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Are Arabic and Verbal Numbers Processed in Different Ways?

Roi Cohen Kadosh
Ben-Gurion University and University College London

Avishai Henik and Orly Rubinsten
Ben-Gurion University

Four experiments were conducted in order to examine effects of notation—Arabic and verbal numbers—on relevant and irrelevant numerical processing. In Experiment 1, notation interacted with the numerical distance effect, and irrelevant physical size affected numerical processing (i.e., size congruity effect) for both notations but to a lesser degree for verbal numbers. In contrast, size congruity had no effect when verbal numbers were the irrelevant dimension. In Experiments 2 and 3, different parameters that could possibly affect the results, such as discriminability and variability (Experiment 2) and the block design (Experiment 3), were controlled. The results replicated the effects obtained in Experiment 1. In Experiment 4, in which physical size was made more difficult to process, size congruity for irrelevant verbal numbers was observed. The present results imply that notation affects numerical processing and that Arabic and verbal numbers are represented separately, and thus it is suggested that current models of numerical processing should have separate comparison mechanisms for verbal and Arabic numbers.

Keywords: size congruity, numerical processing, Arabic number, verbal number, automaticity

Research in the field of number processing shows two well-known effects. The first is referred to as the *distance effect* (Moyer & Landauer, 1967). As the name implies, the distance between two numbers influences the response time needed to compare stimuli; the larger the distance, the shorter the reaction time (RT). Since its discovery, this effect has been found in many other studies (Dehaene, 1996; Dehaene & Akhavein, 1995; Duncan & McFarland, 1980; Henik & Tzelgov, 1982; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002; Schwarz & Heinze, 1998; Schwarz & Ischebeck, 2003; Tzelgov, Meyer, & Henik, 1992) and is considered a general phenomenon that applies not only to the number field but to other areas as well (Moyer & Landauer, 1967). The second effect is called the *size congruity effect* (SCE; Paivio, 1975) and is a Stroop-like phenomenon. When a stimulus has two dimensions but only one has to be considered while the other has to be ignored, participants process the irrelevant dimension unintentionally. For example, in number comparison, participants have to relate to the numerical value and ignore the physical size. In the congruent condition, one of the two digits is larger in both dimensions (e.g., 2 4). In the incongruent condition, one of the digits is larger in one dimension, while the other is larger in the second dimension (e.g., 2 4). In the neutral condition, there is no difference in the irrelevant dimension (e.g., 2 4). The SCE is observed when incongruent and congruent conditions significantly differ. Facilitation is observed when the response to the congruent trials is faster than to the neutral trials. Interference is observed when the response to the incongruent trials is slower than to the neutral trials.

The SCE is found when the numerical value is the relevant dimension and the physical dimension must be ignored, and also in the reverse task, when the physical dimension is relevant and the numerical dimension is irrelevant. This implies that not only physical size but also numerical value is processed automatically (Cohen Kadosh & Henik, 2006; Girelli, Lucangeli, & Butterworth, 2000; Henik & Tzelgov, 1982; Rubinsten et al., 2002; Schwarz & Heinze, 1998; Schwarz & Ischebeck, 2003; Tzelgov et al., 1992).

In the current study, we aimed to examine numerical representation as a function of notation (i.e., format) under automatic and intentional processing by using the distance effect and the SCE. According to most of the models and theoreticians in numerical cognition (discussed later), numbers are represented abstractly. That is, numerical representation of quantity is amodal and notation independent. Therefore, processing of numerical information should not be affected by different numerical notations (e.g., Arabic numbers, verbal numbers) (Dehaene, Piazza, Pinel, & Cohen, 2003). In the next sections, we give a short overview of the main models and the different findings in the field of numerical cognition, followed by four experiments that examined the issue of abstract numerical representation.

Automaticity in Number Processing

When a process is executed without intention (i.e., it is not part of the task requirement), it is referred to as *autonomous automatic*.

Roi Cohen Kadosh, Department of Psychology and Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer-Sheva, Israel, and Institute of Cognitive Neuroscience and Department of Psychology, University College London, London; Avishai Henik and Orly Rubinsten, Department of Psychology and Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev.

Orly Rubinsten is now also at the Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, Department of Learning Disabilities, University of Haifa.

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Correspondence concerning this article should be addressed to Roi Cohen Kadosh, University of Cognitive Neuroscience, University College London, 17 Queen Square, London, WC1N 3AR United Kingdom. E-mail: r.cohenkadosh@ucl.ac.uk

However, when the process is part of the task requirement, it is referred to as *intentional automatic* (e.g., Tzelgov, Henik, Sneg, & Baruch, 1996). For example, in numerical comparison, the distance effect is observed. This is referred to as intentional automatic because evaluating the quantity of the digit is part of the task requirement. In physical comparison, the SCE is observed. This implies that the quantity of the digit affects processing, in spite of being completely irrelevant to the task. Thus, it is referred to as autonomous automatic (Tzelgov et al., 1996).

How automatic is the processing of numerical values? A survey of the literature reveals that this might depend on the type of notation, that is, whether it is Arabic notation (e.g., 8) or verbal notation (e.g., eight). The data regarding automaticity of processing Arabic notation are clear (Girelli, Lucangeli, & Butterworth, 2000; Henik & Tzelgov, 1982; Rubinsten et al., 2002; Schwarz & Heinze, 1998; Schwarz & Ischebeck, 2003; Tzelgov et al., 1992). When a participant is instructed to judge which of two digits is physically larger and to ignore the numerical dimension, an SCE appears. That is, the numerical value modulates performance and is processed autonomously. When participants are instructed to refer to the numerical dimension and decide which of two stimuli is larger while ignoring the physical dimension, an SCE appears as well. Thus, we can conclude that the numerical values of Arabic numbers are processed automatically, whether autonomously or intentionally. In order to differentiate between the SCE in physical and in numerical tasks, we will abbreviate the SCE in the physical task as P-SCE (Physical-SCE) and in the numerical task as N-SCE (Numerical-SCE).

In contrast to the results with Arabic numbers, the results with verbal numbers are ambiguous. Besner and Coltheart (1979), who found an N-SCE with Arabic numbers, failed to find an N-SCE with verbal notation and argued that these results indicated a distinction in the processing of Arabic and verbal numbers. In contrast, Foltz, Poltrock, and Potts (1984) found an N-SCE for verbal numbers as well as for Arabic numbers. However, they analyzed the N-SCE for each notation separately and did not examine the interaction between N-SCE and notation.

