Size and Spatial Congruity Effects in Single-Digit Magnitude Judgment Tasks

by

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Abstract

The spatial-numerical association of response codes (SNARC; Dehaene, Bossini, & Giraux, 1993) effect and size congruity effect (SiCE; Henik & Tzelgov, 1982) are the results of relationships of numerical magnitude with response location and physical size respectively. These relationships have been the subjects of thorough investigation in the numerical cognition literature. However, such investigations have largely occurred independently of each other, with few studies known to the author offering simultaneous investigation of the relationships between numerical magnitude and response location and between numerical magnitude and physical size. Four experiments using single-digit magnitude judgment tasks resulted in reliable SNARC effects, with little evidence of SICEs and no interactions between the factors that give rise to these relationships. Obtained results suggest the spatial-numerical and size-numerical relationships that give rise to SiCE and SNARC effects are the result of separate representational processes rather than a singular representation of physical and numerical magnitude information.

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Introduction

The Investigation of Numerical and Physical Magnitudes

Within the area of numerical cognition, the relatedness of numerical magnitude to other aspects of the mental representation of digits has been the subject of intense investigation. Of primary interest to the present research are the relationships between numerical magnitude, response location, and physical magnitude. Previous research has extensively investigated the relationship between numerical magnitude and response location (i.e., the spatial numerical association of response codes effect, or SNARC effect; Dehaene, Bossini, & Giraux, 1993) and between numerical magnitude and physical magnitude respectively (i.e., the size congruity effect, or SiCE; Henik & Tzelgov, 1982), resulting in a large body of literature concerning each of these relationships. Despite the extensive research pertaining to each of these relationships separately, little research has investigated the co-occurrence of SiCE and SNARC effects in the same experimental task, with only a select few studies known to the author at the time of writing. Whereas the limited evidence available suggests that SiCE and SNARC effects may co-occur in single-digit judgment tasks without resulting in an interaction between all of their respective factors (e.g., a three-way interaction between response location, numerical magnitude, and display size of the stimulus), models within the literature such as ATOM (Walsh, 2003), polarity correspondence (Proctor & Cho, 2006), and that of Gevers, Verguts, Reynvoet, Caessens, and Fias (2006) would posit that physical magnitude information is processed similarly to numerical magnitude. Thus, the physical magnitude of a presented stimulus may be expected to influence response times in a manner analogous to that of numerical magnitude in binary forced-choice judgment tasks. Given the relatively small number of studies available that have examined both SiCE and SNARC effects in single-digit tasks, additional research on this topic, such as that of

the present study, is necessary in order to improve the understanding of the nature of the information processing that gives rises to congruity effects such as the SiCE and SNARC effects.

The Spatial Numerical Association of Response Codes (SNARC) Effect

The SNARC effect (Dehaene et al., 1993) is characterized by an interaction between numerical magnitude and response location and is generally presumed to indicate the presence of a relationship between numbers and mental space. More specifically, it refers to a relationship between numerical magnitude (i.e., small and large relative to a numerical standard) and response location (i.e., left-side and right-side responses), such that small numbers tend to receive faster left-side responses, whereas large numbers tend to receive faster right-side responses. In its original instantiation (e.g., Dehaene et al., 1993) this relationship was observed in the context of a parity judgment task, in which participants judge randomly presented Arabic digits as being either even or odd. Such a relationship was later observed in the context of a magnitude judgment task, in which participants judge randomly presented Arabic digits as being either larger or smaller than a numerical standard (Gevers et al., 2006). According to Dehaene et al. (1993), this relationship arises due to a direct mapping between the relative spatial representation of numerical magnitude and response location, such that numerically smaller numbers are represented in left-side space, whereas numerically larger numbers are represented in right-side space. Such a representation might be described as a sort of mental number line, where numbers are spatially aligned according to relative magnitude in a manner that corresponds to the written direction of the number system.

Later research on the SNARC effect found that this overt manifestation of the relationship between numerical magnitude and space is not restricted to horizontal response

mappings. Vertical SNARC effects refer to cases where numerically larger numbers are responded to faster with upper response locations and numerically smaller numbers are responded to faster with lower response locations. Such an effect has been previously demonstrated using button presses (Ito & Hatta, 2004), where participants engaged in a parity judgment task requiring them to judge randomly presented numbers as being either even or odd using one of two response keys arranged vertically. In that experiment, a relationship between numerical magnitude and response location was observed, such that numerically smaller numbers tended to receive faster responses with the bottom keys, whereas numerically larger numbers tended to receive faster responses with the top keys. As well, Schwarz and Keus (2004) observed a similar pattern of responses in a situation where participants engaged in a parity judgment task and responded to randomly presented numbers using upward and downward eye saccades. These authors observed a tendency for faster upward saccades in response to numerically larger numbers and faster downward saccades in response to numerically smaller numbers. However, more recently it has been argued that such an arrangement of numbers does not occur spontaneously, but rather arises as a result of specific ways of conceptualizing numerical magnitude according to task demands (Holmes & Lourenco, 2012). Furthermore, horizontal SNARC effects tend to be stronger than vertical SNARC effects when both horizontal and vertical organizations are elicited, suggesting a predominant tendency toward horizontal representation.

Additional previous research conducted by Bächtold, Baumüller, and Brugger (1998) has demonstrated that context serves to inform the direction of the interaction that results in the SNARC effect. In their experiment, Bächtold et al. (1998) instructed participants to conceptualize presented digit stimuli as corresponding to hour positions on a clock face and to

respond to these stimuli as being either "earlier" than 6 o' clock or "later" than 6 o' clock. The authors observed a reversed relationship from that of Dehaene et al. (1993)'s results, such that numerically smaller numbers were now associated with faster right-side responses, whereas numerically larger numbers were associated with faster left-side responses, corresponding to the spatial arrangement of numbers on a clock face. Later work by Viarouge, Hubbard, and Dehaene (2014) further explored the influence of reference frames on the SNARC effect. In this study, the authors examined the effect of object-based reference frames and context informed by the specific language used in presented instructions. In the first experiment, the authors manipulated the task instructions, such that half of participants received instructions concerned with participants' hands, whereas the remaining half of participants received instructions concerned with the response location mappings. The authors observed a lack of a Digit Magnitude x Hands interaction, indicating that the observed SNARC effect was affected primarily by the global reference frame (i.e., with the instructions pertaining to the response locations) in both instruction conditions. However, a marginally significant Instructions x Magnitude x Hands interaction indicated that task instructions were somewhat effective in manipulating participants to focus on the hand-centered reference frame, rather than the global reference frame. In the second experiment, Viarouge et al. (2014) explored the role of object-centered reference frames on the SNARC effect. Participants engaged in a parity judgment task using response buttons arranged on an object with a clearly defined axis of symmetry, which was described to participants as being representative of a boat. The authors observed significant main effects of hand (where right-hand responses were faster), parity (where responses to even numbers were faster), and response button (where responses using the bottom button were faster). Importantly, although no interactions corresponding to object-based reference frames were observed, trends

toward hand-based reference frames were observed. Together, these results indicate that the SNARC effect is linked to several reference frames that may be modulated based on experimental contextual factors.

The role of context in the directionality of the SNARC effect was further explored by Shaki and Fischer (2008). Using a sample of Hebrew-Russian bilingual participants, the authors engaged participants in a magnitude judgment task performed twice, each time preceded by a reading comprehension task in Hebrew, which is read right to left, or Russian, which is read left to right. An additional experiment using an independent sample employed Hebrew and Russian listening comprehension tasks and used otherwise identical methodology. The authors observed significant differences between magnitude judgment tasks associated with the Hebrew and Russian reading comprehension task conditions, such that the Hebrew condition resulted in a weaker traditional SNARC effect pattern than the Russian condition. The authors attribute this pattern of results to weaker visuospatial mappings in the Hebrew condition. Because Hebrew is read from right to left, the written organization of the language is contrary to the left-to-right mapping associated with Arabic digits. Thus, the authors assert that contextual cues, in the form of reading direction, are capable of influencing the strength and direction of the SNARC effect. Further evidence of the influence of reading direction on the SNARC effect is provided by Shaki, Fischer, and Petrusic (2009). In this experiment, the authors compared the effects of the directionality of the written languages and number systems used. The authors recruited three samples: Canadian participants, whose written language (i.e., English) and number system (i.e., Arabic) are read left to right; Palestinian participants, whose written language (i.e., Arabic) and number system (i.e., Arabic-Indic) are read right to left; and Israeli participants, whose written language (i.e., Hebrew) is read right to left but whose number system (i.e., Arabic) is read left to

right. The authors observed SNARC effects for groups where written language direction and written number direction were consistent (i.e., Canadian and Palestinian participants), such that Canadian participants demonstrated a SNARC effect in the traditional direction, but Palestinian participants demonstrated a reversed SNARC effect, where numerically smaller numbers received faster right-side responses and numerically larger numbers received faster left-side responses. In contrast, no such effects were observed among Israeli participants, whose written language direction and written number direction were inconsistent.

A similar context-based reversal of the traditional direction of the SNARC effect may also be elicited through the use of priming via positive and negative signs (Tse & Altarriba, 2010). These authors tasked participants with parity judgments, in which the fixation point preceding each trial consisted of either a negative (i.e., "-") or positive (i.e., "+") sign. Both fixation points were intermixed within each block of the experiment. A SNARC effect in the typical direction was observed on trials primed with a positive sign and a reversed SNARC effect on trials primed with a negative sign. Furthermore, no reversed SNARC effect was observed when the fixation point remained consistent within a given block, suggesting that this information is ignored, and that numbers preceded without a sign are assumed to be positive by default (Tse & Altarriba, 2010).

Two Accounts of the SNARC Effect

The SNARC effect has thus far been explained via two accounts. The first such account is the direct mapping account of Dehaene et al. (1993). This account proposes that numbers are mentally represented in a manner similar to how they would be spatially represented in physical space. Thus, for Arabic digits, numerically smaller digits would be represented in relatively

leftward locations in space, whereas numerically larger numbers would be represented in relatively rightward locations in space. Accordingly, when making numerical judgments, numerically smaller numbers receive faster left-side responses, whereas numerically larger numbers receive faster right-side responses. The second account used to explain the SNARC effect is the intermediate mapping account. This account proposes that numbers are mentally represented via intermediate processes following stimulus onset that serve to codify aspects of the stimulus which, in turn, influence its representation and, subsequently, responding.

In the literature, two influential models providing intermediate coding accounts of the SNARC effect exist. The first intermediate coding account is based on a model by Verguts, Fias, and Stevens (2005). This model describes the representation of numbers based on inputs and outputs, and consists of three layers. The first layer of the model represents the mental number line and consists of two fields of 15 nodes representing the numbers 1 to 15, with one field (the "number" field) representing the stimulus on an instantiated mental number line, and the other field (the "standard" field) representing some task-dependent numerical standard to which the stimulus must be compared. The second layer consists of a magnitude field, where input from both fields in the first layer is coded as either small or large. Additional task-dependent fields (such as even or odd) may be activated using input received from the number fields in the first layer. A third layer, added by Gevers et al. (2006) to account for the SNARC effect, consists of laterally inhibited spatially-defined responses that are activated once a threshold is achieved, after which the appropriate response (i.e., left or right) is initiated. The key aspect of this model that gives results in the SNARC effect is the presence of fixed (or “hard-wired”) connections between the small and large intermediate coding units in the second layer and the, respective, left and right response units in the additional third layer.

