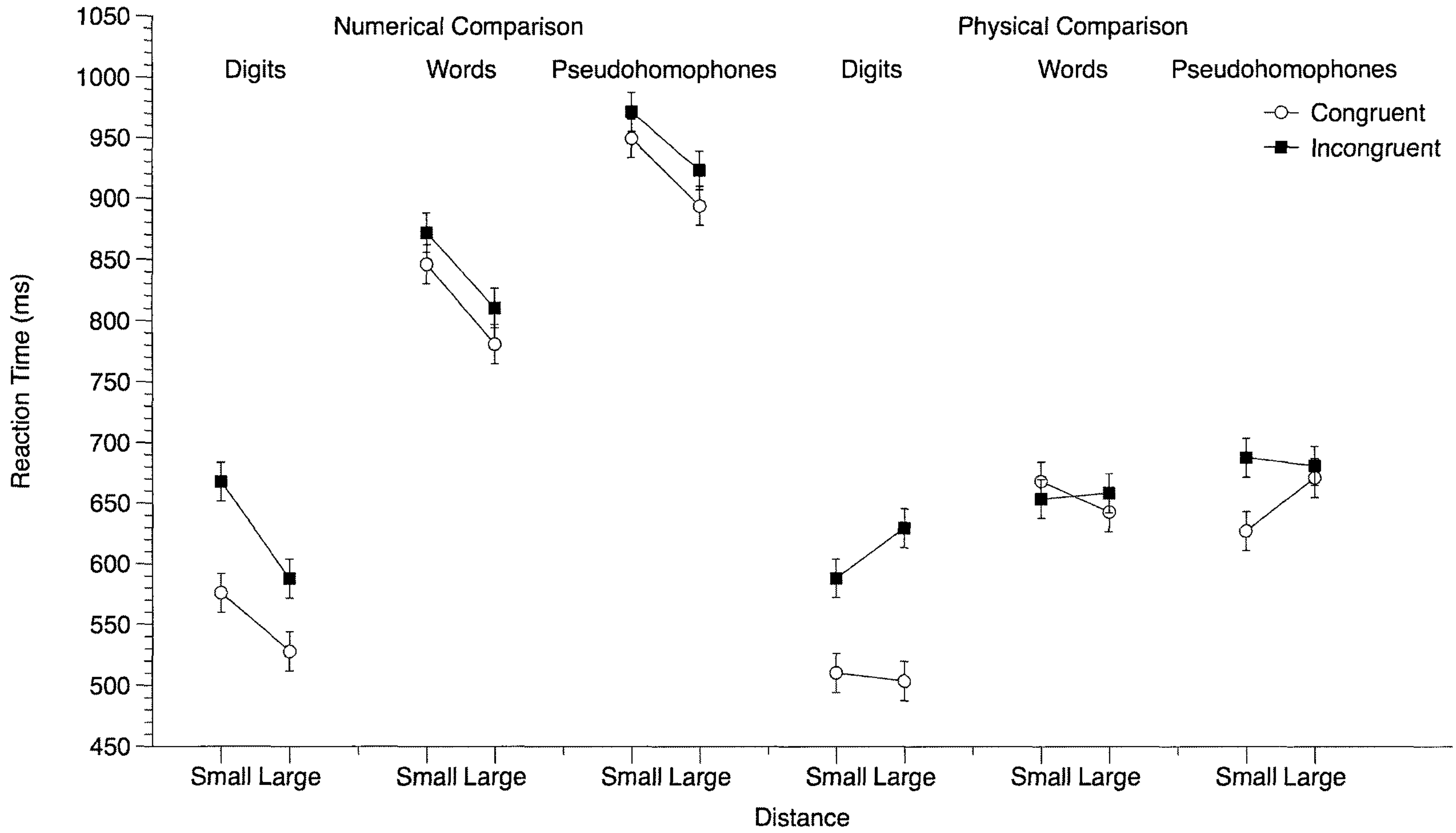
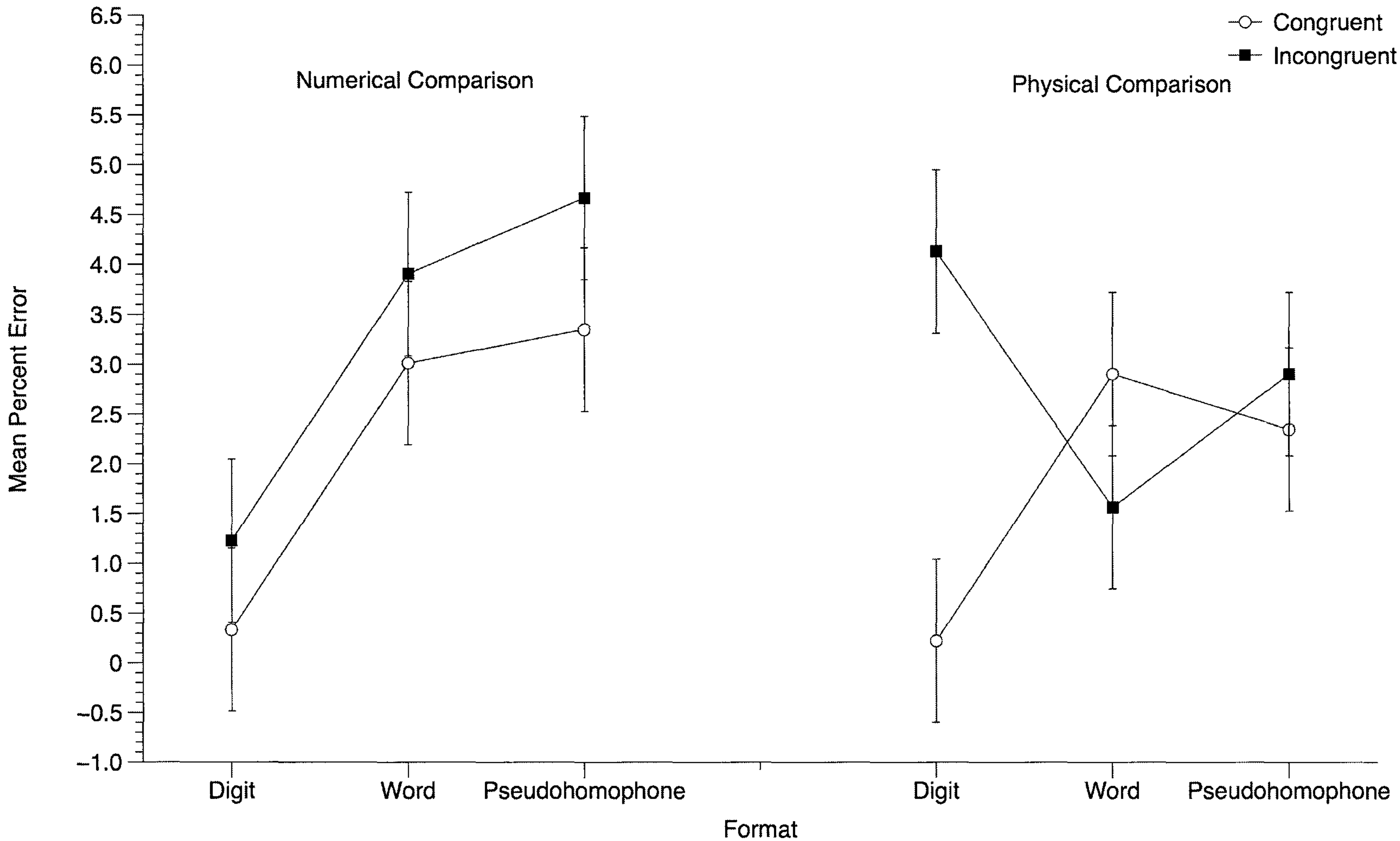


Figure 2: Mean percent error for the Task x Format x Congruity interaction with 95% confidence intervals for that interaction in Experiment 1.



in unintentional activation of quantity. For digits in the physical comparison task there was a significant Congruity x Distance interaction, $F(1, 27) = 14.13$, $p = .001$, $\eta^2 = 34$, such that, for small distance pairs the congruity effect (78 ms) was less than for large distance pairs (125 ms).