Dehaene and Akhavein (1995) argued that numbers, whether Arabic or verbal, are processed in the same manner. In their experiment, participants were asked to decide whether two members of a pair of stimuli were the same or different. The notations were Arabic–Arabic, verbal–verbal, or a mixed notation (e.g., verbal–Arabic). A distance effect was observed for numerical matching and physical matching, independent of the notation. This implies that both notations were processed intentionally and autonomously in the same fashion. Such autonomous processing of both Arabic and verbal numbers raises the following question: Will a P-SCE appear also with verbal numbers when participants have to ignore the numerical dimension and attend only to the physical dimension? Although both the distance effect (in Dehaene & Akhavein, 1995) and the P-SCE are elicited autonomously, they are not the same. The distance effect indicates that digits are processed in a refined way (e.g., placing the digits on a mental number line). In contrast, the P-SCE may indicate crude processing of the numerical dimension (e.g., such as small or large; R. Cohen Kadosh, 2008a; Tzelgov et al., 1992).

Additional studies added to the controversy of whether Arabic and verbal numbers are processed in the same manner (Fias, 2001; Fias, Reynvoet, & Brysbaert, 2001; Ischebeck, 2003; Reynvoet & Brysbaert, 2004). Fias (2001) used the SNARC (spatial numerical association of response codes) effect to examine the processing of verbal numbers. The SNARC effect is observed in numerical processing tasks (e.g., parity task, magnitude task) and is indicated by faster responses to small numbers with a left key press and to large numbers with a right key press (Dehaene, Bossini, & Giraux, 1993; for a review, see Gevers & Lammertyn, 2005). Fias (2001) found a SNARC effect when the participants were asked to make a parity judgment. However, he failed to find a SNARC effect when verbal numbers were processed autonomously, that is, when the participants were asked to monitor the occurrence of certain phonemes of verbal numbers. Notably, in a previous study, the SNARC effect was observed for both parity and phoneme monitoring tasks with Arabic numbers (Fias, Brysbaert, Geypens, & d'Ydewalle, 1996). These findings suggest that under unintentional processing, the spatial representation of the two notations might differ. Some studies also found dissociation between Arabic and verbal numbers; however, name tasks were used in these studies (Fias, Reynvoet, & Brysbaert, 2001; Ischebeck, 2003). Naming tasks are biased because words are the preferred format for naming (Dehaene, 1992).

Other studies that used magnitude comparison with manual responses found mixed results. Koechlin, Naccache, Block, and Dehaene (1999) found a similar semantic effect for Arabic and verbal numbers under numerical priming. In contrast, under stringent temporal constraints (i.e., masked prime 66 ms prior to the target), they found dissociation in the semantic effect: there was no cross-notation priming. However, in a later study, Naccache and Dehaene (2001b) failed to replicate this dissociation (see also Reynvoet, Brysbaert, & Fias, 2002). Finally, imaging studies strongly support the existence of a shared neuronal substrate for numerical comparison that is notation independent (Dehaene, 1996; Naccache & Dehaene, 2001a; Pinel, Dehaene, Rivière, & LeBihan, 2001). In conclusion, the similarity (or difference) in processing between Arabic and verbal numbers is still controversial.

Architectures for Number Processing

Models of number processing differ with respect to the issue at hand (i.e., are verbal and Arabic numbers processed similarly or differently?). Campbell and colleagues (Campbell, 1994; Campbell & Epp, 2004) introduced the *encoding complex hypothesis*, which offers modality-specific number codes. They proposed that number processing is mediated by modality-specific processes (e.g., visual, Arabic) and not by an abstract code. According to the recent update for this model (Campbell & Epp, 2004), the more familiar and practiced the participant is with the format, the more efficient the retrieval of the numerical magnitude from the mental representation is. Therefore, this model can explain differences in numerical processing as a factor of notation. For example, an interaction between notation and the distance effect is predicted, due to easier retrieval of numerical information in Arabic number format. Campbell and Epp (2004) found an interaction between notation and distance effect. In numerical comparison of Arabic numbers and Mandarin number symbols, Chinese–English bilinguals showed a smaller distance effect with Arabic numbers. In addition, since the access to mental representation of Arabic numbers is easier, we predicted in the current study that we would find an interaction between notation and P-SCE. More specifically, we predicted that the P-SCE would be larger for Arabic numbers than for verbal numbers.

Dehaene (1992) offered the *triple-code model*. His model assumes that numerical comparison and number approximation are performed by the analog magnitude code, in which numbers are converted into the same code before comparison is performed. The model's prediction is that the pattern of results in a comparison task should be the same for Arabic numbers and verbal numbers. Namely, in contrast to the encoding complex hypothesis, this model predicts additivity, and not interaction, between notation and numerical distance (or factors that modulate numerical distance).

Moreover, Dehaene (1996) suggested that "the distance effect originates from a level of representation that abstracts away from the *physical* and *notational* characteristics of the stimulus" (p. 64, italics added). However, an exception to this prediction should be made in light of a modification to the triple-code model suggested by Koechlin et al. (1999). They suggested the existence of quantity subsystems devoted to different notations. Nevertheless, this modification of the model does not change the prediction that the pattern of results in a comparison task should be the same for Arabic numbers and verbal numbers because Koechlin et al.'s modification assumes that the distinct representations are revealed only under subliminal priming.

Although the models we have described are designed to explain numerical and notational processing (i.e., numerical cognition), none of them explicitly explains the SCE. Schwarz and Ischebeck (2003) presented the *coalescence model* that nicely explains the influence of the irrelevant dimension on the relevant dimension, and the interaction between the size congruity (the difference between incongruent and congruent) and the ir/relevant dimension, for RT as well as for error rates. This model takes into account various components that affect processing, such as the degree of automaticity of the ir/relevant dimension and the distance effect (as indicated by the drift rate [or the speed of processing] of each dimension). For example, greater automaticity of one of the dimensions results in a larger SCE when this dimension is irrelevant and in a smaller SCE when the same dimension is relevant. As in the triple-code model, the coalescence model assumes an analog representation of quantities (moreover, the coalescence model further assumes that the same magnitude representation is used for physical sizes and numbers). Another assumption that is made only by the coalescence model concerns the pattern of the facilitation and interference components (cf. Figures 1 & 2 in Schwarz & Ischebeck, 2003). In the congruent condition, both relevant and irrelevant dimensions yield the same response, and the signs of the ir/relevant drift rates are identical. Hence, the overall drift rate will increase, relative to the drift rate of the relevant attribute alone (i.e., neutral condition in our case). In contrast, in the incongruent condition, the relevant and the irrelevant attributes are associated with different responses, and therefore the signs (+, −) of the individual drift components differ. Therefore, the drift rate of the incongruent condition will decrease relative to the drift rate of the relevant attribute alone. Since the drift rate of the irrelevant dimension is constant, whether the trial is congruent or incongruent, a symmetrical drift rate of interference and facilitation should be observed. However, the nonlinear relation between drift rate and RT should eventually lead to smaller facilitation than interference. In addition, due to the nonlinear relation between the drift rate and RT, which results in nonadditive RT effects, interactions between notation and distance or congruity can be explained by this model.