The second intermediate coding account involves the polarity correspondence principle (Proctor & Cho, 2006). The polarity correspondence principle asserts that dimensional aspects of stimuli, such as numerical magnitude and parity, are assigned one of two possible binary codes which may be either positive (+) or negative (-). In the case of numerical magnitude, for example, a relatively large number would be assigned a '+' code, whereas a relatively small number would be assigned a '-' code. Furthermore, under the polarity correspondence principle (Proctor & Cho, 2006), left-side responses are assumed to be coded negatively, whereas right-side responses are assumed to be coded positively. These authors assert that when the codes for the stimulus dimension and response correspond (i.e., when both codes are either positive or negative), response times are generally shorter when compared to the non-correspondence case (i.e., a mismatch between the stimulus dimension and response codes).

Additionally, though, the polarity correspondence model may also be used to explain patterns of results pertaining to non-numerical aspects of stimuli, such as those observed in tasks pertaining to emotional valence. In a study conducted by Lynott and Coventry (2014), the authors examined response times to happy and sad faces randomly presented in one of two locations on a computer screen: a relatively high position or a relatively low position. Participants were instructed to judge these faces as either "happy" or "sad" using key presses arranged horizontally. The authors observed an interaction between stimulus location and emotional valence, such that participants responded to happy faces faster when they were presented in the upper area of a computer screen and to sad faces faster when they were presented in the lower area of the screen. Similarly, de la Vega, Dudschig, De Fellipis, Lachmair, and Kaup (2013) tasked participants with judging the emotional valence of German words. The authors observed an interaction between response hand and emotional valence, such that happy

words received faster right-hand responses, whereas sad words received faster left-hand responses. Such a result can be deemed consistent with the polarity correspondence principle, whereby positive emotional valence (i.e., happiness) would be expected to achieve correspondence with a positively-coded response (i.e., a right-side response) and, similarly, negative emotional valence (i.e., sadness) would be expected to achieve correspondence with a negatively-coded response (i.e., a left-side response), as was observed by the authors. These associations between valence and space are thought to be the result of structural overlap between the words and their respective polarities (Lakens, 2012), such that positive- and negative-polarity words would receive faster response times when responded to in a spatial location with a polarity that corresponds to the polarity of the word.

Some Further Results Pertaining to the SNARC Effect

Of importance to the current proposed work, though, is that further evidentiary support exists for mental number space represented in three dimensions (Winter, Matlock, Shaki, & Fischer, 2015). Namely, in addition to the aforementioned horizontal (Dehaene et al., 1993) and vertical SNARC effects (Ito & Hatta, 2004), distance-based or saggital SNARC effects have also been observed. In such studies, saggital SNARC effects are revealed through the use of a proximo-distal response layout where response keys are arranged so as to extend away from the body. Although such studies are relatively limited within the literature, some of the work previously considered to demonstrate vertical SNARC effects, such as that of Ito and Hatta (2004), may actually be considered to be demonstrative of saggital SNARC effects due to the placement in the horizontal plane of the computer keyboard that was used to collect responses. This assertion is further supported by Mourad and Leth-Steensen (2017), who observed a pattern of results indicating that organizations of response keys previously considered to be in a

"vertical" arrangement are more accurately described as being organized according to a proximo-distal arrangement. In these studies, participants who were instructed to generate an imagined bottom-to-top vertical arrangement of numbers (akin to an arrangement of elevator buttons) displayed no significant SNARC effect, whereas participants who were instructed to generate an imagined proximo-distal arrangement of numbers (described as labeled pylons extending away from the participant, with smaller numbers located closer to participants) did produce a significant SNARC effect. Additional support for the existence of saggital SNARC effects using proximo-distal response locations can be found in Müller and Schwarz (2007) and Shaki and Fisher (2012), where similar associations were observed between numerical magnitude and distance, such that numerically smaller numbers were associated with closer keys and numerically larger numbers with farther keys. Furthermore, these saggital SNARC effects are sometimes conceptualized as a more broad proximo-distal relationship, rather than a relationship strictly defined as occurring along the saggital axis. These "radial" SNARC effects (Hartmann, Gashaj, Stahnke, & Mast, 2014) extend from the body along the horizontal plane and are thought to be symmetrical. As well, in Santens and Gevers (2008), a symmetrical radial SNARC effect was observed, such that, for both left and right response directions employing "close" and "far" response locations, numerically smaller numbers were associated with faster close responses, whereas numerically larger numbers were associated with faster far responses.

The Size Congruity Effect (SiCE)

In somewhat related research, the effects on response times of the physical size at which numbers are displayed has also been the subject of intense investigation. Namely, the size congruity effect (SiCE; Henik & Tzelgov, 1982) refers to an interaction between numerical magnitude and physical size, such that in magnitude judgment tasks in which participants are

instructed to choose one of two numbers of different physical magnitudes based on numerical magnitude, response times tend to be shorter when the physical magnitude of the displayed digit corresponds to its numerical magnitude. For example, when instructed to choose the larger of two numbers, response times will be shorter for trials where the numerically larger number is displayed in a physically larger size, as compared to a mismatch between physical and numerical magnitudes. Note, as well, that an analogous effect occurs for judgments of physical size, such that deciding which digit is physically larger or smaller is also affected by the numerical magnitude of the digits.

Two Models of the SiCE

Two models have emerged in the literature to explain the SiCE. The first is an early interaction model (Schwarz & Heinze, 1998) which asserts that physical and numerical size information is extracted separately, then integrated into a singular representation before informing later processing stages. Some such models, such as Walsh (2003)'s A Theory of Magnitude (ATOM), propose that magnitude information in general, such as that also pertaining to time and space, is represented in the same way suggesting that such information is processed and integrated in a single, centralized location in the brain. In contrast, a late interaction model (Faulkenberry, Cruise, Lavro, & Shaki, 2016; Santens & Verguts, 2011; Sobel, Puri, & Faulkenberry, 2016) asserts that physical and numerical size information is represented and processed separately and in parallel until being integrated into a singular representation during decision making. Faulkenberry et al. (2016) observed evidence for a late interaction model by examining recorded response trajectories (made using a mouse to point to the chosen stimulus locations) across three experiments. These authors observed significant deflections toward the alternative response throughout 50% of the response trajectory during the incongruent trials of a

typical SiCE paradigm task suggesting that numerical and physical size information is only integrated at decision making (i.e., at the choice of the response movement). Furthermore, this effect was modulated by the numerical distance between the response alternatives and occurred irrespective of directed speeded response initiation (i.e., whether participants were instructed by the researchers to respond to stimuli as quickly as possible).

Nonetheless, some recent evidence for the early interaction model can be found in the context of visual search tasks (Krause, Bekkering, Pratt, & Lindemann, 2017). In this study, the authors engaged participants in visual search in which they were instructed to identify a physically large or small target item amongst a collection of numerically small or large distractors, resulting in congruity amongst both the dimensions of the target (i.e., physical and numerical magnitude) and between the target and distractors. Krause et al. (2017) observed significant interactions between the numerical and physical magnitudes of the target, indicating that participants responded faster when the target's numerical and physical magnitudes were congruent. Importantly, Krause et al. (2017) noted that such findings demonstrate a SiCE outside of the classical SiCE paradigm. Whereas classical SiCE paradigms engage participants in explicit comparisons between binary choices, a visual search task requires participants to identify and respond to the target among multiple distractors. Given Krause et al. (2017)'s results, a response competition account does not provide sufficient explanation for such findings obtained in the context of visual search. Hence, whereas there exists a multitude of evidence indicating the presence of an interaction between numerical and physical magnitudes on response times (and thus demonstrating the SiCE), some disagreement remains regarding which model (i.e., early or late interaction) represents a more accurate depiction of this effect.

The SiCE in Single-Digit Magnitude Judgment Tasks

The earliest example of research investigating simultaneous numerical and physical magnitude changes involving single digits was provided by Schwarz and Heinze (1998). These authors tasked participants with single-digit numerical magnitude and physical size judgments randomly intermixed within each block. Stimuli consisted of the numbers 3, 4, 6, and 7 displayed randomly in four possible font sizes. In this study, each trial began with a coloured square acting as a fixation point displayed in the center of a computer screen. The colour of the square informed participants of the judgment type of the forthcoming digit (e.g., a red square directed participants to make a smaller-larger physical size judgment, whereas a green square directed participants to make a smaller-larger numerical magnitude judgment), to which participants responded using bimanual button presses.

Importantly, Schwarz and Heinze (1998) observed significant size and numerical congruity effects (i.e., faster responses when physical size and numerical magnitude matched), as well as a task by congruity interaction which indicated a stronger effect for size judgments than for numerical judgments. This asymmetry in task performance suggested an asymmetry in processing physical size and numerical magnitude information which may be attributed to temporal differences in information extraction prior to integration. Importantly, these authors also examined both early and late ERP wave forms which indicated that congruity effects were more evident earlier on than later on. As well, congruity effects tended to manifest themselves in the ERPs slightly earlier for size judgments even though response times for such judgments were slower than those for numerical judgments.

Some more recent research has also attempted to investigate the extent to which simultaneous numerical and physical magnitude changes affect response times in single-digit magnitude judgment tasks. Namely, Wiemers, Bekkering, and Lindemann (2017) presented

participants with random single digits from 1 to 9 (excluding 5) in one of four possible sizes and 6 possible locations, ranging from an extreme leftward position to an extreme rightward position. Given such an arrangement, the authors calculated a value system for all possible combinations ranging from -1 to 1, which indexed the congruity of a trial digit's numerical value relative to its displayed physical size, with -1 indicating maximum incongruity (e.g., the digit 9 in the smallest size) and 1 indicating maximum congruity (e.g., the digit 9 in the largest size). Additionally, a similar measure was also computed to index spatial-numerical congruity and the authors employed vocal responses so as to remove any effects related to response location.

Importantly, Wiemers et al. (2017) outlined a key theoretical distinction between what they referred to as numerical compatibility effects and numerical congruency effects. Compatibility effects, according to these authors, refers to correspondence between the organization of response locations in space and the mental spatial organization of numbers (i.e., in a left-to-right manner). Thus, when response locations are arranged horizontally, such as through the use of relatively leftward and rightward keys on a keyboard common to the classical SNARC effect paradigm, compatibility effects emerge. Conversely, congruency effects concern the relative dimensions of the stimuli themselves (e.g., numerical magnitude) with regards to other stimulus dimensions (e.g., physical magnitude, resulting in a SiCE) or stimulus location organization (e.g., a small-left, large-right association; a SNARC-like effect).

In this light, Wiemers et al. (2017) observed both significant size congruency and spatial congruency effects, indicating that both physical size and spatial location interact with numerical magnitude to affect response times in single-digit magnitude judgment tasks. Furthermore, the lack of a significant three-way interaction between spatial location, physical magnitude, and numerical magnitude suggested differences in the nature of the mental representations

underlying each of these effects. Namely, according to Wiemers et al. (2017), whereas number-space congruency effects arise due to interference between ordinal representations, number-size congruency effects are based on interference between, what they refer to as, cardinal representations.

One potential caveat to such a conclusion, however, is the fact that Ren, Nicholls, Ma, and Chen (2011) observed an interaction between physical magnitude and response location for participants engaged in a physical size discrimination task. In this task, participants were instructed to judge the stimulus (presented as a grey disc) as being either larger or smaller than a reference presented in the same trial. A significant interaction between response hand and physical magnitude occurred, such that relatively larger discs tended to receive faster right-hand responses, whereas relatively smaller discs tended to receive faster left-hand responses (i.e., a spatial magnitude association of response codes or SMARC effect). In this study, similar results were also observed with numbers (i.e., a SNARC effect), luminances, and verbally referenced object sizes, indicating consistent spatial representation of non-numerical magnitude of stimuli.