For number words, there were no significant effects of either distance or congruency, all *p*s > .05. These results replicate Cohen Kadosh et al. (2008), suggesting that physical comparisons of number words are not affected by semantic processing. For pseudohomophones, however, there was a congruity effect, but only for small distance pairs (e.g., tue, thrie), not for large distance pairs (e.g., tue, sevin), as indicated by the Congruity x Distance interaction, $F(1, 27) = 6.99$, $p = .014$, $\eta^2 = .21$. To ensure that the congruity effect observed was not due to differential amounts of practice, another analysis with distance and congruity was performed on the 14 participants who performed the physical comparison first on data from the first block of the experiment only. These participants did not have any experience with pseudohomophones except for reading a list of them once in random order during the instruction phase of the experiment. The Congruity x Distance interaction approached significance with approximately the same effect size as in the full analysis, $F(1, 13) = 4.49$, $p = .054$, $\eta^2 = .26$ and a similar pattern of means. Thus, these results suggest that the Congruity x Distance interaction is reliable across participants for pseudohomophones.

Because the finding for pseudohomophones was unexpected, an item analysis was run to determine if the congruity effect for pseudohomophones was consistent for all items for both large and small distances. Recall that there were only four items for each distance category. In this analysis, neither the congruity, $F(1, 6) = .190$, $p = .68$, $\eta^2 = .03$, nor the distance effect, $F(1,6) = 3.15$, $p = .13$, $\eta^2 = .345$, were significant. Furthermore, the Congruity x Distance interaction was not significant, $F(1, 6) = .08$, $p = .79$, $\eta^2 = .01$. These results indicate that the congruity effect was not stable across the different pseudohomophone pairs. As discussed below, the lack of reliability of the effects for the congruity and distance effects across items suggests that some additional consideration of the characteristics of the stimuli might be relevant in understanding the unexpected congruity x distance interaction for pseudohomophones.

Discussion

Most of the key predictions were confirmed in Experiment 1. There was evidence of activation of quantity information in that the distance effect occurred with all three surface formats in the numerical comparison task. As expected, digits were compared the fastest, words were slower, and pseudohomophones were the slowest. In the physical comparison task, evidence of unintentional activation of quantity information for digits is shown in the highly significant size congruity and distance effects for digits. In contrast to digits, there was no evidence of any unintentional activation of quantity information for number words. However, for pseudohomophones there was a size congruity effect for pairs with a small distance. Separate analyses indicated that this effect was not due to practice making numerical judgments first with pseudohomophones. Whereas the size congruity effect for digits was significant for pairs with a distance of one and five, the size congruity effect for pseudohomophones was only significant for pairs with a distance of one.

The results concerning the numerical comparison are consistent with previous research. In Experiment 1, a significant distance effect emerged for all three formats. In terms of digits and number words these results are consistent with several previous studies (e.g., Cohen Kadosh et al., 2008; Dehaene et al., 2003; Foltz et al., 1984). As the numerical comparison task required participants to compare the numerical magnitude of pseudohomophones it is also not surprising that a distance effect emerged for this format. The size congruity effect did differ across formats and this finding will be addressed in the general discussion.

The results for digits in the physical comparison task replicated Cohen Kadosh et al. (2008). That is, the significant size congruity and distance effects are evidence that digits activated quantity information. Furthermore, the size congruity effect was greater for Arabic digits that had a large distance (126 ms; e.g., 1 6) than those that had a small distance (78 ms, e.g., 1 2). Schwarz and Ischebeck (2003) hypothesized that when the distance between two numbers in a physical comparison task is smaller the activation of quantity information in semantic memory for these two quantities is more similar than when the distance is larger. The similar quantity information, for small distance pairs, results in the magnitude information being processed slower than those with a large distance. As the quantity information is available earlier the magnitude information leads to a stronger effect of congruity for large distance number pairs than small distance pairs.

The results concerning number words were also in agreement with previous research. Several researchers have found that number words do not unintentionally activate quantity information (Cohen Kadosh et al., 2008; Ito & Hatta, 2003; Koechlin et al., 1999). The results from Experiment 1 also concur with word comprehension models (Coltheart et al., 1993; 2001), which posit that when semantic access is not required for the task, words do not unintentionally access their semantic representation.

There is evidence from the semantic priming literature that a masked word that is semantically related to a visible target (e.g., dog – cat) reduces reaction times in lexical decision tasks (e.g., Perea & Gotor, 1997). These results would appear to indicate that when words are unintentionally processed they activate semantic representations. However, a key difference between the current study and priming studies concerns the task. Specifically, in word priming research participants must either decide if the target is a word or a non-word, or name the word. In a meta-analysis, Lucas (2000) suggested these task demands might predispose participants to activate semantic representations because the lexical decision task biases participants to consider the content of the target. In the current study, the physical comparison did not require participants to make any judgments concerning the meaning of the stimuli. Participants simply had to decide which number was physically larger or smaller. Accordingly, the present finding that number words do not unintentionally activate quantity information in the physical comparison task is consistent with the view that the word is not processed semantically. The same tasks have been used to examine if pseudohomophones can unintentionally activate quantity information (Lukatela et al., 1998; Lukatela & Turvey, 1994). Therefore, the same interpretation of results from masked priming that indicated that pseudohomophones can unintentionally activate semantic representations can be applied.

It is tempting to conclude that the small distance pseudohomophone pairs activated quantity information because they elicited a size congruity effect. However, the item analysis for pseudohomophones indicated that the congruity effects on a per-item basis were not consistent within the two distance conditions. Closer inspection of the results for pseudohomophones revealed problems with the physical characteristics of the stimuli. The size congruity effect was completely driven by the faster responses to congruent small distance pseudohomophone pairs. All other means did not significantly differ from each other. The pseudohomophones as they appeared in Experiment 1 are displayed in Table 2. Examination of the pseudohomophone pairs used in the current study indicated a confound between word length and physical size. Specifically, for the pseudohomophones, large numbers had more letters (e.g., wun, tue vs. sevin, nyne). In the congruent condition this resulted in two pairs where the numerically larger number also had more characters making it appear even larger on screen. This confound could have artificially facilitated responses to these congruent pairs, because it was easier to distinguish them. This confound only existed for one pair in the incongruent condition. As can be seen by examining Table 2, small distance pseudohomophone pairs also had more variability in their overall number of characters than far distance pairs. It could be that the similar large distance pairs reduced the facilitatory impact of the pseudohomophone length and congruity confound relative to the small distance pairs. Therefore, an artifactual size congruity effect for small distance pseudohomophone pairs may have occurred that did not reflect activation of quantity information.