The Current Study

According to Tzelgov and Ganor-Stern (2004), mental representations are best probed when their processing is automatic and not part of the requirement of the task that is intentionally performed. It was suggested that in order to learn about basic features of mental representations, one should use paradigms in which the involvement of intentional strategies is minimal. This is achieved when processing of the mental entities in question is not part of the task requirements (i.e., they are processed automatically). Accordingly, to study the characteristics of numerical representation, we used the size congruity paradigm.

Similarly, Barsalou (2003) suggested that abstract representation is not an existing fixed property but rather is created temporarily online. Therefore, intentional tasks, in contrast to tasks that examine mental representation under automatic processing, are more prone to create temporary, abstract numerical representations. This, in turn, leads to "contamination" of the default representation by intentional strategies the participant can adopt (Tzelgov & Ganor-Stern, 2004). Clearly, participants *can* alter the numerical representations according to intentional strategies (Fischer & Rottmann, 2005; Shaki & Petrusic, 2005).

However, it seems that currently most of the studies in the field of numerical cognition that tapped an abstract representation, as well as the various cognitive models, (e.g., the triple-code model) were based on intentional processing of numbers (i.e., numerical comparison). In contrast to these studies, a recent study (R. Cohen Kadosh, K. Cohen Kadosh, Kaas, Henik, & Goebel, 2007) showed that under automatic processing of Arabic and verbal numbers, notation-dependent representations can be revealed. Cohen Kadosh et al. examined the function of the parietal lobes—an area that is positioned superior to the occipital lobe and posterior to the frontal lobe and is involved, among other functions, in numerical processing (see R. Cohen Kadosh, Lammertyn, & Izard, 2008, for a recent review and meta-analysis). A deviation from abstract representation was found in the right parietal lobe, while the left parietal lobe showed notation-independent representation. It might be that the absence of an interaction with notation in the behavioral studies was due to similar processing of different notations in the left parietal lobe, which masked the superiority of the right lobe for digits. In this case, the nonabstract processing in the right parietal lobe is "hidden," and the differences between the notations cannot be revealed (i.e., functional degeneracy; Price & Friston, 2002). However, it might be that by manipulating an additional process that recruits mainly the right parietal lobe, an interaction between notation and numerical representation could appear. The size congruity paradigm might be a suitable paradigm in this case since it has been shown with transcranial magnetic stimulation (TMS) that the right parietal lobe is crucial for the SCE (R. Cohen Kadosh, K. Cohen Kadosh, Schuhmann, et al., 2007). Together with the left lateralization of verbal numbers as revealed during automatic processing (e.g., R. Cohen Kadosh, K. Cohen Kadosh, Kaas, et al., 2007), we predicted that deviation from abstract representation could be revealed using the current size congruity paradigm with Arabic and verbal numbers. That is, we expected to find an interaction between notation and SCE due to a reduced SCE with verbal number processing as compared with Arabic number processing because the former depends to a lesser degree on the right parietal lobe.

The current study had two goals: one was to find out whether the pattern of N-SCE and distance effects with verbal numbers would match the pattern produced by Arabic numbers. More precisely, would we obtain an interaction between notation and SCE or distance effect? Such a result would challenge the commonly held view that numerical representation is abstract (e.g., Dehaene, Dehaene-Lambertz, & Cohen, 1998; Dehaene et al., 2003; Libertus, Woldorff, & Brannon, 2007). The second goal was to discover whether verbal numbers are processed in the same fashion as Arabic numbers when the numerical dimension is irrelevant to the task requirement and therefore produces a P-SCE. Again, an interaction between notation and the P-SCE would challenge the idea that numerical representation is abstract.

Four experiments were conducted with Arabic and verbal numbers. We manipulated the physical and numerical values of the stimuli and examined the distance effect and the SCE under numerical and physical comparisons.

Experiment 1

As discussed earlier, most of the models in the field predict similar effects in numerical comparison for various notations, and Experiment 1 was designed to verify this. Another part of the experiment, the physical comparison task, enabled us to find out whether verbal numbers produced a P-SCE, similar to the P-SCE produced by Arabic numbers. Thus, we examined whether Arabic and verbal numbers are processed in the same way, intentionally and unintentionally.

Method

Participants. Sixteen university students (mean age = 24.65 years, *SD* = 1.31) from Ben-Gurion University of the Negev, Beer-Sheva, Israel, took part in the experiment. All participants had normal or corrected-to-normal vision and had no reading or mathematical deficits; Hebrew was their mother tongue. They were paid 25 Israel new shekels (approximately 6 USD) for their participation in the experiment.

Stimuli. Two numbers appeared at the center of a computer screen. The center-to-center distance between the two digits subtended a horizontal visual angle of 10° and the participants sat 55 cm from the screen. There were two different notations in separate blocks: Arabic notation (e.g., 4 3) and verbal notation (e.g., שלוש ארבע, which are the Hebrew words for four and three, respectively). Both notations subtended a vertical visual angle of 0.7° or 0.9° and a horizontal visual angle of 1.7°–5.4° or 0.6°–0.8° (for verbal and Arabic numbers, respectively). There were three types of pairs: congruent, neutral, and incongruent. A congruent stimulus was defined as a pair of digits in which a given digit was larger in both the relevant and irrelevant dimensions (e.g., 3 4 or ארבע שלוש). A neutral stimulus was defined as a pair of digits that differed only in the relevant dimension (e.g., 3 4 or ארבע שלוש, for numerical comparisons and 4 4 or ארבע ארבע, for physical comparisons). An incongruent stimulus was defined as a pair of digits in which one of the digits was simultaneously larger on one dimension and smaller on the other (e.g., 3 4 or ארבע שלוש). The digits 1 through 9 were used with the digit 5 excluded. The two digits in each pair could be the same physical size (neutral pair in numerical comparisons) or could differ in height (physical dimension) by 0.2°. In addition, the digits in each pair could be of the same numerical value (neutral pair in physical comparisons) or could differ in numerical distance. There were three numerical distances: 1 (the digits 1–2, 3–4, 6–7, or 8–9), 2 (the digits 1–3, 2–4, 6–8, or 7–9) or 5 (the digits 1–6, 2–7, 3–8, or 4–9).[1] Each digit was presented an equal number of times for each distance. Stimuli were arranged in blocks of trials with each block composed of 72 different stimuli that were presented twice (a total of 144 trials in each block). Within the set of stimuli prepared for numerical or physical comparisons, each digit and each physical size appeared an equal number of times on the left and the right. Each block had 9 different conditions: 3 numerical distances × 3 congruency conditions. Each condition was represented by 16 trials (i.e., 4 digit combinations × 2 physical sizes × 2 sides of the computer screen) in a given block. Each participant was presented with 4 blocks of trials: 2 tasks (physical or numerical comparison) × 2 notations (Arabic or verbal).