The Present Study

Although Schwarz and Heinze's (1998) study resembled more the classical single-digit magnitude judgment task than did that of Wiemers et al. (2017), it should be noted that in their study the response key mapping remained consistent in a compatible arrangement (i.e., all "smaller" responses were made using the left key and hand, whereas all "larger" responses were made using the right key and hand) across all blocks and tasks. Thus, while Schwarz and Heinze (1998) demonstrated the co-occurrence of numerical and size congruency effects in a single-digit

judgment task, the lack of counterbalanced response key mappings prevents the assessment of possible spatial compatibility effects in this study.

On the other hand, Wiemers et al.'s (2017) study employed several notable deviations from the more classical SiCE and SNARC paradigms. First, as mentioned previously, the authors employed vocal responses, rather than manual responses. Second, Wiemers et al. (2017) made use of a single presented digit per trial, rather than two digits per trial, as is common in the classical SiCE paradigm. Third, unlike what might normally be expected for single-digit judgment tasks (e.g., Dehaene et al., 1993), stimuli were presented in locations either to the left or to the right of the fixation point, rather than simply replacing the fixation point itself in the center of the screen.

Hence, the current research will attempt to further explore SiCEs in single-digit magnitude judgment tasks using methodology more similar to the conventional SiCE and SNARC effect paradigms than the methodology employed by Wiemers et al. (2017). Presently, the effect of physical and numerical size congruity in the context of single-digit judgment tasks is not that well understood. Thus, the current research represents a twofold opportunity to further examine the SiCE in the context of a single-digit magnitude judgment task more typical to the SNARC paradigm and hence, to also examine the relationship between this effect and the classic SNARC effect.

Hence, the current research will expand upon the findings of Wiemers et al. (2017) using a methodology more typical to the SNARC paradigm, with the addition of size transformations (in the form of changes in font size) at stimulus presentation. As well, the use of physical, size-based judgment tasks in addition to numerical-based ones will specifically direct attention to the

sizes of the digits, which should enhance the likelihood of eliciting both the SiCE and spatial-magnitude association of response codes (SMARC) effect. Furthermore, as a novel aspect of the current research, two other manipulations, will attempt to induce a distance-based interpretation of font size changes. As discussed extensively in Mourad and Leth-Steensen (2017), the alignment of the response keys could be regarded as providing a frame of reference through which to interpret the spatially-based (and, now also, the physical size-based) aspects of the stimuli. Hence, the use of vertically/proximo-distally aligned response keys should serve to induce a distance-based conception of the presented sizes of the digit stimuli, in which the smaller-sized stimuli would be regarded as being far away and larger-sized stimuli as being close. Therefore, the current research will further expand upon previous work by examining size compatibility effects in single-digit magnitude judgment tasks in which responses to physical size of the digit will be made using either horizontal or vertical manual button presses. As well, in this study, a final group of participants will be assigned to a vertical response condition but will also be further divided based upon provided cueing instructions. In other words, these participants will be cued to view the changes in physical size of stimuli between trials as perceived changes in distance using methodology similar to that of Mourad and Leth-Steensen (2017). Moreover, distance cues, in the form of converging lines, will be employed in order to further cue participants to perceive changes in physical size amongst the stimuli as perceived changes in distance.

In general, if numerical-size and spatial-numerical associations represent separate processes in single-digit magnitude judgment tasks, as assumed by Wiemers et al. (2017), then an interaction between physical size and numerical magnitude (i.e., a SiCE), an interaction between numerical magnitude and response location (i.e., a SNARC effect), but no interaction

between these three factors will be observed. Conversely, if physical size, numerical magnitude, and spatial location are all processed in a similar fashion (either as analog quantities, e.g., Walsh, 2003, or through intermediate coding, e.g., Gevers et al., 2006, or Proctor & Cho, 2006), then an interaction between physical size and numerical magnitude (i.e., a SiCE), an interaction between numerical magnitude and response location (i.e., a SNARC effect), an interaction between physical size and response location (i.e., a spatial magnitude association of response codes, or SMARC effect), and an interaction between physical magnitude, numerical magnitude, and response location should all be observed. Finally, in the final study, if task manipulations are able to influence the manner in which physical size of the stimuli is perceived then the direction of any size congruency or compatibility effects should be reversed when participants are cued to view changes in physical magnitude as perceived changes in distance. Namely, given a vertical/proximo-distal alignment of response keys, it would now be the case that larger physical sizes are associated with the smaller numerical magnitudes and closer bottom response keys and smaller physical sizes and larger numerical magnitudes with the farther top response keys.

Experiment 1

Participants

Participants consisted of 30 self-reported right-handed individuals (17 females, M = 19.70 years, SD = 2.54) with normal or corrected-to-normal vision recruited from Carleton University's undergraduate student research pool. Participants received partial course credit as compensation for their participation.

Method

The experiment was conducted using SuperLab Pro v2.0 on a computer running Microsoft Windows XP. All stimuli were presented to participants seated approximately 50 cm away from the monitor in a dimly lit room. Participants engaged in a magnitude judgment task and responded to the stimuli 1, 4, 6, and 9 using one of two keys. All stimuli were presented in an Arial font in one of three possible sizes: the "small" font, displayed at size 16 (0.23˚ x 0.40˚), the "control" font, displayed at size 24 (0.40˚ x 0.69˚), and the "large" font, displayed at size 36 (0.63˚ x 1.03˚). The experiments each consisted of 4 blocks of 132 trials each. The first 12 trials of each block were practice trials, but were not differentiated as such to the participants. Each digit stimulus was displayed 10 times in each font size during experimental trials and once each during practice trials.

Procedure

The experiment was conducted in one session lasting approximately 40 minutes. At the beginning of each block, participants were presented with a set of instructions describing the response mapping. Participants commenced each trial by pressing the "J" key (hereafter referred to as the "middle" key) on a QWERTY keyboard with their right index fingers. After pressing the middle key, a "+" sign (the fixation point), appeared in the center of the screen for 1000 ms and was immediately replaced by a random number. This fixation point subtended 0.69˚ x 0.69˚ of participants' visual fields, thus corresponding to the height of the control-sized stimuli. Participants responded to this random number as being either larger than or smaller than 5 by pressing keys to the immediate left or immediate right of the middle key (i.e., the "H" and "K" keys) with their right index finger. After each response, or if no response was provided after 3000 ms, the screen turned blank, indicating that participants were able to initiate the next trial. Response mappings alternated between blocks for each participant, such that the "smaller"

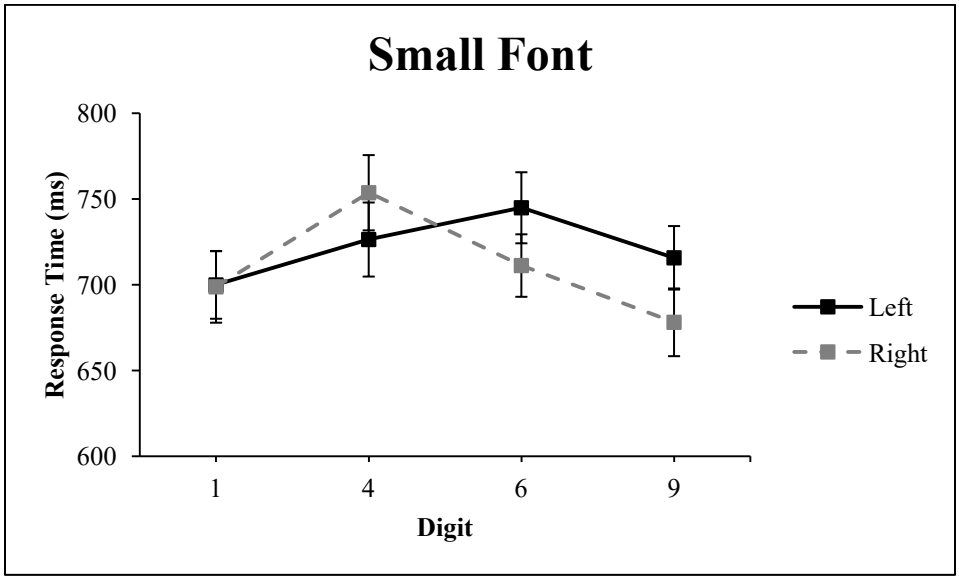
response key in the previous block became the "larger" response key in the current block, and vice versa (hence, ensuring that all stimuli were eventually responded to with each response key). Initial response mappings were counterbalanced across participants, such that half of participants began by responding with the "H" key if the number was smaller than 5 and with the "K" key if the number was larger than 5, whereas the remaining half of participants began by responding with the "K" key if the number was smaller than 5 and the "H" key if the number was larger than 5. The researcher observed participants during their first few practice trials to ensure that participants understood the task demands and response mappings.

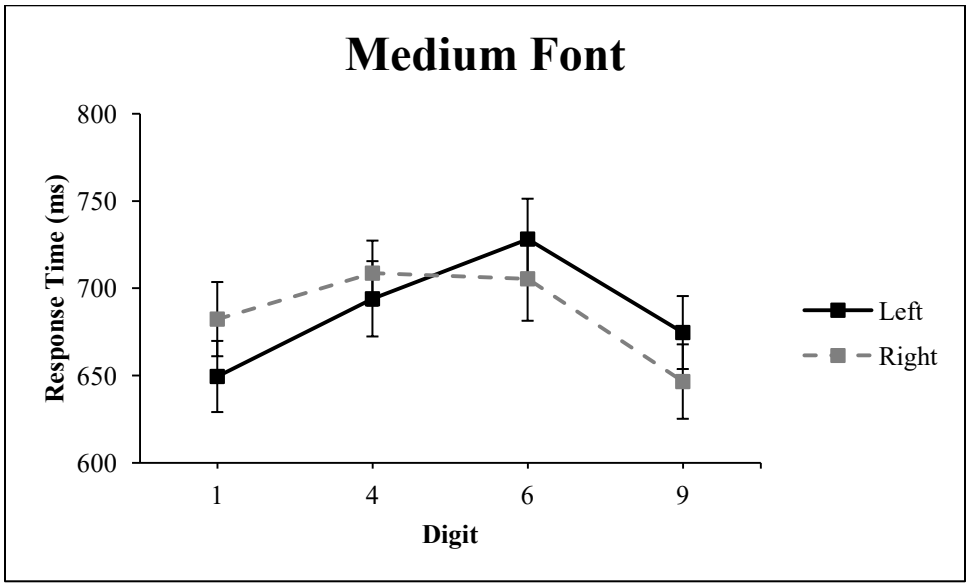
Results

Of the 30 participants in this experiment, 1 was excluded from further analysis due to a high error rate (i.e., an error rate exceeding 10% of trials), leaving 13920 trials. Only correct trials were included in analyses. Trials with RTs greater than 3 SDs from participants' mean RTs were excluded from further analysis. In total, of 14400 trials conducted, 13200 were used for analysis.

A 2 (response location: left vs. right) by 3 (font size: small, control, and large) by 4 (digit: 1, 4, 6, and 9) repeated-measures ANOVA was conducted on participants' mean RTs. Significant main effects of digit, $F(3, 84) = 23.400$, $p < .001$, $\eta_p^2 = .455$, and font size, $F(2, 56) = 37.348$, $p < .001$, $\eta_p^2 = .572$ were observed, indicating that participants responded slower to numbers closer to the standard and slower to smaller font sizes, respectively. Additionally, an interaction between digit (1, 4, 6, and 9) and response location (left and right), $F(3, 84) = 6.438$, $p < .01$ (Greenhouse-Geisser corrected), $\eta_p^2 = .187$, indicated the presence of a SNARC effect. All other

main effects and interactions failed to achieve significance (all *F*'s < 1.79). The results are depicted below in Figure 1.