The goal of Experiment 2 was to minimize the confound between physical size and number size in the congruent condition and thus provide a better test of whether pseudohomophones unintentionally activate quantity information. Therefore, in Experiment 2 all pseudohomophones and number words were constrained to fit within a set physical space, therefore controlling for physical size of the stimuli. In addition, all pseudohomophones and number words were presented in uppercase format to ensure they were all of equal height (Figure 3). These manipulations ensured that number words and

Table 2

Pseudohomophone pairs used in Experiment 1 that illustrates how length and congruity were confounded in these stimuli.

Distance			
Small		Large	
Congruent	Incongruent	Congruent	Incongruent
wun -tue	wun - tue	wun -siks[a]	wun - siks
thrie - fowr	thrie -fowr[a]	tue -sevin[a]	tue - sevin
siks -sevin [a]	siks - sevin	thrie -eit	thrie -eit[a]
eit -nyne [a]	eit - nyne	fowr -nyne	fowr - nyne

[a] Pairs that should be faster, based on the combination of letters and size. This confound may have resulted in faster response times in the congruent compared to the incongruent conditions.

Moderate Difference		Big Difference	
THREE	FOUR	THREE	FOUR
TWO	SEVEN	TWO	SEVEN

Figure 3: A sample of congruent number word stimuli used in Experiment 2.

pseudohomophones were as homogenous as possible, reducing the chance that physical characteristics of the stimuli would influence the results.

Another change was that neutral pairs were coded as Cohen Kadosh et al. (2008) did so that they were included in the analysis. The neutral pairs in Experiment 1 were coded to reflect the true distance between them (e.g., 2 2; distance is zero) which meant that they could not be included in the analysis. Furthermore, the physically neutral pairs were all presented in the smaller font size. This reduced the variability among the neutral pairs that could have affected participants' response times to them (Schwarz & Ischebeck, 2003). Cohen Kadosh et al. (2008) created the neutral pairs by using each number in the close and far number pairs and assigning them their respective distance from the pair they were derived from (e.g., 2 2 from the near distance pair 2 3 would have a distance of one). This method was used to create a compatible neutral pair set in Experiment 2. Including neutral pairs allowed a distinction to be made between facilitation and interference effects from congruent and incongruent pairs respectively. This change will also allow a fine-grained comparison between Experiment 2 and previous research that has included neutral trials.

The number pairs used in Experiment 2 were the same as Experiment 1 and are listed in Appendix 1. Another change that was introduced in Experiment 2 to ensure the distance and congruity effects were robust was a variation in the difference in the physical size of the number pairs. Specifically, half of the participants saw number pairs that had a moderate difference in size. The other half saw number pairs that had a large difference in their physical size. Cohen Kadosh et al. (2008) found that decreasing the difference in physical size between large and small numbers in a pair amplified the effect of congruity and distance. This manipulation also ensured that the distance and congruity effects observed in Experiment 1 were not due to idiosyncratic characteristics of the stimuli.

Experiment 2

In summary, the changes in stimuli from Experiment 1 were the following. First, all pseudohomophones and number words were constrained to be the same size no matter the number of characters (Figure 3). Second, all pseudohomophones and number words were in uppercase format unlike in Experiment 1 where they were all in lowercase format. Finally, half of the participants saw number pairs with a small difference in physical size and the other half saw number pairs with a large difference in physical size. All other materials and procedures were the same as in Experiment 1.

Predictions

I expected to replicate the results of the numerical comparison for all three formats in Experiment 2. Furthermore, the results for the physical comparison task were expected to be the same as those obtained in Experiment 1 for digits or words. Crucially, if the significant size congruity effect for small distance pseudohomophone pairs was due to the pseudohomophone length and physical size confound in the congruity confound, then no size congruity effect was expected for pseudohomophones in Experiment 2. Finally, Cohen Kadosh et al. (2008) found that when the difference in physical size of two numbers in a pair was large, the distance and size congruity effects were amplified. We expected to replicate these results. Assuming these results are found, this research would fulfill two important goals. First, it will provide a replication of the results reported by Cohen Kadosh et al. (2008) for digits and number words. No other experiments have included both intentional and unintentional processing tasks in a within-subjects design. Second, the results will illustrate the importance of considering the other features of the stimuli that are relevant to the dimension that is being manipulated. For words (and pseudohomophones), physical size varies across items whereas it does not vary across digits. Controlling the physical size for number words is as important as controlling it for pseudohomophones. When stimulus properties such as word length are controlled then it is clear if pseudohomophones unintentionally activate quantity information. In Experiment 2, I controlled the space occupied by words and pseudohomophones and therefore it was be possible to conclude how surface format affects the activation of quantity information. In a more general sense the results of Experiment 2 allowed us to examine how numbers in various formats are processed which will speak to the validity of theories of numerical cognition.

Methods

Participants. Fifty-six undergraduates whose first language was English participated in the current experiment for course credit. The majority of participants were female (n = 32). Participants ranged in age from 17 to 37 years (median = 19).

Materials. The numbers that were used to form the pairs in the current study were the same numbers, formats, and congruencies as Experiment 1. Neutral pairs were considered to originate from a small or large distance number pair such that they could be assigned a distance of one or five (e.g., 2 2 and 3 3 were considered having a distance of one as they were based on the number pair 2 3). All number words and pseudohomophones were presented in Courier font. The font is monospaced where all uppercase letters occupy the same vertical and horizontal area. Moderate physical distance pairs consisted of one word or pseudohomophone in 18-point font and the other in 22-point font. Big physical distance pairs consisted of one word or pseudohomophone in 18-point font and the other in 24-point font. Digits were presented in the same font and sizes but no modification was made to their width due to the potential distortion of the digits that would have occurred. All words and pseudohomophones were constrained to fit an area occupied by a four-letter word of the corresponding font size. This minimized the compression of five-letter words (e.g., seven) and stretching of three-letter words (e.g., one).

Design and procedure. The design of Experiment 2 was similar to the design of Experiment 1. Participants completed the same number of trials (576) as in Experiment 1. Due to the addition of neutral trials to the analysis and the physical size difference between-subjects variable Experiment 2 can be summarized as a 2(task: physical, numerical) x 3(format: digits, words, pseudohomophones) x 3(congruency: congruent, incongruent, neutral) x 2(distance: small, large) x 2(size difference: moderate, big) design with repeated-measures on all variables except size difference. Participants were randomly assigned to either the moderate or big size difference conditions. The procedure was precisely the same as the one used for Experiment 1. No participants had errors that exceeded 10% of all trials. Therefore, all participants described above were included in the current analysis.

Results

Participants completed 32,256 trials of which 1397 (4.3%) were errors. Trials with errors were removed from the reaction time analyses. Trials where reaction times were greater than 2000 ms or less than 200 ms (1.3%) were also excluded from the reaction time analyses. Therefore, reaction time analyses are based on 30,465 trials. Mean reaction times were analyzed in a 3(Congruency: Congruent, Incongruent, Neutral) x 3(Format: Digits, Words, Pseudohomophones) x 2(Distance: Small, Large) x 2(Task:

Numerical Comparison, Physical Comparison) x 2(Size Difference: Moderate, Big) mixed ANOVA with repeated measures on the first four variables. Mean percent errors were also analyzed in the same five-way mixed factor ANOVA. Results from the error analysis should be interpreted cautiously as the overall rate of errors was low. When the assumption of sphericity was violated results were interpreted with a Greenhouse-Geisser adjustment. However, the degrees of freedom reported are those based on the design of the study. All effect sizes are reported as partial eta squared. All figures show 95% confidence intervals to facilitate interpretation (Jarmasz & Hollands, 2009). Significant effects were followed-up with Tukey's HSD post-hoc tests.