Congruent and incongruent trials were the same for the two tasks, while the neutral stimuli were different. Neutral stimuli for physical comparisons included the same digit in two different physical sizes. For example, because the pair 1–2 was used to produce congruent and incongruent stimuli for a numerical distance of 1 unit, neutral pairs created using these two digits (i.e., 1 1 and 2 2) were included in the analysis as neutral trials for Distance 1. In this way, the statistical analyses of congruent, incongruent, and neutral conditions were based on the same digits. Neutral stimuli in the numerical comparisons included two digits that were different in numerical values but of the same physical size. For example, the pair 1–2 was used to produce congruent and incongruent stimuli for a numerical distance of 1 unit. Hence, neutral pairs created using these two digits (i.e., 1–2) were included in the analysis as neutral trials. These pairs were presented twice in a small physical size (i.e., 0.7°) and twice in a large physical size (i.e., 0.9°). In this way, we controlled for the overall different physical sizes in the congruent and incongruent conditions.

Every experimental block was preceded by a block of 36 practice trials. This block was similar to the experimental block with the exception that we used Arabic and verbal numbers that were different from those used in the experimental blocks. For a nu-

[1] One of the reviewers noted that in the numerical task, stimuli involving the numbers 1 or 9 can be solved without performing the comparison because they are end anchors (i.e., there is no stimulus larger than 9 or smaller than 1). However, our aim in the current study was to examine the possible differences between Arabic and verbal numbers. The end-anchor effect should not affect our analyses and conclusions because the same stimuli were presented for each notation and therefore should yield the same effect. Moreover, we were confident in our expectation of the nonexistence of an end-anchor effect in numerical and physical comparison tasks because we examined this issue in previous experimental work (Cohen Kadosh et al., 2005, p. 1242) and found that it had no effect on the results. Nevertheless, we also analyzed the current data (Experiments 1–4) to further examine this issue. Excluding the end-anchor values (1 and 9) did not change the results appreciably.

merical distance of 1 unit, the practice digits were 4–5 and 5–6, and for a numerical distance of 2 units, the digits were 3–5 and 5–7. In the case of the 5-unit numerical distance, we used the pairs 1–6 and 4–9, which were also used in the experiment. This was due to an error in the design of the experiment, and we will examine its effect in the *Results* section.

Procedure. The participant's task was to decide which of two digits in a given display was larger. In two blocks, the term *larger* applied to physical size. In the other two blocks, the term *larger* applied to numerical value. The stimuli in each block were presented in a random order. The order of blocks varied between participants according to a balanced 4 × 4 Latin square design, with 4 participants receiving each order. Participants were asked to respond as quickly as possible but to avoid errors. They indicated their choices by pressing one of two keys (i.e., P or Q on the keyboard), corresponding to the side of the display with the selected member of the digit pair.

Each trial began with an asterisk as a fixation point, presented for 300 ms at the center of a computer screen. Five hundred ms after the fixation point disappeared, a pair of digits appeared and remained in view until the participant pressed a key (but not for more than 5,000 ms). A new stimulus appeared 1,500 ms after the participant's response. The entire experiment lasted approximately 35 min.

Design. The variables manipulated were relevant dimension (physical or numerical), notation (Arabic or verbal), numerical distances (1, 2, or 5), and congruity (incongruent, neutral, or congruent). Thus, we had a 2 × 2 × 3 × 3 factorial design, with all variables within subjects. All effects were tested using a significance level of $p < .05$.

Results

For every participant in each condition, the mean RT was calculated for correct trials. Only trials with RTs longer than 200 ms and shorter than 2,000 ms were considered correct (99.9% from all trials). These means were subjected to a four-way analysis of variance (ANOVA) with all factors as within-subject factors.

All four main effects were significant, all Fs > 41.12. In addition, eight interactions were significant including the four-way interaction of Relevant Dimension × Notation × Numerical Distance × Congruity, $F(4, 60) = 5.64$, $MSE = 839$. The four-way interaction is presented in Figure 1.

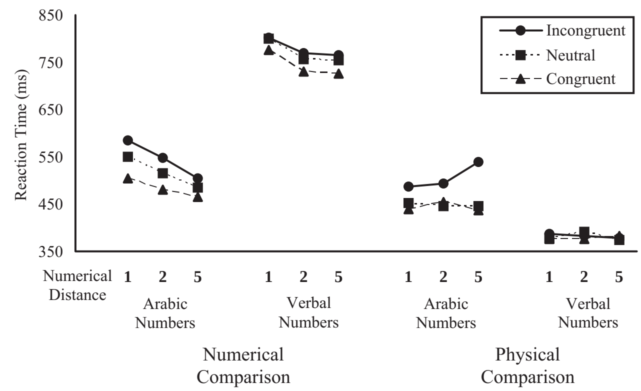

Figure 1. Reaction time as a function of relevant dimension, notation, numerical distance, and congruity in Experiment 1.

It seems that there was a congruity effect across conditions except for physical comparisons of verbal notation. The N-SCE in numerical comparisons seems to have both an interference component and a facilitatory component. Unlike the N-SCE, the P-SCE was interference (and not facilitatorily) based. Moreover, the SCE seems to be modulated by numeric distance for Arabic notation but not for verbal numbers. Additional analyses of the four-way interaction, conducted separately for numerical and physical comparisons (Keppel, 1991), supported these conclusions.

Numerical comparisons. Two simple interactions reached the significant level: the interaction between notation and congruity, $F(2, 30) = 4.45$, $MSE = 1{,}207$, and notation and distance, $F(2, 30) = 3.71$, $MSE = 1{,}042$. Linear trends of congruity conducted separately on the different notations were significant for both Arabic and verbal notations, $F(1, 15) = 56.45$, $MSE = 1{,}513$, and $F(1, 15) = 23.17$, $MSE = 1{,}282$, respectively. However, for the Arabic notation, the linear trend of congruity explained 75% of variance, while for the verbal notation, the linear trend of congruity explained only 25% of the variance. We further analyzed the data of the numerical comparisons for the two notations separately. A detailed analysis of the components of the SCE for each notation revealed a facilitatory component of 34 ms, $F(1, 15) = 28.97$, $MSE = 920$, and an interference of 30 ms, $F(1, 15) = 19.47$, $MSE = 1{,}085$, for Arabic notation. In contrast, for verbal notation, the facilitatory component of 26 ms was significant, $F(1, 15) = 12.28$, $MSE = 1{,}317$, but the interference of 8 ms was not significant, $F(1, 15) = 1.41$, $MSE = 1{,}146$.