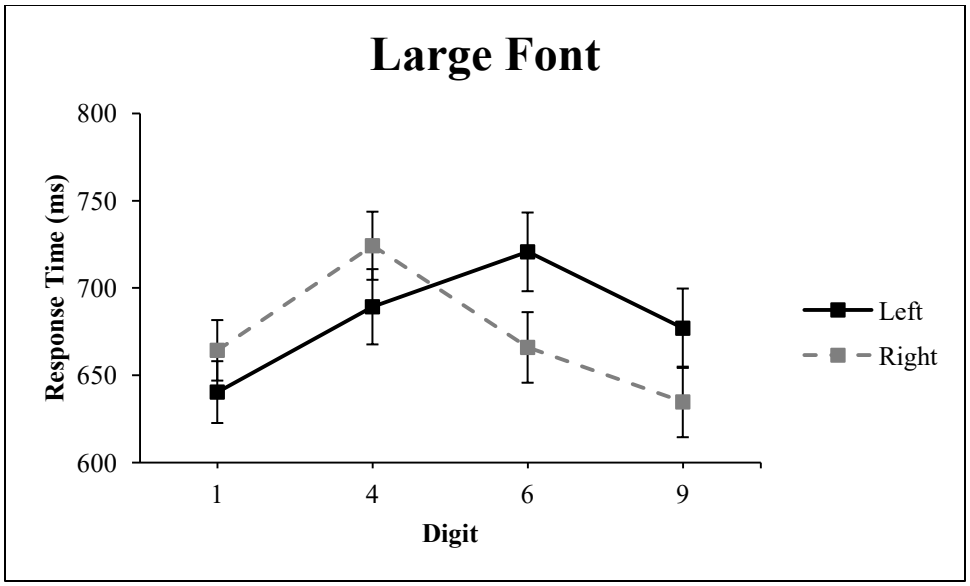


Figure 1. Mean response times for single digits. The solid black line represents left-side responses. The grey dashed line represents right-side responses. Each graph represents response times for the font corresponding to the graph title. Error bars represent standard errors.

Discussion

Experiment 1 replicated previous research findings. Namely, the significant main effect of digit indicates the replication of the well-known numerical distance effect (Moyer & Landauer, 1967), while the significant interaction between digit and response location indicates the presence of a SNARC effect in the expected direction, such that participants responded faster to numerically smaller digits (i.e., 1 and 4) using the left key, whereas participants responded faster to numerically larger digits (i.e., 6 and 9) using the right key.

The main effect of font size in this experiment indicates that participants responded fastest to the large font size. Given that this relationship between font size and response times is a main effect however and, hence, it is not contributing significantly to an interaction with any of the other variables of interest, such a result suggests that the large font size may be more legible than the smaller font sizes. In turn, this increase in legibility may allow for faster response times as compared to numbers displayed in the smaller font sizes. Moreover, no significant relationship between font size and digit was observed, thus indicating a lack of SiCE present in the results. Such a result may be due in part to the increased legibility of the large font size, whereby all digits are responded to significantly faster when displayed in the large font compared to digits displayed in the control and small fonts and thus mitigating the interaction effect of font size and digit that might otherwise have been present.

Of primary interest to the current experiment was the hypothesized three-way interaction between response location, font size, and digit. If numerical-size and spatial-numerical associations arise from the same, singular process for integrating magnitude and spatial information (e.g., Gevers et al., 2006; Proctor & Cho, 2006), then interactions between response location and digit (i.e., a SNARC effect; Dehaene et al., 1993), font size and digit (i.e., a SiCE; Henik & Tzelgov, 1981), and response location, font size, and digit should all be observed. Conversely, if numerical-size and spatial-numerical associations arise from separate processes occurring in parallel (as in Wiemers et al., 2017) such that the magnitude dimensions (i.e., the numerical magnitude information derived from the digit value and the size magnitude information derived from the font size at which the digit is displayed) are not integrated into a singular representation, then the aforementioned interactions indicative of SiCE and SNARC effects should be observed, whereas the aforementioned three-way interaction should not

emerge. As noted previously, the interaction between font size, response location, and digit did not achieve significance, suggesting that spatial-numerical and numerical-size associations are due to the workings of separate processes in the context of a typical SNARC paradigm. However, the lack of an interaction between font size and digit indicated that the conditions required to elicit a SiCE were not met, hence, rendering the presence of a three-way interaction unlikely for this reason.

Experiment 2

Participants

Participants consisted of 30 self-reported right-handed individuals (16 females, *M* = 19.80 years, *SD* = 3.00) with normal or corrected-to-normal vision recruited from Carleton University's undergraduate student research pool. Participants received partial course credit as compensation for their participation.

Method

The stimuli, software, and hardware used were identical to that of Experiment 1.

Procedure

The procedure used in Experiment 2 is nearly identical to that of Experiment 1, and was conducted simultaneously to Experiment 1. However, rather than respond using a horizontal response key arrangement (e.g., responses using the "H" and "K" key as in Experiment 1), participants responded to stimuli using a vertical response key arrangement with the "U" and "N" keys, which are located immediately above and below the middle key respectively.

Results

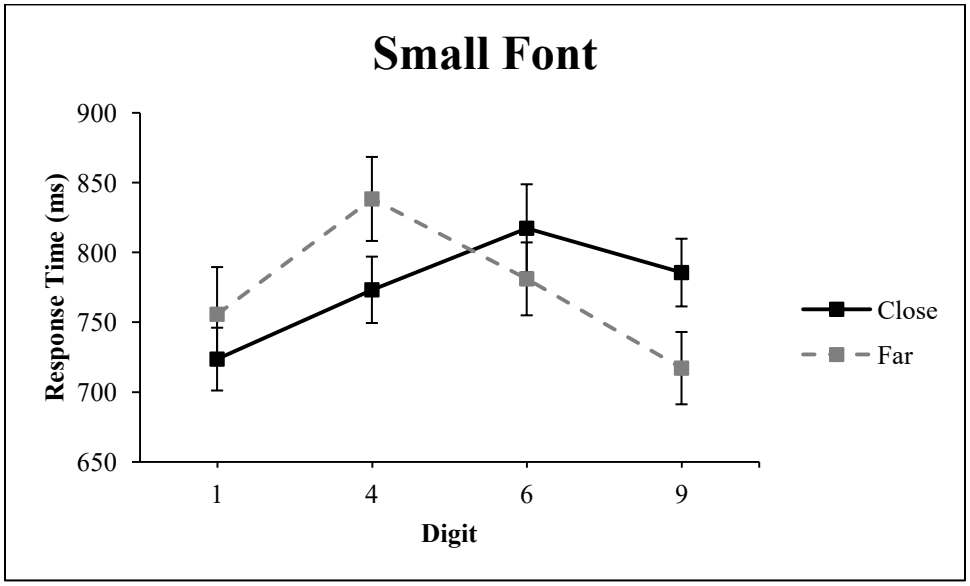
Of the 30 participants in this experiment, 4 were excluded from further analysis due to high error rates (i.e., error rates exceeding 10% of trials), leaving 12480 trials. Only correct trials were included in analyses. Trials with RTs greater than 3 SDs from participants' mean RTs were excluded from further analysis. In total, of 12480 remaining trials, 12060 were retained for analysis.

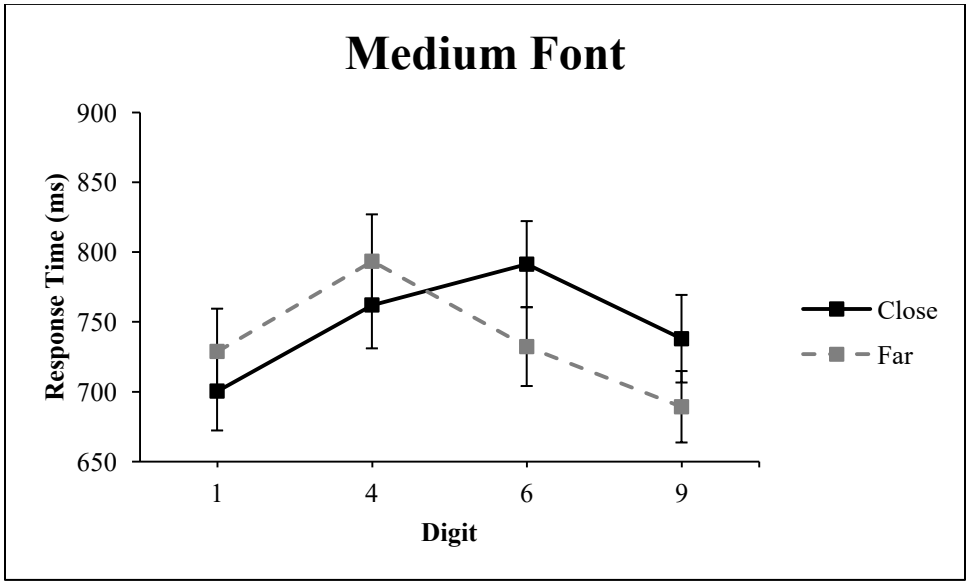
Similarly to Experiment 1, a significant main effects of digit was observed, $F(3, 75) = 24.593$, $p < .001$, $\eta_p^2 = .496$, indicating that participants responded faster to digits farther from the standard (i.e., 1 and 9) than to digits closer to the standard (i.e., 4 and 6). A significant main effect of font size, $F(2, 50) = 18.368$, $p < .001$, $\eta_p^2 = .424$, was also observed, indicating that participants responded faster to digits displayed in the largest font compared to digits displayed in the smallest font. An interaction occurred between digit (1, 4, 6, and 9) and response location (bottom vs. top), $F(3, 75) = 10.512$, $p < .001$ (Greenhouse-Geisser corrected), $\eta_p^2 = .296$, indicating the presence of a vertical SNARC effect. All other main effects and interactions failed to achieve significance (all F's < 0.84). The results are depicted below in Figure 2.

Discussion

As in Experiment 1, the current experiment produced an interaction between digit and response location indicative of a SNARC effect (Dehaene et al., 1993), where numerically smaller digits received faster bottom key responses, whereas numerically larger numbers received faster top key responses (where bottom and top keys could also be regarded proximo-distally as close and far keys, respectively). Whereas Experiment 1 adopted a more typical horizontal response arrangement in the SNARC paradigm using left-side and right-side keys, the present experiment adopted a vertical response arrangement using keys located above and below

a middle key. However, notably absent again in this experiment were relationships between digit and font size (i.e., a SiCE; Henik & Tzelgov, 1981) and the hypothesized relationship between font size, response location, and digit, as was also not observed in Experiment 1.