Main effects. All main effects that were significant in Experiment 1 were significant in Experiment 2. The effect sizes of the main effects were comparable across both experiments. There was a significant main effect of format in the reaction times, $F(2, 108) = 533.63$, $p < .001$, $\eta_P^2 = .91$. Participants responded more quickly to digits (467 ms) than number words (544 ms) and more quickly to number words than pseudohomophones (572 ms). The format main effect was reflected in the error data, $F(2, 108) = 19.20$, $p < .001$,$\eta_P^2 = .26$. Participants made fewer errors on digits (3.0%) than number words (4.7%) and pseudohomophones (5.2%). Although the mean percent error was in the correct direction for number words and pseudohomophones, the two values did not significantly differ.

Participants completed the physical comparison task significantly faster, $F(1, 54) = 626.93$, $p < .001$, $\eta_P^2 = .82$, and with fewer errors, $F(1, 54) = 90.15$, $p < .001$, $\eta_P^2 = .63$ than the numerical comparison task (391 ms vs. 665 ms; 2.2% vs. 6.4%). Note, that in Experiment 1 the reaction times for the physical comparison (626 ms) were much slower than in Experiment 2. This difference was most likely due to the improvements in the stimuli introduced in Experiment 2 and will be addressed in the Discussion.

There was a significant main effect of congruity in reaction times, $F(2, 108) = 72.81, p < .001, \eta_P^2 = .57$. Participants responded more quickly to congruent pairs (514ms) than to neutral pairs (524ms) and more quickly to neutral than to incongruent pairs (544ms) pairs. The main effect of congruency was reflected in percentage of errors, $F(2, 108) = 61.71, p < .001, \eta_P^2 = .53$. Participants made significantly fewer errors to congruent pairs (3.3%) than to incongruent pairs (6.2%). However, errors to neutral pairs (3.5%) were not significantly different from congruent pairs. Therefore, it appears that the effect of congruity primarily manifested itself in response times.

Participants responded more quickly to number pairs separated by five than those separated by one (540 ms vs. 516 ms), $F(1, 54) = 237.57, p < .001, \eta_P^2 = .53$. This effect was reflected in errors, $F(1, 54) = 43.26, p < .001, \eta_P^2 = .45$. Participants made more errors on number pairs separated by one (6.4%) than those separated by five (2.2%).

Physical size difference. The new variable manipulated in Experiment 2, the degree of size difference between numbers in a pair, did not yield a main effect of reaction times, $F(1, 54) = 0.79, p = .38, \eta_P^2 = .01$, or errors, $F(1, 54) = 0.82, p = .32, \eta_P^2 = .02$. Size difference interacted with task for response times, $F(1, 54) = 6.85, p < .01, \eta_P^2 = .11$, but not for errors, $F(1, 54) = .40, p = .53, \eta_P^2 = .01$. Participants responded more slowly to moderate size difference pairs (689 ms) during a numerical comparison than pairs with a big size difference (643 ms). In contrast, size difference did not affect physical comparisons (387 ms and 397 ms for moderate and big size difference, respectively). There were no other significant interactions with size difference.

The form of this interaction is counterintuitive. An effect of the relative differences in size for the stimuli might have been expected in the physical comparison task, but not in the numerical comparison task, as a big size difference pair should be easier to physically compare. However, Pansky and Algom (2002) found that when the irrelevant dimension (i.e., size difference in the numerical comparison task) is more salient (i.e., in the big difference condition) the irrelevant dimension slows down processing while not interacting with other cognitive factors (e.g., distance and congruity) as in the current experiment. In the numerical comparison task when the size difference between numbers in a pair was larger it caused a global slowdown in the processing of number pairs. In the physical comparison task the physical size difference between pairs is the relevant dimension and according to Pansky and Algom (2002) would not lead to any global changes in reaction time.

Four-way interaction. Although several two-way interactions involving the other four variables were significant, the focus of the remainder of the analyses will be on the significant Congruity x Task x Format x Distance four-way interaction for reaction times, $F(4, 216) = 3.34$, $p = .01$, $\eta_P^2 = .06$ (Figure 4). This four-way interaction was also statistically significant for errors, $F(4, 216) = 4.01$, $p = .004$, $\eta_P^2 = .07$ (Figure 5). To better understand the four-way interactions, separate analyses were conducted for the numerical and physical comparison tasks.

Numerical comparison task. As in Experiment 1, there was a highly significant main effect of distance, $F(1, 55) = 249.53$, $p < .001$, $\eta_P^2 = .82$ (see Figure 4). Participants took longer to judge numerical size for digits that were separated by a distance of one than numbers that were separated by five. Neither format, $F(2, 110) = 0.77$, $p = .47$, $\eta_P^2 =$

.01, or congruency, $F(2, 110) = 0.47$, $p = .63$, $\eta_P^2 = .01$, interacted with distance. Furthermore, the distance effect for digits (51 ms), number words (46 ms) and pseudohomophones (46 ms) did not significantly differ. Accordingly, and consistent with the results of Experiment 1, the three-way interaction for the numerical comparison was not statistically significant, $F(4, 220) = 2.25$, $p = .07$, $\eta_P^2 = .04$.

Consistent with effects for latencies, participants made more errors when numbers were separated by one than five (8.5% vs. 4.4%), $F(1, 55) = 57.34$, $p < .001$, $\eta_P^2 = .51$. The Format x Distance interaction was not significant, $F(2, 110) = 0.73$, $p = .48$, $\eta_P^2 = .01$. However, in contrast to the results for latencies, the Congruency x Distance interaction was significant for percentage of errors, $F(2, 110) = 9.02$, $p < .001$, $\eta_P^2 = .14$: Participants made significantly more errors on incongruent trials when numbers were separated by one (11.9%) than when the distance between numbers was large (5.8%). The three-way interaction for the error data was also not statistically significant, $F(4, 220) = 2.17$, $p > .05$, $\eta_P^2 = .04$.

Both the congruity and format of a pair had significant effects on reaction times in the numerical comparison task. Specifically, there was a significant Congruency x Format interaction, $F(4, 220) = 10.63$, $p < .001$, $\eta_P^2 = .16$. Figure 6 displays the magnitude of the size congruity effect and decomposes that effect into the facilitation and inhibitory components for the reaction time data. The size congruity effect was larger (i.e., congruent vs. incongruent) for digits (81 ms) than for words (36 ms) and pseudohomophones (37 ms). The size congruity effect was broken down to examine if both facilitation and inhibition occurred. The size congruity effect is *facilitory* if congruent trials are responded to significantly faster than neutral trials. In contrast, the size congruity effect is *inhibitory* if incongruent trials take significantly longer to respond to than neutral trials. As can be seen in Figure 6 both facilitation and inhibition occurred for digits. In contrast, for words and pseudohomophones there was little facilitation but more inhibition.