For the distance effect, analysis of Arabic notation revealed a simple main effect of numerical distance, $F(2, 30) = 41.04$, $MSE = 1{,}107$. We found a decrease of RT with distance (546 ms for 1 unit of distance, 514 ms for 2 units of distance, and 484 ms for 5 units of distance). The differences between 1 unit and 2 units and between 2 units and 5 units were significant, $F(1, 15) = 41.70$, $MSE = 592$, and $F(1, 15) = 20.94$, $MSE = 992$, respectively. The distance effect for verbal notation was also significant, $F(2, 30) = 19.04$, $MSE = 1{,}516$. The difference between 1 unit (792 ms) and 2 units (752 ms) was significant, $F(1, 15) = 29.14$, $MSE = 1{,}319$, while the 4-ms difference between 2 units and 5 units (748 ms) was not significant, $F < 1$].

Physical comparisons. The three-way interaction among notation, numerical distance, and congruity was significant, $F(4, 60) = 5.63$, $MSE = 768$. We further examined the sources of the three-way simple interaction by analyzing each notation separately.

In the Arabic notation, only the simple main effect of P-SCE was significant, $F(2, 30) = 56.91$, $MSE = 1{,}054$, and was composed of an interference component of 59 ms, $F(1, 15) = 78.92$, $MSE = 1{,}054$, but not a facilitatory component (4 ms), $F(1, 15) = 1.08$, $MSE = 444$. Moreover, the interaction between congruity and numerical distance was significant, $F(4, 60) = 7.17$, $MSE = 850$. This interaction was due to an increase in the P-SCE (incongruent relative to congruent) as the numerical distance increased, $F(1, 15) = 15.27$, $MSE = 774$, from 48 ms for a distance of 1 unit to 102 ms for a distance of 5 units. The analysis of the verbal notation did not produce any significant effect (all ps > 0.34).

In our experiment, some of the 5 unit pairs (i.e., 1–6 and 4–9) were used both in the experiment and during practice. We excluded these pairs from the analysis in order to avoid any argument regarding the practice effect of the 5-unit pairs, even though the same pattern of results was still observed.

Error rates. The four-way interaction of Relevant Dimension $\times$ Notation $\times$ Numerical Distance $\times$ Congruity was significant, $F(4, 60) = 2.83$, $MSE = 0.0016$, $p < .05$. The pattern of results was similar to that produced in the RT analysis. A correlation analysis that was conducted between RTs and error rates confirmed this. The results did not show any RT–accuracy tradeoff ($r = .46$).

Discussion

Similar to previous reports, in the numerical comparison, Arabic notation yielded faster responses than verbal numbers, and a distance effect was obtained (e.g., Dehaene, 1996; Dehaene & Akhavein, 1995). We also obtained the SCE for Arabic numbers for both the numerical and physical comparisons. For the N-SCE, the effect was composed of an interference component and a facilitatory component, whereas for the P-SCE, it was composed of an interference component only. In contrast, verbal notation produced an SCE only when comparisons were numerical. We conclude that numerical comparison of both verbal and Arabic numbers is affected by physical size.

We should emphasize that a number of distinctions between Arabic and verbal notation were found in the numerical comparison task: (a) As evidenced by the interaction between notation and distance, for Arabic numbers, all three numerical distances produced significantly different RTs, while this was not the case for verbal numbers; and (b) the pattern of the SCE was modulated by notation. These kinds of discrepancies between Arabic and verbal numbers contradicted models that assume abstract numerical representation. A further evaluation of the models will be presented in the General Discussion.

In the physical comparison, which reflects automatic processing of numerical values, an additional distinction was observed between the Arabic and verbal notation. The Arabic notation yielded a P-SCE, indicating that the participants processed the numerical dimension although it was irrelevant to the task. In contrast, the verbal notation stimuli did not produce a P-SCE, and therefore, it can be speculated that the numerical dimension was not processed or was processed differently so that it did not affect performance. The current findings partly resemble the findings of Ito and Hatta (2003) who found that Kana numbers, the equivalent of verbal numbers in the current study, did not yield a P-SCE, in contrast to Arabic numbers or Kanji numbers (ideographic script). In contrast to our findings, however, they did not found any interaction between notation and distance or notation and N-SCE.

Finding that physical comparisons of verbal numbers do not elicit autonomous numerical processing while Arabic numbers do elicit autonomous numerical processing is in contrast with an earlier result. Dehaene and Akhavein (1995), using a same–different task, observed the distance effect for both notations, albeit numerical information was task irrelevant. However, the SCE that represents another aspect of number processing was not manipulated in their experiment, and physical comparisons seem to be affected by this aspect of the stimuli. Another distinction is that in the current experiment, as well as in the study by Ito and Hatta (2003), both notations were presented in separate blocks. In contrast, in Dehaene and Akhavein's experiment, stimuli were mixed within a block. Thus, it can be argued that the participants in our experiment adopted a strategy that brought about this pattern of results (e.g., Shaki & Petrusic, 2005). This explanation will be further examined in Experiment 3.

For Arabic numbers, we observed an interaction between N-SCE and numerical distance. This is in line with previous findings (R. Cohen Kadosh, K. Cohen Kadosh, Linden, et al., 2007; R. Cohen Kadosh & Henik, 2006; Henik & Tzelgov, 1982; Schwarz & Heinze, 1998; Schwarz & Ischebeck, 2003; Tzelgov et al., 1992). Schwarz and colleagues explained this pattern as a result of relative speed of processing. According to this account, the irrelevant physical information has more time to affect the comparison when the numerical distance is smaller and hence is processed slower (Schwarz & Ischebeck, 2003). For physical comparisons, a similar interaction showed an increase in the P-SCE as the irrelevant numerical distance increased. This interaction could also be explained by suggesting that larger numerical distances are processed faster and thus manage to affect congruity more, relative to smaller numerical distances that are processed relatively slower (Schwarz & Ischebeck, 2003; but see R. Cohen Kadosh, 2008a, and Tzelgov et al., 1992, for another explanation).