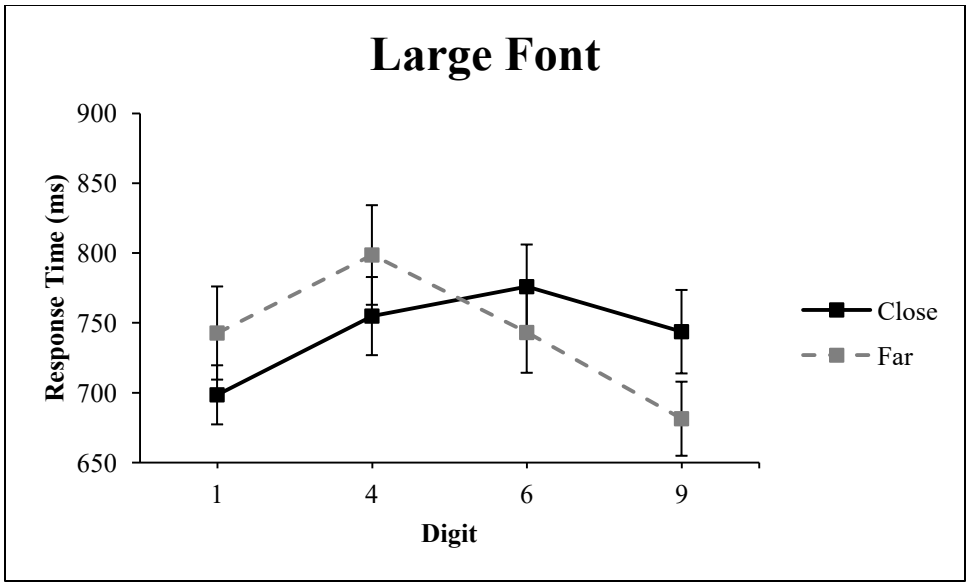


Fig. 2. Mean response times for single digits. The solid black line represents bottom/close responses. The grey dashed line represents top/far responses. Each graph represents response times for the font corresponding to the graph title. Error bars represent standard errors.

Such a result suggests that, as in Experiment 1, the size transformations used alone, with no other stimuli on screen to act as a reference (as when comparing two differently sized digits), are insufficient for eliciting a SiCE. Moreover, the lack of the hypothesized three-way interaction suggests that size transformations have no effect on the relationship between response location and digit and, thus, do not affect the strength of the SNARC effect in this context. If participants were codifying and using physical and numerical magnitude information in a similar manner, then congruity among the different aspects of a given stimulus (e.g., a numerically small number displayed in a small font) should produce faster response times than incongruity among these aspects, according to intermediate coding models such as that of Proctor and Cho (2006). Thus far, the obtained results suggest that a relationship between font size and digit, let alone a

relationship where response location is included as an additional factor, does not emerge under the conditions of the typical SNARC paradigm. However, it should be noted that both the current experiment and Experiment 1 provided participants with instructions that were concerned exclusively with numerical magnitude judgments; participants were instructed to judge presented digits as being either larger than or smaller than the standard, while no mention was made of the font size transformations that would occur during the experiment. Thus, it may be the case that in the absence of a standard by which to compare physical size and of instructions pertaining to physical size, this information was not considered to be task-relevant according to intermediate coding accounts of the SNARC effect (Gevers et al., 2006) and, thus, was not codified and integrated into a singular representation for later use during decision-making. Regardless, as in Experiment 1, the results of the current experiment suggest separate representations for spatial-numerical and numerical-size associations as in Wiemers et al. (2017), rather than similar processing strategies exemplified through either analog encoding strategies (i.e., Walsh, 2003) or intermediate coding accounts (e.g., Gevers et al., 2006).

Experiment 3

Both Experiments 1 and 2 demonstrated clear evidence of SNARC effects in both horizontal and vertical response arrangements (as evidenced by significant interactions between digit and response location in both experiments), while simultaneously exhibiting a lack of either two-way interaction between digit and font size (i.e., a SiCE) or a three-way interaction. In order to evaluate the possible influence of task and instructions on response times, a mixed design was adopted wherein participants were randomly assigned to one of two instruction conditions. The first condition provided participants with instructions identical to that of Experiments 1 and 2, and thus engaged participants in a numerical magnitude judgment task. The second condition

provided participants with instructions to evaluate the relative physical size of the number, such that participants responded to small-sized numbers with one key and to large-sized numbers with another key.

Participants

Participants consisted of 80 self-reported right-handed individuals (45 female, *M* = 19.18 years, *SD* = 1.93) with normal or corrected-to normal vision recruited from Carleton University's undergraduate student research pool. Participants received partial course credit as compensation for their participation in this research.

Method

The experiment was conducted using SuperLab Pro v2.0 on a computer running Microsoft Windows XP. All stimuli were presented to participants seated approximately 50 cm away in a dimly lit room. Participants engaged in a magnitude judgment task or size judgment task and responded to the stimuli 1, 4, 6, and 9 using one of two keys. All stimuli were presented in an Arial font but now in only one of two possible sizes: the "small" font, displayed at size 16 (0.23˚ x 0.40˚) and the "large" font, displayed at size 36 (0.63˚ x 1.03˚). The experiment consisted of 4 blocks of 136 trials each. The first 16 trials of each block were practice trials, but were not differentiated as such to the participants. Each digit stimulus was displayed 15 times in each font size during experimental trials and twice each during practice trials.

Procedure

The experiment was conducted in one session lasting approximately 40 minutes. Participants were randomly assigned to one of two task conditions. At the beginning of the

experiment, participants were shown a short paragraph describing the upcoming task. For one half of participants, this paragraph described the numerical magnitude judgment task, in which participants would judge the presented numbers as being larger than or smaller than the reference number, 5. For the remaining half, this paragraph described the size judgment task, in which participants would judge the presented numbers as being displayed in either the small font or the large font. Examples of the font sizes using the digit "9" were provided at the bottom of the paragraph. At the beginning of each block, participants were presented with a set of instructions describing the response mapping. Participants were randomly assigned to one of two response mapping conditions, such that half of participants responded using a horizontal response mapping (as in Experiment 1), whereas the remaining half of participants responded using a vertical response mapping (as in Experiment 2).

Participants commenced each trial by pressing the middle ("J") key on a QWERTY keyboard with their right index fingers. After pressing the middle key, a "+" sign (the fixation point) subtending 0.69˚ x 0.69˚ of participants' visual fields, appeared in the center of the screen for 1000 ms and was immediately replaced by a random number. Participants responded to this random number by pressing keys to the immediate left or immediate right of the middle key (i.e., the "H" and "K" keys) with their right index finger if assigned to the horizontal mapping, or by pressing keys immediately above or below the middle key (i.e., the "U" and "N" keys) with their right index finger if assigned to the vertical mapping. After each response, or if no response was provided after 3000 ms, the screen turned blank, indicating that participants were able to initiate the next trial. Response mappings alternated between blocks for each participant, such that the "smaller" response key in the previous block became the "larger" response key in the current block, and vice versa. Initial response mappings were counterbalanced across participants, such

that half of participants began by responding with the "H" ("N") key if the number was smaller than 5 (or displayed in a small font) and with the "K" ("U") key if the number was larger than 5 (or displayed in a large font), whereas the remaining half of participants began by responding with the "K" ("U") key if the number was smaller than 5 (or displayed in a small font) and the "H" ("N") key if the number was larger than 5 (or displayed in a large font). The researcher observed participants during their first few practice trials to ensure that participants understood the task demands and response mappings.

Results

Of the 80 participants in this experiment, 5 were excluded from further analysis due to high error rates (i.e., error rates exceeding 10% of trials), resulting in the removal of 2400 trials. Only correct trials were included in analyses. Trials with RTs greater than 3 SDs from participants' mean RTs and anticipatory responses (i.e., correct trials with RTs of less than 200 ms) were excluded from further analysis. In total, of 38400 conducted trials, 8.6 % were removed, leaving 35099 trials.

To examine the effects of the factors on mean RTs, a 2 (task: numerical judgment vs. physical size judgment) by 2 (response orientation: horizontal vs. vertical) by 2 (response location: bottom vs. top for the vertical response orientation, and left vs. right for the horizontal response orientation) by 2 (font size: small font vs. large font) by 4 (digit: 1, 4, 6, and 9) mixed-design ANOVA was conducted with both task and response orientation treated as between-participant factors. A significant main effect of digit was observed, $F(3, 210) = 35.16$, $p < .001$ (Greenhouse-Geisser corrected), $\eta_p^2 = .33$, indicating that participants responded faster to digits farther from the standard (i.e., 1 and 9) than to digits closer to the standard (i.e., 4 and 6). A

significant main effect of font size was also observed, $F(1, 70) = 50.94$, $p < .001$, $\eta_p^2 = .42$, indicating that participants responded faster to digits displayed in the large font than to digits displayed in the small font. Finally, a significant main effect of response orientation was observed, $F(1, 70) = 10.59$, $p < .01$, $\eta_p^2 = .13$, indicating that participants responded to digits faster when using a horizontal response orientation compared to a vertical orientation. The effect of task was marginally significant, $F(1, 70) = 3.86$, $p = .054$, indicating that participants tended toward responding faster to the digits when engaged in the physical magnitude judgment task as compared to the numerical magnitude judgment task.

An interaction between response location and digit was observed, indicating that participants responded faster to digits in a SNARC-compatible response layout (i.e., smaller digits were responded to quicker using the bottom or left key, and larger digits were responded to quicker using the top or right key), $F(3, 210) = 7.06$, $p < .01$ (Greenhouse-Geisser corrected), $\eta_p^2 = .09$, indicating the presence of a SNARC effect (Dehaene et al., 1993). Moreover, this interaction was not qualified by an interaction involving response orientation, indicating that this relationship was observed in both the horizontal and vertical response orientations. Moreover, this interaction was not qualified by an interaction involving task, which indicates that the SNARC effect was observed regardless of the relevance of number magnitude. A further interaction was observed between digit and task, $F(3, 210) = 47.86$, $p < .001$, $\eta_p^2 = .41$, indicating that participants demonstrated a numerical distance effect (Moyer & Landauer, 1967) in the numerical magnitude judgment task, where digits closer to the standard (i.e., 4 and 6) were responded to slower than digits farther from the standard (i.e., 1 and 9), but responded comparably to all digits in the physical magnitude judgment task. A further interaction was observed between digit and response orientation, $F(3, 210) = 2.87$, $p < .05$, $\eta_p^2 = .04$, indicating

that participants who responded using the vertical response orientation demonstrated a weaker numerical distance effect compared to those who responded using the horizontal response orientation. Additionally, an interaction between font size and task was found to be significant, $F(1, 70) = 10.83$, $p < .01$, $\eta_p^2 = .13$, indicating that the effect of font size was smaller in the physical magnitude judgment task compared to the numerical magnitude judgment task. Importantly, an interaction between font size and digit (i.e., a SiCE) was now present, $F(3, 210) = 30.60$, $p < .001$, $\eta_p^2 = .30$. However, this interaction was further qualified by a three-way interaction between font size, digit, and task, $F(3, 210) = 9.73$, $p < .001$, $\eta_p^2 = .12$ (see Figure 3). For participants engaged in the physical magnitude judgment task, a simple interaction between font size and digit was observed (i.e., a SiCE), whereas no such relationship was observed for participants engaged in the numerical magnitude judgment task. Finally, a significant interaction between response orientation, response location, font size, and digit was observed, $F(3, 210) = 2.69$, $p < .05$, $\eta_p^2 = .04$, as well as a significant interaction between task, response orientation, font size, and digit, $F(3, 210) = 3.30$, $p < .05$, $\eta_p^2 = .05$. All other main effects and interactions failed to achieve significance (all F's < 3.19).

Discussion

In Experiment 3, participants were assigned to one of two task conditions, wherein participants were instructed to make either numerical magnitude judgments (i.e., to judge whether the presented digit was smaller than or larger than the standard) or physical magnitude judgments (i.e., to judge whether the presented digit was displayed in the small font or the large font). The purpose of Experiment 3 was to evaluate the effect of task instruction on the relationships between font size, response location, and digit.