For errors, there was a significant main effect of congruity, $F(2, 110) = 27.96$, $p < .001$, $\eta_P^2 = .34$ (Figure 5). Participants made significantly fewer errors on congruent pairs (5.0%) than incongruent (8.9%) and neutral (5.4%) pairs but congruent and neutral pairs did not significantly differ. Thus, in contrast to the results for latencies, the size congruity effect was only inhibitory for errors. Furthermore, the effect did not significantly differ across format as indicated by the non-significant Congruency x Format interaction, $F(4, 220) = 0.74$, $p = .57$, $\eta_P^2 = .01$. Overall, the results concerning the numerical comparison replicated those from Experiment 1.

Physical comparison task. The results of the physical comparison differed from those of Experiment 1. First, the Congruency x Format x Distance (Figure 4) interaction was not statistically significant in Experiment 2, $F(4, 220) = 1.33$, $p = .26$, $\eta_P^2 = .02$. This lack of a significant three-way interaction appears to be due to the reduced effect of distance on the congruity effect for digits and the lack of effect for pseudohomophones relative to Experiment 1. This finding will be addressed in the discussion. In fact, there were no effects of distance in the physical comparison task, all *p*s > .11. Crucially to the primary hypothesis, the Congruency x Format interaction was significant, $F(4, 220) = 17.12$, $p < .001$, $\eta_P^2 = .24$. As shown in Figure 4, there was a size congruity effect for digits that was due to interference. There was no size congruity effect for words as in Experiment 1. As predicted, there was also no evidence of a size congruity effect for

Figure 4: Mean reaction times with 95% confidence intervals based on the four-way interaction for Experiment 2.

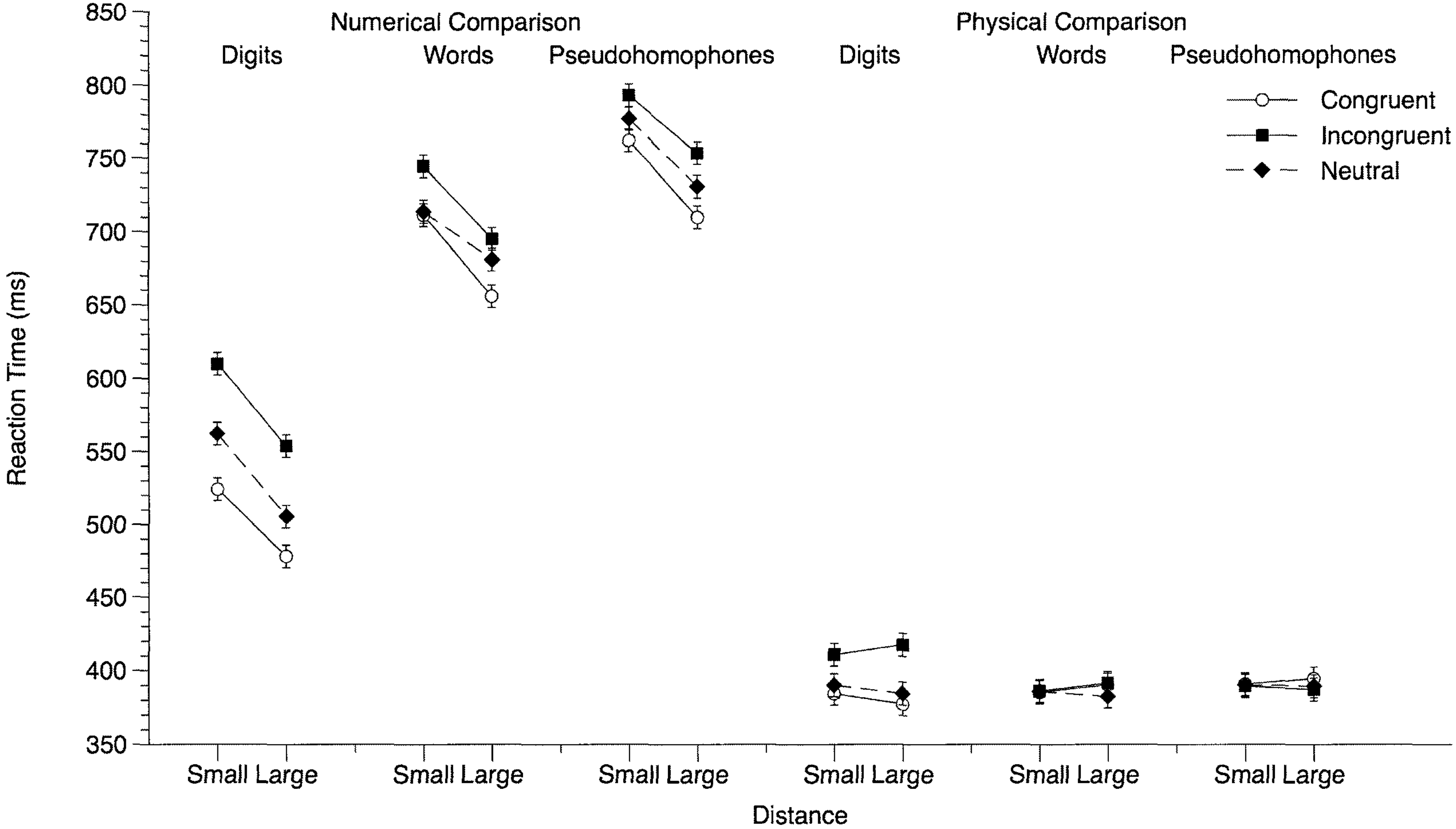


Figure 5: Mean percent error and 95% confidence intervals based on four-way interaction for Experiment 2.