In light of the current results, the following experiments were conducted in order to control factors that might bias our results. Experiment 2 examined whether the pattern of the SCE in Experiment 1 was a result of a variability mismatch—an asymmetric design in which physical stimuli varied less (two sizes) than numerical stimuli (eight values). In addition, in Experiment 1, there was an RT difference between the two comparisons; the physical comparison was faster than the numerical comparison. As Algom, Dekel, and Pansky (1996) pointed out when the discriminability is (approximately) matched, numerical values and physical size appear separable. However, when numerical values and physical size are mismatched, asymmetric interference effects (e.g., Stroop effect) occur, with the more discriminable dimension interfering with the processing of the less discriminable dimension. Accordingly, the two dimensions were matched on general RT (discriminability) in Experiment 2. We carried out Experiment 3 in order to find out if the lack of a P-SCE for verbal numbers could be due to the blocked presentation of notation. Experiment 4 tested further the possibility that the absence of a P-SCE for verbal numbers was a result of the speed of processing of the physical comparison. Note that in Experiments 2 and 4, stimuli had different notations, and the experiments did not have the same design as Experiment 1. That is, we presented the two notations in separate experiments: Experiment 2—Arabic numbers, and Experiment 4—verbal numbers. It was not possible to compare Arabic and verbal numbers in the same design because the physical stimuli had to be different for each notation. The differences in the physical size between Experiment 2 and Experiment 4 were due to the fact that Arabic and verbal numbers require different processing time (i.e., different discriminability for Arabic and verbal numbers). Since we conducted Experiments 2–4 in order to control for several variables that might affect the interpretation of Experiment 1, the discussion for these experiments will be relatively brief.

Experiment 2

Researchers in recent studies involving the SCE (Algom et al., 1996; Pansky & Algom, 1999, 2002) have claimed that it is affected by two factors: discriminability, as assessed by an RT difference between the neutral conditions of the two tasks, and asymmetry in the variability of the relevant and irrelevant dimensions. That is, previous studies have suggested that the P-SCE (Algom et al., 1996; Pansky & Algom, 1999, 2002) or the N-SCE (Algom et al., 1996) can disappear or be reduced when discriminability and/or variance of the relevant and irrelevant dimensions are matched. The reason behind these suggestions is that differences in discriminability can lead to (or augment) processing of the irrelevant dimension when it is processed faster than the relevant dimension. In addition, differences in variability can increase the saliency of the more variable dimension. Therefore, when the irrelevant dimension is more variable, it can be processed, thus sometimes leading to the wrong conclusion that processing was conducted in an automatic fashion.

Experiment 1 was carried out without an attempt to match discriminability and variability as in other studies (e.g., R. Cohen Kadosh, K. Cohen Kadosh, Linden, et al., 2007, R. Cohen Kadosh, K. Cohen Kadosh, Schuhmann, et al., 2007, R. Cohen Kadosh, Henrik, & Rubinsten, 2007; Girelli et al., 2000; Henik & Tzelgov, 1982; Rubinsten et al., 2002; Tzelgov et al., 1992). With respect to discriminability, for Arabic notation, RT of the physical comparison was faster than RT of the numerical comparison. The asymmetry in variability was produced because the physical stimuli were composed of two sizes, creating only one physical distance, whereas the numerical stimuli were composed of eight values that created 12 different pairs with three different numerical distances. In the current experiment, we controlled for these two variables and examined whether the SCE that was obtained in Experiment 1 would be affected by these factors.

Method

Participants. Sixteen students (mean age = 23.26 years, *SD* = 1.48) participated in the experiment. None of them participated in the previous experiment.

Stimuli. Two blocks, one of physical comparison and the other of numerical comparison with Arabic numbers, were presented. Numerical stimuli were the same as those of Experiment 1. For the physical stimuli, we used eight new, different stimuli that created a set similar to the set of numerical stimuli. Selection of the physical sizes was based on a pilot study, which we ran in order to match these stimuli to the numerical stimuli. We used eight different sizes to create 12 different pairs with three different physical distances: distance of Size 1 (1.1°–1.2°, 1.3°–1.4°, 1.5°–1.6°, and 1.8°–2.1°), distance of Size 2 (1.1°–1.3°, 1.2°–1.4°, 1.5°–1.8°, and 1.6°–2.1°), and distance of Size 5 (1.1°–1.5°, 1.2°–1.6°, 1.3°–1.8°, and 1.4°–2.1°). Each block was composed of 432 different stimuli that were presented twice. Each digit and each physical size appeared an equal number of times on the left and the right of the fixation point. Every block had 27 different conditions: 3 physical distances × 3 numerical distances × 3 congruency conditions. Each of the 27 conditions was represented by 32 trials (4 digit combinations × 4 physical combinations × 2 sides of the computer screen) in a given block. An experimental block was preceded by a block of 24 practice trials. This block was similar to the experimental block except that we used numbers and physical distances that were different from those used in the experimental blocks. The pairs for the three units of numerical distance were 1–4, 3–6, 4–7, and 6–9, and the pairs for four units of numerical distance were 2–6, 3–7, 4–8, and 5–9. For the three units of physical distance, the pairs were 1.1°–1.4°, 1.3°–1.5°, 1.4°–1.6°, and 1.5°–2.1°, and for the four units of physical distance, the pairs were 1.2°–1.5°, 1.3°–1.6°, 1.4°–1.8°, and 1.5°–2.1°. The stimuli in the practice block were randomly sampled so that in each block there were 2 physical distances × 2 numerical distances × 3 congruency conditions, with equal left and right responses.

Procedure. Each participant took part in two sessions, 1 week apart. Each session was composed of one task. The order of the two blocks was counterbalanced, and each block lasted approximately 40 min.

Design. The variables manipulated were relevant dimension (physical or numerical), physical distance (1, 2, or 5), numerical distance (1, 2, or 5), and congruity (incongruent, neutral, or congruent). Thus, we had a 2 × 3 × 3 × 3 factorial design, with all variables within subjects. Except for the items mentioned earlier, all other conditions were identical to those in Experiment 1.

Results

Only trials with RTs longer than 200 ms and shorter than 2,000 ms were considered correct (99.9% from all trials). Average baseline RT was 585 ms for numerical comparisons and 599 ms for physical comparisons, indicating comparable discriminability of the two tasks. The 14-ms difference in performance (in favor of numerical comparison) was not significant, $F < 1$. For every participant in each condition, we calculated mean RT for correct trials only. These means were subjected to a four-way ANOVA.