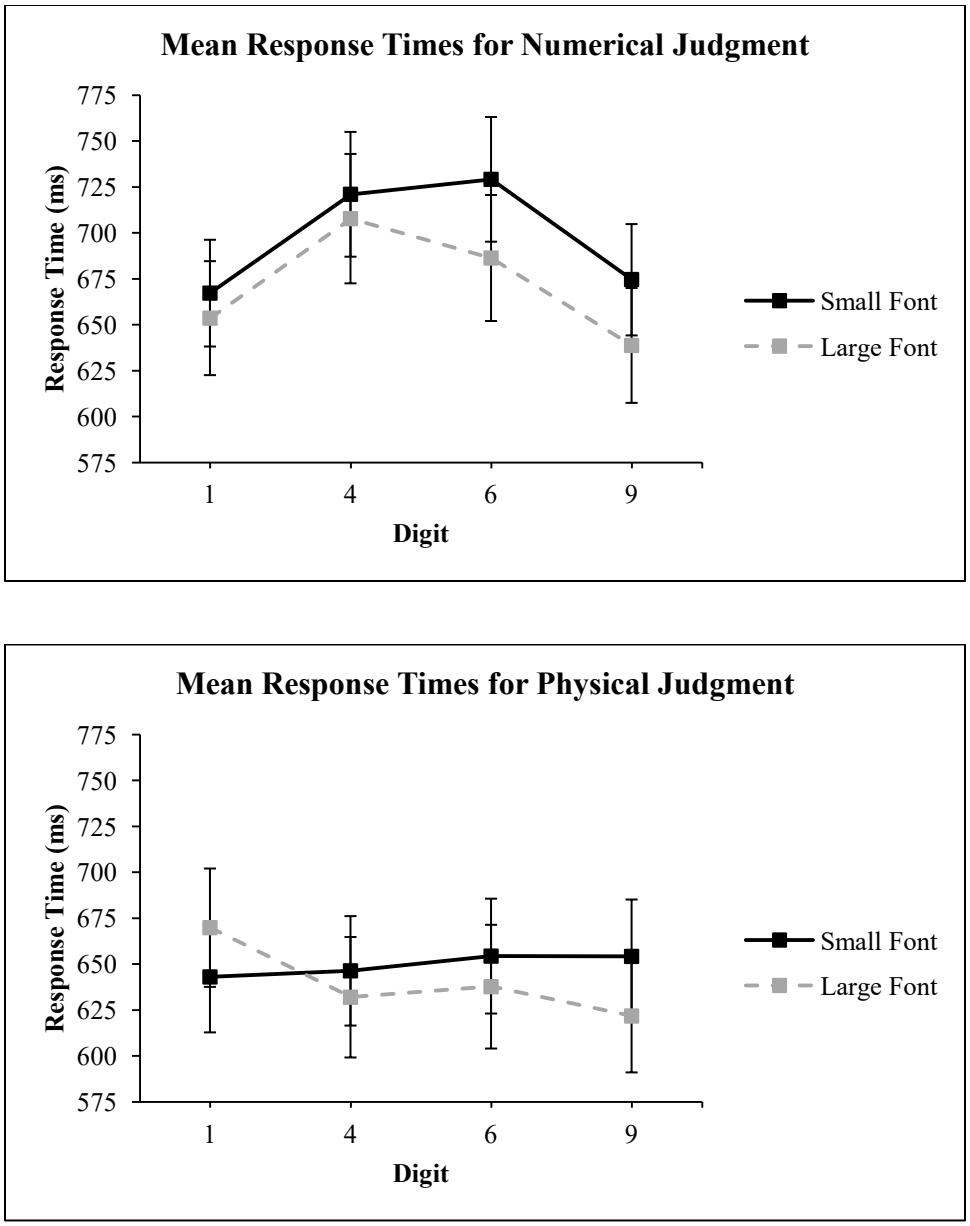


Fig. 3. Mean response times for small-font and large-font digits in the numerical magnitude and physical magnitude judgment tasks. The black lines represent small-font digits. The grey lines represent large-font digits. Error bars are standard errors.

As was observed in Experiments 1 and 2, a relationship between digit and response location was observed. In the case of the horizontal response arrangement, participants tended to respond to numerically smaller numbers faster using left-side responses and to numerically larger numbers faster using right-side responses (i.e., a horizontal SNARC effect). Similarly, participants assigned to the vertical response arrangement responded faster to numerically smaller numbers with the bottom key and to numerically larger numbers with the top key.

Unlike Experiments 1 and 2, participants in Experiment 3 demonstrated an interaction between font size and digit indicative of a SiCE (Henik & Tzelgov, 1982). This relationship was further qualified by an interaction between font size, digit, and task, such that participants demonstrated a simple interaction between font size and digit only when engaged in the physical magnitude judgment task. However, as in the previous two experiments, the lack of significant three-way interaction between digit, font size, and response location suggests the use of separate, parallel processes for physical and numerical magnitude information respectively, rather than a single process. Such processes are similar to what would be expected according to predictions derived from Wiemers et al. (2017)'s study, but do not correspond with what would be predicted according to intermediate coding accounts of the SNARC effect (Gevers et al., 2006; Proctor & Cho, 2006).

Experiment 4

All of the previous experiments in the present study demonstrated clear relationships indicative of SNARC effects. Of particular importance are the results obtained in Experiment 3, where interactions between font size and digit and between font size, digit, and experimental task were observed, indicating the presence of a SiCE. The purpose of Experiment 4 is to further

examine the role of task instructions on the relationships of interest. This will be accomplished through the addition of a visualization exercise at the beginning of the experiment designed to cue participants to perceive the changes in font size on the computer screen as changes in distance. The effect of this visualization exercise will be further augmented through the use of angled lines similar to those employed by Murray, Boyaci, and Kersten (2006), such that participants will be induced to perceive digits displayed in the small font as being located farther away in space than digits displayed in the large font.

Participants

Participants consisted of 60 self-reported right-handed individuals (47 females, *M* = 20.58 years, *SD* = 3.95) with normal or corrected-to-normal vision recruited from Carleton University's undergraduate research participant pool. Participants received partial course credit as compensation for their participation.

Method

The method employed in this experiment is similar to that of Experiment 3. The experiment was conducted using SuperLab Pro v2.0 on a computer running Microsoft Windows XP. All stimuli were presented to participants seated approximately 50 cm away in a dimly lit room. Participants engaged in a magnitude judgment task or size judgment task and responded to the stimuli 1, 4, 6, and 9 using one of two keys. All stimuli were presented in an Arial font in one of two possible sizes: the "small" font, displayed at size 16 (0.23˚ x 0.40˚) and the "large" font, displayed at size 36 (0.63˚ x 1.03˚). The experiment consisted of 4 blocks of 136 trials each. The first 16 trials of each block were practice trials, but were not differentiated as such to the participants. Each digit stimulus was displayed 15 times in each font size during experimental

trials and twice each during practice trials. A pair of converging lines, designed to act as distance cues, were presented simultaneously with the random digit during each trial. The lines were positioned such that the random digit was displayed centrally between the endpoints of the lines. For trials in which the digit was displayed in a large font, the lines were positioned such that the point of convergence appeared above the digit, cueing the participant to perceive the digit as relatively close. For trials in which the digit was displayed in a small font, the lines were positioned such that the point of convergence was much closer to the digit, cueing the participant to perceive the digit as being relatively far away. Examples of the line arrangement during trials are depicted in Figure 4.

Procedure

The experiment was conducted in one session lasting approximately 40 minutes. As in Experiment 3, participants were randomly assigned to one of two task conditions: the size judgment condition, in which participants judged the presented digits as being displayed in either a small font or large font, and the magnitude judgment condition, in which participants judged the numerical magnitude of the presented digits as being either larger than or smaller than the standard, 5. Additionally, participants were further divided by random assignment to one of two visualization conditions. In the first condition, participants were instructed to imagine a line of street cones in front of themselves. These street cones were numbered 1 through 9 and arranged such that the "1" street cone was located in front of the participant, followed by the "2" street cone. through to the "9" street cone. After reading the visualization instructions, participants were instructed to close their eyes and imagine the described sequence for 1 minute, which was tracked by the experimenter. A copy of these instructions is provided in Appendix A. The second condition provided no visualization instructions to participants and thus acted as the control

condition. Participants all responded with vertically aligned response keys in this final experiment.

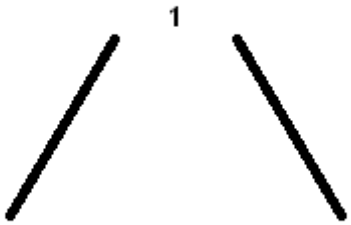


Fig. 4. An example line arrangement in Experiment 4. Digits were displayed in the center of the screen, while the converging lines were offset in order to be placed below (as in the figure) or above the digit for small (as in the figure) and large-sized digits respectively.

Participants commenced each trial by pressing the middle ("J") key on a QWERTY keyboard with their right index fingers. After pressing the middle key, a "+" sign (the fixation point) subtending 0.69˚ x 0.69˚ of participants' visual fields, appeared in the center of the screen for 1000 ms and was immediately replaced by a random number between two converging lines. Participants responded to this random number as being either larger than or smaller than 5 (or as being in either a small font or large font) by pressing keys immediately above or below the middle key (i.e., the "U" and "N" keys) with their right index finger. After each response, or if no response was provided after 3000 ms, the screen turned blank, indicating that participants were able to initiate the next trial. Response mappings alternated between blocks for each participant,

such that the "smaller" response key in the previous block became the "larger" response key in the current block, and vice versa. Initial response mappings were counterbalanced across participants, such that half of participants began by responding with the "N" key if the number was smaller than 5 (or displayed in a small font) and with the "U" key if the number was larger than 5 (or displayed in a large font), whereas the remaining half of participants began by responding with the "U" key if the number was smaller than 5 (or displayed in a small font) and the "N" key if the number was larger than 5 (or displayed in a large font). The researcher observed participants during their first few practice trials to ensure that participants understood the task demands and response mappings.

Results

Data in the form of mean RTs for each participant were analyzed using a 2 (task: numerical magnitude judgment vs. physical magnitude judgment) by 2 (priming paragraph: present vs. absent) by 2 (font size: small vs. large) by 2 (response location: bottom/close vs. top/far) by 4 (digit magnitude: 1, 4, 6, and 9) mixed-design ANOVA, where task and priming paragraph were treated as between-participants factors. Participants who achieved less than 90% accuracy were excluded from analyses, thus resulting in the removal of 9 participants and 4320 trials. Only correct trials were included in analyses. Anticipatory responses (i.e., correct responses on trials where the RT was less than 200 ms) and outliers (i.e., trials where RTs exceeded 3 SDs from participants' mean RTs) were excluded from analyses. In total, of the 24480 remaining trials, 23694 were retained for analysis.

A significant main effect of font size was observed, $F(1, 47) = 32.57$, $p < .001$, $\eta_p^2 = .41$, indicating that participants responded faster to digits displayed in a large font compared to digits

displayed in a small font. Furthermore, a significant main effect of digit was observed, $F(3, 141) = 21.85$, $p < .001$ (Greenhouse-Geisser corrected), $\eta_p^2 = .32$, indicating that participants tended to respond faster to numerically larger digits than numerically smaller digits. A significant main effect of task was observed, $F(1, 47) = 7.90$, $p < .01$, $\eta_p^2 = .14$, indicating that participants responded faster to stimuli when making judgments regarding the physical size of the stimuli, rather than numerical magnitude. Finally, it should be noted that the effect of priming paragraph trended toward significance, $F(1, 47) = 3.45$, $p = .069$, such that participants in the priming paragraph condition tended to exhibit slower responses compared participants who were not exposed to the priming paragraph.