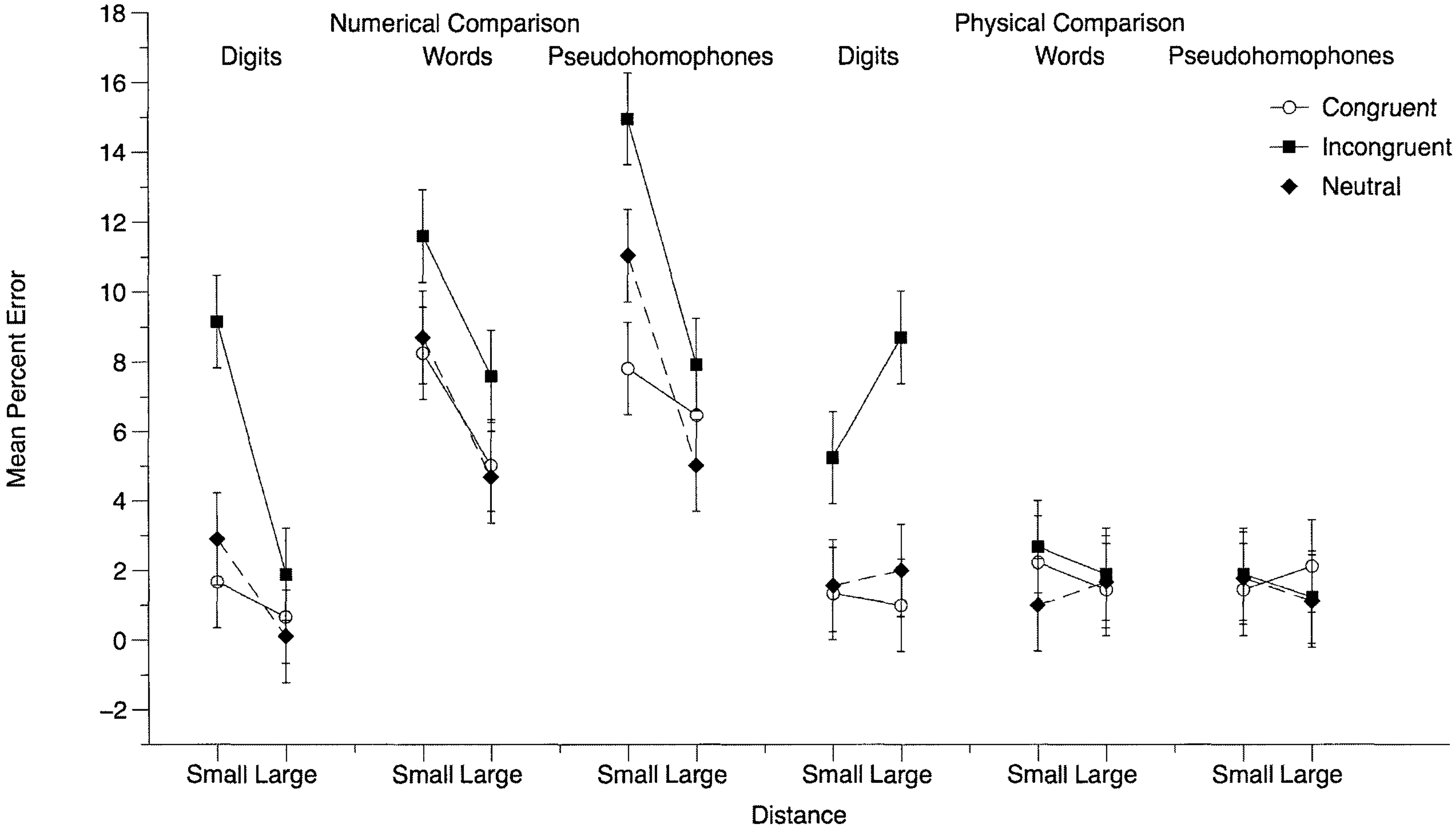
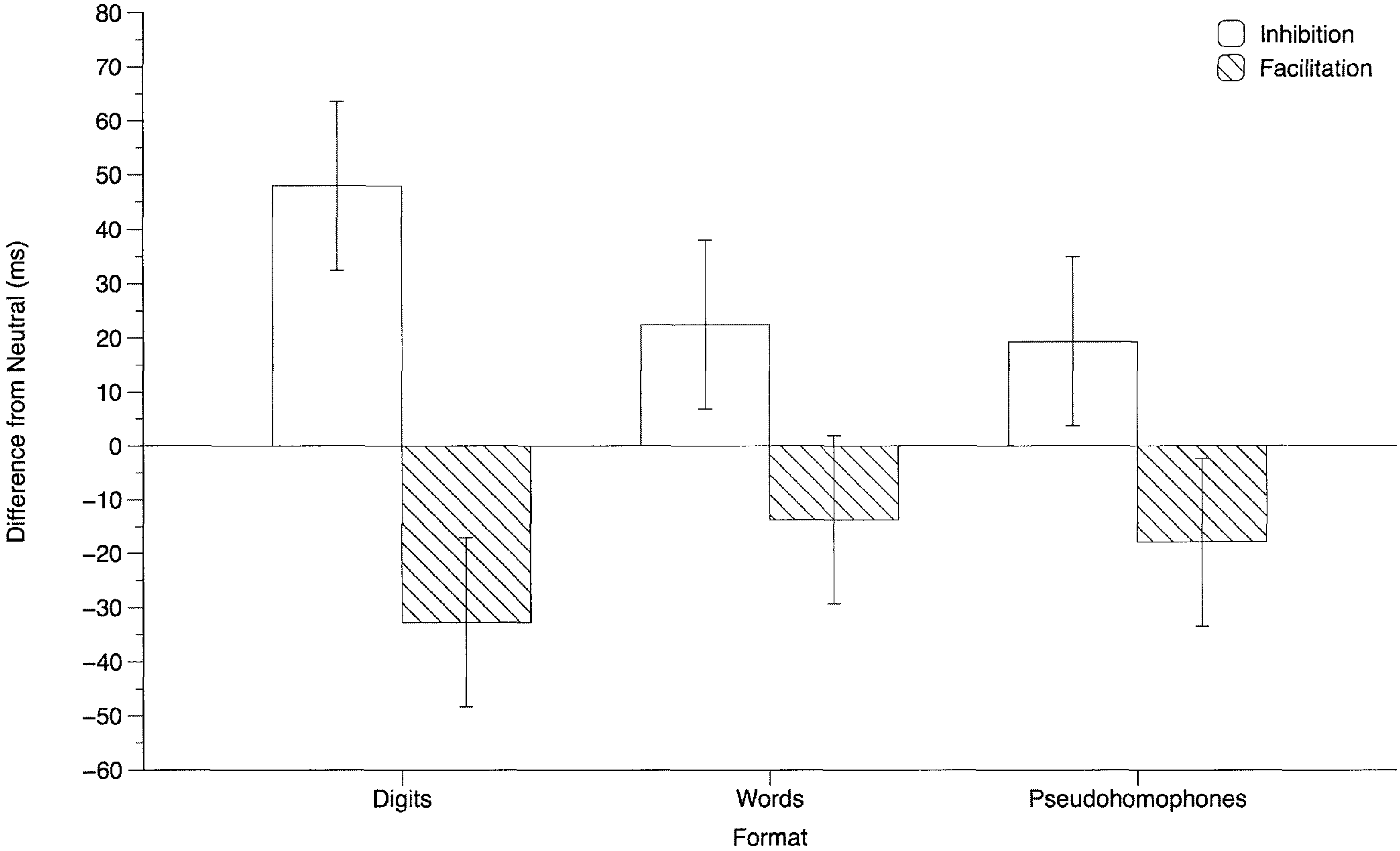


Figure 6: Facilitation and inhibition effects in reaction time data (zero represents reaction time for neutral pairs) for Experiment 2 with 95% confidence intervals based on the Congruency x Format interaction.



pseudohomophones. Thus, the superior control of the stimulus characteristics eliminated the spurious size congruity effect for small distance pseudohomophone pairs observed in Experiment 1.

The error analyses largely corresponded to the results of the reaction time data for the physical comparison but with one important exception. The Congruity x Format x Distance interaction was statistically significant, $F(4, 220) = 6.37$, $p < .001$, $\eta_P^2 = .10$. For digits, participant made more errors on incongruent large distance pairs (8.7%) than incongruent small distance pairs (5.2%). There was no effect of congruity or distance for word or pseudohomophone number pairs. In summary, by removing the congruity and stimulus size confound, the size congruity effect for pseudohomophones with a small distance observed in Experiment 1 was eliminated. Digits, however, showed size congruity effects consistent with the view that there was obligatory activation of numerical size that interfered with responses in the physical comparison task.

Discussion

The primary objective of Experiment 2 was to determine if the size congruity effect for small distance pseudohomophones found in Experiment 1 was replicable when the pseudohomophone length and congruity confound was controlled. To accomplish this objective, both number words and pseudohomophones were constrained to fit within a set space. As predicted, elimination of the length and congruity confound resulted in the size congruity effect being eliminated for pseudohomophones. Thus, no evidence of unintentional quantity information activation was observed for either pseudohomophones or number words. Another objective of Experiment 2 was to include neutral trials in the analysis to determine if the size congruity effect was facilitory, inhibitory, or both. For digits in the numerical and comparison task there was both facilitation and inhibition: congruent pairs were faster than neutral pairs and incongruent pairs were slower than neutral pairs. In contrast, for number words and pseudohomophones in the numerical comparison the size congruity effect was only inhibitory: incongruent pairs were slower than neutral and congruent pairs. In the physical comparison task, the size congruity effect was found only for digits and was due entirely to interference. There was no size congruity effect for either number words or pseudohomophones in the physical comparison task.