All main effects except for relevant dimension were significant, all $Fs > 73.84$. Seven interactions were significant, including the four-way interaction of Relevant Dimension × Physical Distance × Numerical Distance × Congruity, $F(8, 120) = 2.45$, $MSE = 1{,}175$. The four-way interaction is presented in Figure 2. Additional analyses of the four-way interaction were conducted separately for each comparison.

Numerical comparisons. Only the simple main effects for numerical distance, $F(2, 30) = 127.61$, $MSE = 1{,}254$, and congruity, $F(2, 30) = 59.66$, $MSE = 3{,}527$, were significant. The

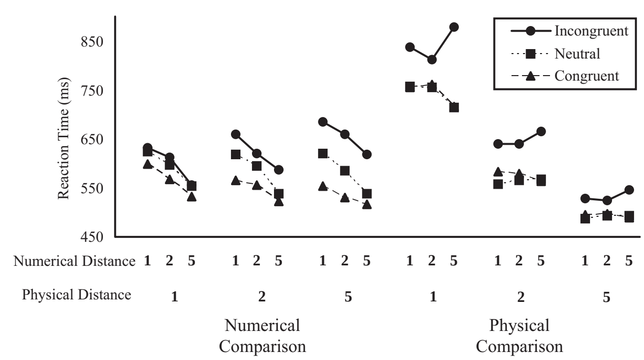

Figure 2. Reaction time as a function of relevant dimension, physical distance, numerical distance, and congruity in Experiment 2.

congruity effect was composed of both interference (40 ms) and facilitation (36 ms), $F(1, 15) = 56.68$, $MSE = 2{,}044$, and $F(1, 15) = 38.88$, $MSE = 2{,}441$, respectively. The simple interaction between congruity and physical distance was significant, $F(4, 60) = 36.62$, $MSE = 684$: the SCE increased as the physical distance increased, $F(1, 15) = 105.33$, $MSE = 880$, from 34 ms for a distance of 1 unit to 122 ms for a distance of 5 units. The simple interaction between congruity and numerical distance was also significant, $F(4, 60) = 5.59$, $MSE = 542$: the congruity effect decreased as the numerical distance increased, $F(1, 15) = 15.30$, $MSE = 405$, from 86 ms for a distance of 1 unit to 63 ms for a distance of 5 units.

Physical comparisons. Only the simple main effects for physical distance, $F(2, 30) = 123.30$, $MSE = 22{,}126$, and congruity, $F(2, 30) = 53.31$, $MSE = 4{,}791$, were significant. The congruity effect was only interference based (75 ms), $F(1, 15) = 73.90$, $MSE = 5{,}551$ ($F < 1$, for facilitation). The simple interaction between congruity and physical distance was significant, $F(4, 60) = 7.49$, $MSE = 1{,}963$; the congruity effect decreased as the physical distance increased, $F(1, 15) = 18.38$, $MSE = 2{,}331$ (99 ms for a distance of 1 unit, 39 ms for a distance of 5 units). The simple interaction between congruity and numerical distance was also significant, $F(4, 60) = 5.81$, $MSE = 2{,}439$; the congruity effect increased as the numerical distance increased, $F(1, 15) = 7.74$, $MSE = 3{,}765$ (57 ms for a distance of 1 unit, 107 ms for a distance of 5 units).

Error rates. Error rates were generally low (2.2% for numerical blocks and 3.9% for physical blocks). Due to lack of variance in several conditions (i.e., accuracy of 100% in the fastest conditions), we did not conduct an ANOVA on the error rates. A correlation analysis between RTs and error rates did not reveal any RT–accuracy trade-off ($r = .90$).

Further examination of discriminability and variability was carried out by comparing results of Experiments 1 and 2. The analyses were conducted separately for the physical and numerical tasks. The variables manipulated were experiment (Experiment 1 or Experiment 2), numerical distance (1, 2, or 5), and congruity (incongruent, neutral, or congruent). Thus, we had a $2 \times 3 \times 3$ factorial design, with only experiment as a between-subjects factor. No variable interacted with experiment in any of the comparisons (ps > 0.37 for all interactions that contained congruity and experiment). The comparison between Experiment 1 and 2 is presented in Figure 3.

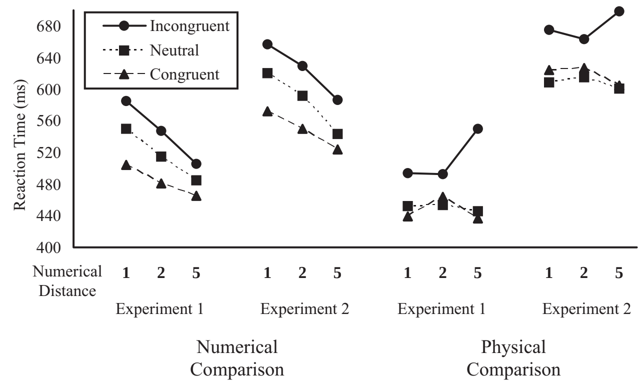

Figure 3. Reaction time as a function of experiment, relevant dimension, numerical distance, and congruity.

Discussion

In spite of matching discriminability and variability of the relevant and irrelevant dimensions, the effects obtained in Experiment 2 precisely replicated the results that were obtained for Arabic notation in Experiment 1. Hence, the current experiment challenges Algom and colleagues' arguments (Algom et al., 1996; Pansky & Algom, 1999, 2002) and strengthens our confidence in the results of Experiment 1.

Experiment 3

In Experiment 1, the magnitude of Arabic numbers was processed in an autonomous fashion while this was not the case for verbal numbers, as indicated by the presence (for Arabic numbers) and absence (for verbal numbers) of a P-SCE. Such results are in contrast to those of Dehaene and Akhavein (1995) who found autonomous activation of magnitude for both verbal and Arabic notations. Since, in Dehaene and Akhavein's study, notations were mixed within blocks, it is possible that the elimination of the effect with verbal numbers in our study was due to the fact that notation was blocked. This critique could also apply to the study by Ito and Hatta (2003) in which, similar to our study, a P-SCE for Kana script was not found. In order to examine this possibility, we used the same task and stimuli as in the physical comparison of Experiment 1, with the two notations mixed within the same block of trials. In addition, by using the mixed design, we created a greater variability in the irrelevant dimension compared with the blocked design of Experiment 1 (16 different stimuli instead of only 8 stimuli). According to Algom and colleagues (Pansky & Algom, 1999, 2002), this increase in variability increases the saliency of the more variable dimension, which, in the current case, might attract the attention of the participants toward the numerical values and, by that, cause interference.

Method

Participants. Seventeen university students (mean age = 22.11 years, $SD = 1.21$) took part in the experiment. None of them participated in the previous experiments.