The observed significant interaction between response location and digit indicates that numerically smaller digits were responded to faster with bottom/close responses, whereas numerically larger digits were responded to faster with top/far responses, $F(3, 141) = 3.78$, $p < .05$ (Greenhouse-Geisser corrected), $\eta_p^2 = .07$. Furthermore, an interaction was observed between digit and task, $F(3, 141) = 51.54$, $p < .001$, $\eta_p^2 = .52$, indicating that participants demonstrated a pattern of results consistent with the numerical distance effect (Moyer & Landauer, 1967) when engaged in the numerical magnitude judgment task, where numbers closer to the standard (i.e., 4 and 6) tended to receive slower responses as compared to numbers farther from the standard (i.e., 1 and 9). In contrast, participants responded comparably to all digits when engaged in the physical judgment task.

An additional interaction between font and digit, $F(3, 141) = 9.45$, $p < .001$, $\eta_p^2 = .17$, indicates that participants responded faster to numerically larger digits when such digits were displayed in the large font, and to numerically smaller digits when such digits were displayed in the small font (i.e., the SiCE). Finally, an interaction between font, digit, and task was observed,

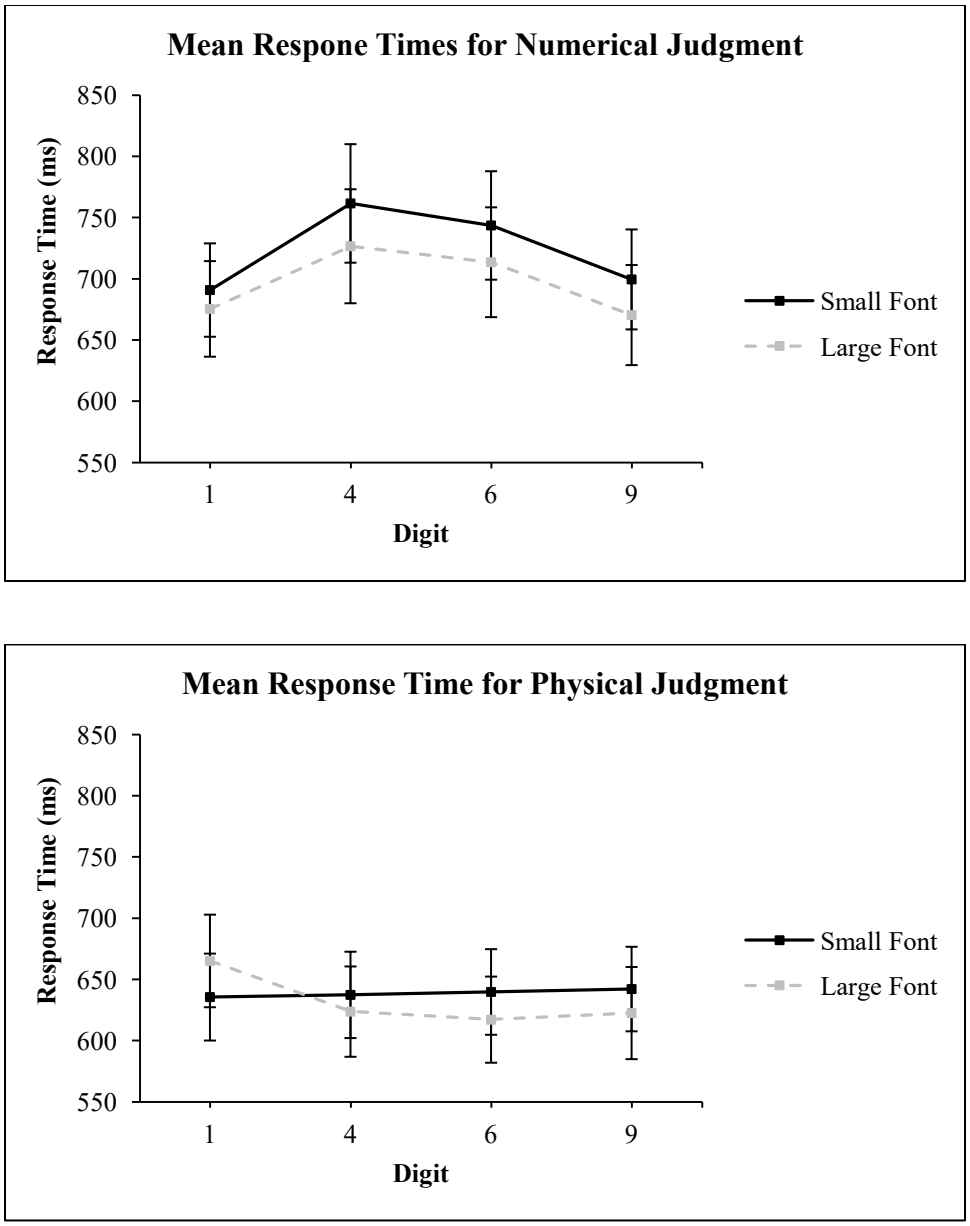


Fig. 5. Mean response times for small-font and large-font digits in the numerical magnitude and physical magnitude judgment tasks. The black lines represent small-font digits. The grey lines represent large-font digits. Error bars are standard errors.

$F(3, 141) = 3.10$, $p < .05$, $\eta_p^2 = .06$, indicating that when engaged in the physical magnitude judgment task, a simple interaction between font size and digit was observed trending toward significance, whereas no significant simple interaction was observed in the numerical magnitude judgment task. These results are depicted in Figure 5. No other main effects or interactions were significant (all F's < 3.00).

Discussion

The purpose of Experiment 4 was to manipulate participants' perceptions of the size transformations occurring on-screen during the experiment, such that for participants exposed to the priming cue at the beginning of the experiment, the changes in font size would be perceived as changes in distance. Thus, these participants would perceive numbers displayed in the small font as being farther away than numbers displayed in the large font, which should in turn affect direction of all two-and three-way interactions involving font size.

While the present experiment successfully replicated both standard size congruity and SNARC effects, a lack of three-way interaction between response location, font size, and digit was observed, as well as a lack of interaction between font size and response location. As noted previously, converging lines similar to that of Murray et al. (2006) were employed to facilitate a distance-based perception of size transformations, regardless of task, during the experiment. While font size significantly affected response times as both a main effect and via an interaction with digit, the lack of interaction between response location, font size, and digit suggests that, as observed in Wiemers et al. (2017), spatial-numerical and size-numerical congruity effects are represented by separate processes and do not interact to produce an effect as might be expected for stimuli that are maximally congruent.

Moreover, neither interactions involving priming nor a main effect of priming itself were present, indicating that cueing participants to perceive the size transformations on screen as distance transformations did not significantly affect performance. However, given that the effect of priming was marginally significant, such that participants were slower to respond when presented with the priming paragraph, and that previous research has demonstrated significant effects of priming on the relationship between digit and response location using similar language (Mourad & Leth-Steensen, 2017), the present result may be due to the presence of converging lines in all conditions. Despite the known influence of contextual priming on the SNARC effect, the perception of font size appeared to be largely unaffected in the present experiment. The presence of these lines may have mitigated the effect of priming by affecting performance in the non-priming condition, where participants may have perceived the size transformations as distance transformations despite the lack of priming directing them to do so. Given the marginally significant effect of cue observed in this experiment, such a pattern may also be due to collapsing mean RTs across cue and non-cue conditions. As noted previously, the effect of cue on response times was marginally significant, such that participants who received the priming paragraph exhibited a tendency toward slower responses as compared to participants who did not receive the priming paragraph. Such an observation suggests the possibility of increased difficulty in processing information as a result of maintaining the instructed visualization in memory, which may in turn influence the magnitude and direction of any font size effects in such a way so as to produce the observed results.

General Discussion

The goal of the present study was to investigate the co-occurrence of spatial-numerical and numerical-size associations in the context of a single-digit judgment task typical to the

SNARC paradigm. While both size congruity and SNARC effects have been the subjects of intense investigation, little previous research exists that investigates the relationships that give rise to both SNARC and size congruity effects in a single experimental task. In the context of the single-digit comparison tasks employed in this study, there are two competing predictions. One prediction of interest is that of Gevers et al. (2006)'s intermediate coding model of the SNARC effect, which predicts that font size should be intermediately coded in the same way as numerical magnitude affecting numerical magnitude processing (i.e., the SiCE) but also moderating the strength of its relation to the spatial response locations (i.e., a three-way interaction between response location, font size, and digit). The other prediction is derived from Wiemers et al. (2017)'s study, which asserts that different aspects of physical and numerical magnitude information are encoded separately using parallel processes with only the cardinal aspect of numerical magnitude interacting with physical magnitude. Thus, one would expect to observe separate two-way interactions between response location and digit and between font size and digit (indicative of a SNARC effect and SiCE respectively), but not a three-way interaction between response location, font size, and digit.

Across all four experiments in the present study, significant relationships between digit magnitude and response location were observed, thus clearly demonstrating SNARC effects (Dehaene et al., 1993) across changes in response orientation. Importantly, despite the novel and extensive manipulations of font size throughout, associations consistent with SNARC effects in expected directions were observed, suggesting that the relationship between digit and response location is a robust one when compared to the relationships that involve font size.

In contrast, relationships between font size and digit that would indicate the presence of SiCEs were only observed in a select number of experiments in the present study. Namely, a

SiCE was observed in both Experiments 3 and 4, which were the only experiments to include a physical judgment task. Not surprisingly, the lack of significant SiCEs in Experiments 1 and 2 contributed to a lack of significant three-way interactions between font size, response location, and digit that would indicate processing strategies predicted by intermediate coding accounts of the SNARC effect (e.g., Gevers et al., 2006; Proctor & Cho, 2006). Were results in support of intermediate coding accounts of the SNARC effect to occur, one should expect to observe the aforementioned three-way interaction wherein maximum correspondence among stimulus dimensions and response location (e.g., in the case of Proctor & Cho, 2006, a trial where digit magnitude, font size, and response location all receive the same '-' or '+' code) tends to produce the fastest RTs. By extension, different combinations of stimulus dimension coding should produce RTs that generally correspond to the degree of correspondence between those dimensional codes and the response location code for the given trial. However, the results of the present study tend to support the account asserted by Wiemers et al. (2017), where the spatial-numerical and size-numerical relationships that give rise to SiCE and SNARC effects are the result of separate processes rather than to a singular collection of information used to inform decision-making at the time of response. This pattern of results is evident in both Wiemers et al. (2017)'s study and the present study, where the separate relationships indicative of SiCE and SNARC effects, but not the three-way interaction predicted by intermediate coding accounts, emerged.

Furthermore, the pattern of results obtained in the present study suggests that only the physical magnitude information relevant to the current task informs decision-making processes with regards to responses. In the present study, the experiments herein employed a largely typical SNARC paradigm, with notable changes being made to the size of presented digits, and in later

experiments, the task instructions provided to participants (i.e., the physical magnitude judgment task). For three of the four experiments, the only items displayed at stimulus onset were the stimuli themselves (i.e., the random single digits). Thus, in the numerical magnitude judgment task, the physical magnitude information is not only task-irrelevant, but lacks additional stimuli on screen that may otherwise help to provide cardinal reference with regards to the digit stimulus' physical size. However, as observed in Experiment 3, the relationship between task, font size, and digit suggests that the different forms of magnitude information may still experience some level of integration when physical magnitude is the relevant aspect. Importantly, while all experiments exhibited a main effect of font size (where digits displayed in a larger font received faster responses than digits displayed in a smaller font), font size was not a factor in any significant interaction (with the exceptions of the interaction between digit and font size that was qualified by the interaction between font size, digit, and task, observed in Experiments 3 and 4). Such a result suggests that the effect of font size on RTs when it is irrelevant to the task might be largely due to a matter of legibility, where numbers displayed in a larger font are more legible under the experimental conditions used, and are thus responded to faster than numbers displayed in a smaller font.