The final objective of Experiment 2 was to determine the effect of physical size difference on the distance and size congruity effect. With one exception, there was no effect of size difference between the numbers in a pair on processing times or errors. The Size Difference x Task interaction was statistically significant but as described above this was most likely due to increased salience of the irrelevant dimension that affects encoding but not cognitive processes (Pansky & Algom, 2002). There was no evidence in the current study that the degree of physical size difference had differential effects on the activation of quantity information, as it did not enter into any other interaction.

Other than the predicted loss of the size congruity effect for small distance pseudohomophones the results of Experiment 2 largely replicated the results of Experiment 1. There were a few exceptions. First, the most pronounced difference between the two experiments was the faster reaction times to all three formats of numbers in the physical comparison task. Participants took on average 627 ms to complete physical comparisons in Experiment 1 but only 391 ms in Experiment 2. This reduction in reaction time was most likely attributable to the more homogenous stimulus set used in the current study. Recall that number words and pseudohomophones were all presented in uppercase format and constrained to fit within a certain width in Experiment 2. These constraints homogenized the physical appearance of the number word and pseudohomophone pairs, which made comparisons easier for the participants in Experiment 2 than those in Experiment 1.

A second difference between the results of the two experiments was that the three-way interaction for the physical comparison task was not statistically significant in Experiment 2. This discrepancy appeared to be a consequence of distance having little effect on the size congruity effect for digits in Experiment 2 relative to Experiment 1 and was probably a consequence of the overall faster reaction times in Experiment 2. Specifically, as participants took less time to complete physical comparisons in Experiment 2, it is possible that incongruent quantity information had less time to interfere with cognitive processing (Schwarz & Ischebeck, 2003). This effect will be examined in more detail in the General Discussion.

In summary, the results were largely compatible across experiments. When participants were forced to intentionally process quantity information in the numerical comparison task there was a significant distance effect for all three formats. As discussed in the literature review the distance effect indicates that quantity information was activated. For the physical comparison task there was a size congruity effect for digits only. There was neither a size congruity nor distance effect for either number words or pseudohomophones. The theoretical implications of these results will be discussed in the general discussion to follow.

General Discussion

The objective of the current research was to examine whether quantity information is intentionally and unintentionally activated when numbers are presented in different formats. Comparisons were made between two common formats (i.e., digits and number words) and a novel format (i.e., pseudohomophones). In two experiments, participants completed a numerical comparison task, where quantity information was necessary for successful task completion, and a physical comparison task, where quantity information was not necessary for successful task completion. Due to unanticipated problems with the stimuli the results of Experiment 2, particularly for pseudohomophone and number word format, are very clear and allow for conclusions on the effect of surface format on the activation of quantity information.

The primary results of the current research were as follows. First, in the numerical comparison task the distance effect, which indicates that quantity information was intentionally activated (e.g., den Heyer & Briand, 1986), was observed for all three formats. Second, in the physical comparison task both the distance effect and size congruity effect were observed for numbers in digit format, which indicated that quantity information had been activated (e.g., Foltz et al., 1984). Third, there was no evidence that number words unintentionally activated quantity information. Finally, once the length by congruity confound was eliminated in Experiment 2, there was no evidence that pseudohomophones unintentionally activated quantity information. Overall, the results of the current study indicate that only digits can unintentionally activate quantity information.

The size congruity effect does not indicate that quantity information has been intentionally activated in the numerical comparison task. Recall that the size congruity effect reflects interference or facilitation of cognitive processing from the irrelevant dimension in a number pair that can be either congruent or incongruent with the task-relevant dimension (Schwarz & Ischebeck, 2003). Therefore, in the numerical comparison task, the incongruent or congruent physical information, which was task irrelevant, interfered with or facilitated cognitive processing occurring as the participant determined which number was numerically smaller or larger.

In both experiments the size congruity effect in the numerical comparison task was larger for digits than for either number words or pseudohomophones. Cohen Kadosh et al. (2008) obtained the same findings in their study when participants completed a numerical comparison. They hypothesized that the difference in the size congruity effect was due to number words being shallowly processed, reflected in the smaller distance effect for number words, which reduced the interference of incongruent physical information on cognitive processing. However, in Experiment 2 of the current study, the distance effect in the numerical comparison task did not differ across formats. I hypothesize that the difference between the results of the current study and previous research in terms of across formats distance effects was due the controlled nature of the word and pseudohomophone stimuli used in the current study. By carefully controlling such factors as the size of the stimuli reaction times are more stable and there are fewer irrelevant differences relative to previous research.

Integration with Past Research

The results of the current study are in agreement with previous research on the intentional and unintentional activation of quantity information when numbers are presented as digits and number words. Both cognitive and neuroimaging research has indicated that digits can intentionally and unintentionally activate quantity information (Barth et al., 2003; Cohen Kadosh & Walsh, 2009; Dehaene & Akhavein, 1995; Naccache & Dehaene, 2001; Pinel et al., 2001; Tzelgov et al., 1992). The evidence that digits intentionally and unintentionally activate quantity information is also in accord with research that found that digits are processed like pictures (Fias, 2001; Fias et al., 2001) in number naming tasks. That is, when digits are processed they must activate quantity information. The results that indicated number words do not unintentionally activate quantity information are also consistent with some previous research (Cohen Kadosh et al., 2008; Fias, 2001; Fias et al., 2001; Koechlin et al., 1999) although there are competing findings (e.g., Naccache & Dehaene, 2001). Because the current work replicates that of Cohen Kadosh et al., where various confounding factors were controlled, and even went beyond by controlling extraneous physical size factors in the words, I am confident in concluding that numbers words do not activate semantic information in physical comparisons.

There was one finding concerning the unintentional activation of quantity information with digits that did not correspond with previous research. In the current study, when participants made a physical comparison, the size congruity effect was not modulated by numerical distance (see Figure 4). Cohen Kadosh et al. (2008) found that when digits were physically compared, the size congruity effect was larger when the distance was larger. The reason for the difference in the current study may be due to participants' relatively fast responses to digit pairs in the second experiment compared to those in Cohen Kadosh et al. (2008). Because participants were faster to respond to all types of digit pairs in the physical comparison, the incongruent quantity information had less time to interfere with cognitive processing than in Experiment 1 and Cohen Kadosh et al. (2008) experiments. This occurred as both overall response times were slower than in the present Experiment 2. This explanation is in accord with the model of the cognitive foundation of the size congruity effect proposed by Schwarz and Ischebeck (2003) and does not compromise the interpretation that digits produce obligatory activation of quantity information.

The results from Dehaene and Akhavein (1995) are an exception to other research and the results of the current study. They found distance effects for word-word and digit-digit pairs but not word-digit pairs. The lack of distance effects for mixed pairs does decrease the generalizability of the results because if quantity information were activated we would expect priming both within and across number formats. The word-word pair results were most likely a consequence that in both experiments the task focused on the content of the two number words. As reviewed by Lucas (2000), when an experimental task involves processing the semantic content of the stimulus, this predisposes the activation of semantic representations. In summary, the evidence that quantity information was unintentionally activated may simply be due to the task used.