In light of the relationships observed in the present study, the inability for intermediate coding accounts of the SNARC effect to account for the inconsistency between the results of the current study and the results predicted by these models suggests that certain limitations to these models may be present. Namely, such models assume that all dimensional aspects of a given stimulus are encoded and then integrated at the time of decision-making, the result of which facilitates or inhibits responses in the correct direction (determined by task instructions) which is in turn reflected by relatively faster or slower RTs. However, the lack of interactions between

font size and other relevant factors (i.e., digit magnitude and response location) when only the single digit is displayed during a trial suggests that these intermediate coding models rely upon a need for cardinality or ordinality to be explicitly established for each dimension of interest in order for the encoding of such dimensions to be reflected in decision-making. In the case of the numerical magnitude judgment tasks in Experiments 1, 2, and 3, no such cardinality was explicitly established; no reference was made to the size transformations that would occur during the presentation of task instructions, and no additional stimuli were presented concurrently with the random single digits to provide a reference by which to judge the size transformations. In contrast, tasks in which cardinality was explicitly established at the beginning of the task (i.e., in the instructions of the physical magnitude judgment task of Experiments 3 and 4) or reinforced throughout the task (i.e., through the use of converging lines in Experiment 4, which were of a fixed size) produced interactions between font size and digit. Moreover, both the numerical stimuli used in the experiments (i.e., the digits 1, 4, 6, and 9) and the response locations likely have an implicit ordinal representation which facilitates the interaction between these two stimuli without the need for establishing cardinality or ordinality during the presentation of task instructions. Therefore, the results herein suggest that magnitude representation, as described by intermediate coding accounts (i.e., Proctor & Cho, 2006; Gevers et al., 2006), assume that the dimensions of a given stimulus have an established cardinal or ordinal representation prior to the experimental task. When such representation is not established, the corresponding stimulus dimension is not encoded and does not go on to inform decision-making processes at the time of response.

Despite the present study's reinforcement of Wiemers et al. (2017)'s findings and observations indicating the need for established cardinality or ordinality in order to facilitate the

encoding of stimulus dimensions, one key limitation exists that should be addressed in future research. Namely, the present study investigated the co-occurrence of SNARC and size congruity effects using a single-digit judgment task adapted from the typical SNARC paradigm (Dehaene et al., 1993). Although the goal of this study was to investigate the co-occurrence of SNARC and size congruity effects in the context of a single experimental task, all experiments employed methodologies similar to the single-digit numerical magnitude judgment tasks employed in studies examining the SNARC effect, rather than adapting the methodology of a number comparison task typical to those studies investigating the SiCE (Henik & Tzelgov, 1982). Future research may wish to investigate the co-occurrence of SNARC and size congruity effects using a binary digit comparison methodology more similar to that of the SiCE paradigm in conjunction with a methodology similar to the traditional SNARC paradigm.

Conclusion

Research pertaining to both size congruity (Henik & Tzelgov, 1982) and SNARC (Dehaene et al., 1993) effects has led to large bodies of literature for both effects respectively. However, little research has been conducted previously to examine the co-occurrence of the relationships that give rise to these effects in a single experimental task, with Wiemers et al. (2017) being the notable exception at the time of writing. The present study sought to investigate the co-occurrence of these relationships in the context of the typical SNARC paradigm and compare the results obtained to those expected according to intermediate coding accounts of the SNARC effect (Proctor & Cho, 2006; Gevers et al., 2006) and those obtained by Wiemers et al. (2017). The results of the present study are similar to those Wiemers et al. (2017), and suggest that in order for a stimulus dimension to be encoded in order to inform decision-making, such a dimension must have an established cardinal or ordinal representation prior to encoding. Future

research may wish to explore the extent to which establishing cardinal or ordinal representation affects encoding and subsequent decision-making.

Appendix A

Experiment 4 Priming Text

During this experiment, we would like you to imagine a number sequence from 1 to 9 arranged in a line extending away from you. Imagine that these numbers are placed on street cones labeled "1" to "9" arranged in a straight line in front of you. The "1" street cone is closest to you, followed by the "2" street cone, and so on.

Please close your eyes and generate an image of this sequence, with the "1" street cone located closest to you and the "9" street cone located farthest from you. Try your best to maintain this image while you are performing this experiment. This text will disappear after one minute and will be followed by your first set of instructions.

Appendix B

Certification of Institutional Ethics Clearance

CERTIFICATION OF INSTITUTIONAL ETHICS CLEARANCE

The Carleton University Research Ethics Board-B (CUREB-B) has granted ethics clearance for the research project described below and research may now proceed. CUREB-B is constituted and operates in compliance with the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* (TCPS2).

Ethics Protocol Clearance ID: Project # 109514

Research Team: Craig Leth-Steensen (Primary Investigator)
James Vellan (Student Researcher)

Project Title: Size and Number Classification Study [James Vellan]

Funding Source (If applicable):

Effective: **September 27, 2018** Expires: **September 30, 2019**.

Please ensure the study clearance number is prominently placed in all recruitment and consent materials: CUREB-B Clearance # 109514.

Restrictions:

This certification is subject to the following conditions:

1. Clearance is granted only for the research and purposes described in the application.
2. Any modification to the approved research must be submitted to CUREB-B via a Change to Protocol Form. All changes must be cleared prior to the continuance of the research.
3. An Annual Status Report for the renewal of ethics clearance must be submitted and cleared by the renewal date listed above. Failure to submit the Annual Status Report will result in the closure of the file.If funding is associated, funds will be frozen.
4. A closure request must be sent to CUREB-B when the research is complete or terminated.
5. Should any participant suffer adversely from their participation in the project you are required to report the matter to CUREB-B.

Failure to conduct the research in accordance with the principles of the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans 2ndedition* and the *Carleton University Policies and Procedures for the Ethical Conduct of Research* may result in the suspension or termination of the research project.

Upon reasonable request, it is the policy of CUREB, for cleared protocols, to release the name of the PI, the title of the project, and the date of clearance and any renewal(s).

Please contact the Research Compliance Coordinators, at ethics@carleton.ca, if you have any questions.

CLEARED BY: **Date: September 27, 2018**

Bernadette Campbell, PhD, Chair, CUREB-B

Natasha Artemeva, PhD, Vice-Chair, CUREB-B

Appendix C

Informed Consent Protocol

Carleton UNIVERSITY
Canada's Capital University

Consent Form

Title: Size and Number Classification Study

Date of ethics clearance: 27/09/18

Ethics Clearance for the Collection of Data Expires: 30/09/19

I _____, choose to participate in a study on the cognitive processing of numbers. This study aims to examines how individual make decisions about the magnitudes of single digits. The researcher for this study is James Vellan in the Department of Psychology at Carleton University. He is working under the supervision of Dr. Craig Leth-Steensen a faculty member in the Department of Psychology at Carleton University.

Description of Study

In this experiment, you will be presented with single digits of varying sizes and will be asked to provide correct responses regarding the relative difference in numerical or physical magnitude (i.e., smaller or larger) of those digits. These responses will involve pressing one of two keys on the computer keyboard. At the end of each

block of trials, the keys used to respond will change positions with each other. You will be asked to indicate your age and gender.

Duration of Study

The experiment will take approximately 60 minutes to complete. You will be awarded 1% course credit through SONA for completing the experiment.

Risks and Discomfort

There are no potential risks associated with your participation in this experiment.

Anonymity

All data gathered in this experiment will be kept confidential through the use of a coded participant number. You will not be mentioned by name in any publication of the results of this study. The information you provide for this study will be used for research purposes only.

Data Storage

All data gathered from this study will be stored indefinitely on a lab computer. Only the researchers involved in this study will have access to the data. The researchers may use aggregate data in future presentations or publications. Anonymous, aggregate data may be provided to other researchers in the same area who request it.

Right to Withdraw

You have the right to end your participation in the study at any time, for any reason, including before, during, and after your participation in the study. If you wish to withdraw from the study after participating, you must contact the researcher within two days of your participation. If you withdraw from the study, all information you have provided will be immediately destroyed.

Study Results

If you would like a copy of the finished research project, you are invited to contact the researcher to request an electronic copy which will be provided to you.

The ethics protocol for this project was reviewed by the Carleton University Research Ethics Board, which provided clearance to carry out the research (clearance #109514). Should you have any ethical concerns with the study, please contact Dr. Bernadette Campbell, Chair, Carleton University Research Ethics Board-B (by phone: 613-520-2600 ext. 4085 or by email: ethics@carleton.ca). For all other questions about the study, please contact the researcher.

Researcher contact information:

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Supervisor contact information:

Dr. Craig Leth-Steensen

Department of Psychology

Carleton University

Tel: (613) 520-2600 ext. 2254

Email:

craig.lethsteensen@carleton.ca

_____ _____

Signature of participant Date

_____ _____

Signature of researcher Date

Appendix D

Debriefing Protocol

DEBRIEFING

What are we trying to learn in this research?

This research examines the relationship between number magnitude, physical size, and space. The first relationship of interest is the one between number magnitude and space which is called the Spatial Numerical Association of Response Codes (SNARC) effect. The second relationship of interest the one between number magnitude and physical size which is called the Size Congruity Effect (SiCE). This research examines the extent to which these two effects might have a common origin.

Why is this important to scientists or the general public?

Both the SNARC effect and SiCE are well-known to researchers in the area of numerical cognition. However, little research exists that examines the relationship between the two effects. By exploring this relationship, new insights into the mental representation of numbers may be gained, which will allow for new research directions in this area.

What are our hypotheses and predictions?

We predict that there will be an association between number magnitude and response key location, such that smaller numbers will be responded to faster with one of response keys, whereas larger numbers will be responded to faster with the other key. We also predict that there will be an association between number magnitude and physical size, such that responses will be faster when numerically smaller numbers are displayed in a physically smaller size, and when numerically larger numbers are displayed in a physically larger size. Finally, we predict that there will be an association between number magnitude, response key location, and physical size, such that numbers displayed in a font size corresponding to their numerical magnitude will be responded to fastest with their appropriate response key.

Where can I learn more?

If you would like to learn more about this area of research, you may wish to read the following:

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General, 122*(3), 371-396.

Henik, A., & Tzelgov, J. (1982). Is three greater than five: The relationship between physical and semantic size in comparison tasks. *Memory & Cognition, 10*(4), 389-395.

Wiemers, M., Bekkering, H., & Lindemann, O. (2017). Two attributes of number meaning: Numerical associations with visual space and size exist in parallel. *Experimental Psychology, 64*(4), 253-261.

If you feel any distress or anxiety after participating in this study, please feel free to contact the Carleton University Health and Counseling Services at 613-520-6674, or the Distress Centre of Ottawa and Region at 613-238-3311 (http://www.dcottawa.on.ca).

What if I have questions later?

Should you have any ethical concerns with the study, please contact Dr. Bernadette Campbell, Chair, Carleton University Research Ethics Board-B (by phone: 613-520-2600 ext. 4085 or by email: ethics@carleton.ca). For all other questions about the study, please contact the researcher.

James Vellan (Principal Investigator) at: james.vellan@carleton.ca (613-520-2600, ext. 1745); Dr. Craig Leth-Steensen (Faculty Sponsor) at: craig.lethsteensen@carleton.ca (613-520-2600, ext. 2254).

Thank you for participating in this research!

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