Ganor-Stern and Tzelgov (2008) also found, using Arabic number words, that they unintentionally activated quantity information. However, Arabic number words are more similar to digits than to words in English because they are all single character letters (e.g., ١, ٢, ٣) that correspond to specific quantities. Therefore, the unintentional activation of quantity information with Arabic number words in Ganor-Stern and Tzelgov (2008) may reflect their similarity to digits than English number words. Because digits unintentionally activate quantity information and Arabic number words share many properties with digits, their results do not indicate that *English* number words unintentionally activate quantity information. Finally, the results of the current study are in agreement with recent neuroimaging results (Cohen Kadosh et al., 2007; Cohen Kadosh et al., 2010; Piazza et al., 2007). These findings have been used to suggest that number words cannot unintentionally activate quantity information.

One of the primary contributions of the current research was the use of a number format, pseudohomophones, that has never been applied in the context of activation of quantity information. Recall that dual-routes models of word processing propose that words can be processed through a semantic or non-semantic route (Coltheart et al., 2001). The pseudohomophone effect (Briesemeister et al., 2009; Seidenberg et al., 1996; Yates et al., 2003), masked priming (Lukatela et al., 1998), and easy identification made pseudohomophones an ideal comparison format. Contrary to the research using masked priming with pseudohomophones (Lukatela & Turvey, 1997; Lukatela et al., 1998), there was no evidence that pseudohomophones led to any unintentional activation of quantity information once the congruity and pseudohomophone length confound was controlled for in the second experiment.

The current study contributes to the growing literature on the effect of surface format on the intentional and unintentional activation of quantity information in two ways. First, the introduction of pseudohomophones provided a third comparison format that no other study on this topic has ever utilized. Second, no other study has considered how the size of a word or pseudohomophone might affect the results. The use of stimuli in which length was controlled allowed a clear and detailed examination of the effects of size congruity beyond previous studies (e.g., Cohen Kadosh et al., 2008). In fact, the homogenized stimulus set reduced reaction times below that reported in any other research. Thus, the stimuli used in Experiment 2 provided the clearest and least ambiguous results concerning the intentional and unintentional activation of quantity information for numbers presented in different surface formats.

Implications for Theories of Numerical Representation

Consider the notation-independent theories -- the triple-code model (Dehaene, 1992) and the abstract-code model (McCloskey, 1992). The finding that number word and pseudohomophone number pairs did not show any evidence of unintentional activation of quantity information does not support the view that an abstract representation of quantity is necessarily activated when these formats are encoded. Specifically, if the representation of quantity were abstracted away from the format of numbers under unintentional processing conditions, these formats should show evidence that quantity information had been activated.

In contrast, in Campbell and Epp's (2004) encoding-complex model, the strength of activation of quantity is notation-dependent. That is, quantity information will be activated to the extent that the presented format is the typical format. The encoding-complex model predicts that digits should exhibit the strongest activation of quantity information, words less activation, and pseudohomophones very little activation. In the current study, this hypothesis was not borne out in the numerical comparison task (see

Figure 6). Therefore, the results of the current study do not completely support the encoding-complex model.

The goal of the current study was to examine the activation of quantity information not to explicitly test these theories. As can be seen above, the results of the current study do not clearly support either the notation-independent or notation-dependent theories of numerical representation. The theories clearly need to be refined and more explicit testable hypotheses defined to gain a better understanding of the validity of each.

Limitations and Future Research

From a methodological standpoint, both experiments are based on a limited set of number pairs (see Appendix 1) that may limit the generalizability of the results. The use of a limited number of stimuli ensured that no single number was presented more often than any other number. Previous research has indicated that repeating an item several times leads to heightened intra-trial activation of this item in memory (e.g., Ratcliff, Hockley, & McKoon, 1985). Controlling the frequency of times a number was experienced reduced the likelihood that the results of the current study were due to residual intra-trial activation of quantity information attributable to a single often-repeated number. This control came at the expense of basing the entire study on four unique number pairs. Nonetheless, there is no reason to believe that the results would change drastically if different number pairs were used.

There are several directions for future research. First, these experiments have shown that pseudohomophones can provide a useful comparison format for future research on the effect surface format on the intentional and unintentional activation of quantity information. Pseudohomophones consist of the same basic components as number words, are easily understood, and are completely novel. Furthermore, pseudohomophones have been shown to activate phonological information, which can mediate access to semantic information (Luo et al., 1998). Second, the current experiments clearly illustrated that digits, number words, and pseudohomophones can all activate quantity information when they are intentionally processed. However, the strength of the activation differs considerably between digits and the other two formats. Future research should attempt to determine why the strength of quantity information activation differs under unintentional processing conditions. For example, it could be the case that digits activate one representation of quantity and the other formats activate a different one. Finally, future researchers should use pseudohomophones to examine the unintentional activation of quantity information using different methodologies and indices of quantity information activation. For example, pseudohomophones could be used in conjunction with masked priming to determine if a priming distance effect emerges both within and across formats.

Conclusions

Based on the results of the current study the following conclusions can be made. First, when numbers presented as digits, words, and pseudohomophones in a task that requires intentional activation of magnitude, they all produced effects that show magnitude activation. The activation of quantity information was illustrated by the significant distance effect for all three formats in the numerical comparison task. Second, only digits produced obligatory activation of quantity information, as illustrated by size congruity and distance effects for digits in the physical comparison task. Finally, researchers using word or word-like stimuli need to take into consideration all the characteristics of these stimuli when running an experiment. Overall, the results of the current study illustrate the need to consider the impact of the task that participants complete and their implications for the conclusions that are reached when examining phenomena, such as quantity representation, that cannot be directly observed.

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Appendix A

Number pairs used in Experiments 1 and 2.

	Congruent		Incongruent		Physically Neutral		Numerically Neutral	
	Distance							
Format	Small	Large	Small	Large	Small	Large	Small	Large
Digits	1 2	1 6	1 2	1 6	1 2	1 6	1 1	6 6
	3 4	2 7	3 4	2 7	3 4	2 7	2 2	7 7
	6 7	3 8	6 7	3 8	6 7	3 8	3 3	8 8
	8 9	4 9	8 9	4 9	8 9	4 9	4 4	9 9
Words	one two	one six	one two	one six	one two	one six	one one	six six
	three four	two seven	three four	two seven	three four	two seven	two two	seven seven
	six seven	three eight	six seven	three eight	six seven	three eight	three three	eight eight
	eight nine	four nine	eight nine	four nine	eight nine	four nine	four four	nine nine
Pseudohom -ophones	wun tue	wun siks	wun tue	wun siks	wun tue	wun siks	wun wun	siks siks
	thrie fowr	tue sevin	thrie fowr	tue sevin	thrie fowr	tue sevin	tue tue	sevin sevin
	siks sevin	thrie eit	siks sevin	thrie eit	siks sevin	thrie eit	thrie thrie	eit eit
	eit nyne	fowr nyne	eit nyne	fowr nyne	eit nyne	fowr nyne	fowr fowr	nyne nyne

Appendix B: Mean percent error with 95% confidence intervals based on the four-way interaction in Experiment 1