Design. The variables manipulated were notation (Arabic or verbal), numerical distances (1, 2, or 5), and congruity (incongruent, neutral, or congruent). Thus, we had a $2 \times 3 \times 3$ factorial design, with all variables within subjects. Except for the items mentioned earlier, all other conditions were identical to those in Experiment 1.

Results

One participant was dropped from the analyses due to a high error percentage (more than 10%). For the 16 remaining participants who were included, we calculated the mean RT in each condition (for correct trials only). Only trials with RTs longer than 200 ms and shorter than 2,000 ms were considered correct (99.99% from all trials). These means were subjected to three-way ANOVA.

Significant effects were obtained for notation, congruity, and Notation × Congruity (all *F*s > 5.8). In addition, the three-way interaction among notation, numerical distance, and congruity was significant, $F(4, 60) = 3.14$, $MSE = 854$. The three-way interaction is presented in Figure 4. It seems that there was an SCE only for the Arabic numbers. We examined the source of the three-way interaction by analyzing the verbal and Arabic notations separately.

Arabic notation. The significant P-SCE, $F(2, 30) = 9.21$, $MSE = 2{,}831$, was composed from an interference component (41 ms), $F(1, 15) = 13.82$, $MSE = 2{,}916$, but not a facilitation component, $F < 1$. The simple interaction between congruity and numerical distance was also significant, $F(4, 60) = 3.36$, $MSE = 1{,}184$; the congruity effect increased as the numerical distance increased, $F(1, 15) = 5.87$, $MSE = 1{,}971$: 13 ms for distance of 1 unit, and 67 ms for distance of 5 units.

Verbal notation. The effects of numerical distance, $F(2, 30) = 0.65$, $p > .5$, congruity, $F(2, 30) = 2.4$, $p > .1$, and their interaction, $F(4, 60) = 0.82$, $p > .5$, failed to reach significance.

The comparison between the 5-unit pairs that were used during both the experiment and practice trials (i.e., 1–6, 4–9) and the pairs that were used only during the experiment (i.e., 2–7, 3–8) was not significant.

Error rates. Only the main effect of task was significant, $F(1, 15) = 34{,}290$, $MSE = 0.008$, $p < .001$. Mean error rates of Arabic notation and verbal notation were 3.5% and 1.4%, respectively. A correlation analysis between RTs and error rates did not reveal any RT–accuracy trade-off ($r = .86$).

Discussion

In general, the current pattern of results replicated that of physical comparisons of Experiment 1. Hence, the absence of the effects in the physical comparison with verbal notation in Experiment 1 cannot be related to a strategy adopted by the participants due to the blocking of notation. The application of a mixed-within-block design also helped us to increase the RT for verbal numbers by 90 ms. In Experiment 1, the mean RT was 383 ms, whereas in Experiment 3, the mean RT was 473 ms. Note that in the physical comparison with Arabic numbers in Experiment 1, the mean RT was similar to the mean RT here for verbal numbers (466 ms vs. 473 ms for Experiment 1 and Experiment 3, respectively). Still, this similarity did not allow for interference of the irrelevant numerical dimension in the verbal notation.

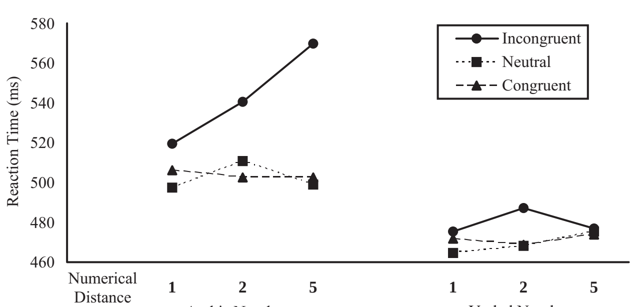

Figure 4. Reaction time as a function of notation, numerical distance, and congruity in Experiment 3.

Is it possible that while physically comparing words, participants were able to ignore the numerical values of the words? Such a result poses a challenge for the idea that verbal numbers are processed automatically. However, another possibility is that verbal numbers need much more time than Arabic numbers in order to be processed automatically. Such an idea fits with the results of R. Cohen Kadosh, K. Cohen Kadosh, Kaas, et al. (2007) who found that areas in the parietal lobes are modulated to a lesser degree when verbal numbers are processed automatically. We further tested this possibility at the behavioral level in Experiment 4.

Experiment 4

In Experiments 1 and 3, there was no P-SCE when verbal numbers were presented, in contrast to when Arabic numbers were presented. It is possible that the elimination of the effect with verbal numbers was due to the fact that the physical comparison was carried out too fast for the verbal numbers. This difference in the speed of processing did not allow enough time for numerical information to interfere when it appeared in verbal notation. In order to examine this possibility, we introduced some changes in the physical stimuli to slow down processing of the stimuli. We increased the processing time of the physical comparison by decreasing the size of the stimuli that were used in Experiment 2 by almost a half. However, such a manipulation is a "two-edged sword"; decreasing the size of the stimuli might slow down the recognition time of the word, which again would produce a null result. In addition, we used verbal numbers that were matched in length in a given pair. The latter change was introduced because a pilot study showed that under physical comparison of height, word length might be a more salient feature than word meaning.[2]

Method

Participants. Fourteen university students (mean age = 24.00 years, $SD = 2.21$) took part in the experiment. None of them participated in the previous experiments.

Stimuli. Two blocks, one for physical comparison and the other for numerical comparison of verbal numbers, were presented. Verbal numbers in each pair were matched on the number of letters. There were three numerical distances: Numerical Distance 1 (the pairs 2–3, 3–4), Numerical Distance 2 (the pairs 2–4, 7–9) or Numerical Distance 4 (the pairs 1–5, 5–9). For the physical stimuli we used seven new, different stimuli that created a set similar to the set of numerical stimuli; that is, there were seven different sizes used to create six different pairs with three different physical distances: Physical Distance 1 (0.6°–0.67° and 0.67°–0.74°), Physical Distance 2 (0.6°–0.74° and 0.96°–1.1°), and Physical Distance 4 (0.56–0.82° and 0.82°–1.1°). Each block was composed of 216 different stimuli that were presented twice. Every

[2] In order to exclude a potential explanation that word length also affected the congruity in the numerical comparison (i.e., intentional processing), we conducted a separate analysis in Experiment 1 with word length as a factor. This factor was not significant, $F = 0.04$. Moreover, we conducted an additional experiment in order to test again whether word length could affect the congruity effect under numerical comparison. Again, word length did not interact with congruity, $F = 0.09$.

block had 27 different conditions: 3 physical distances × 3 numerical distances × 3 congruency conditions. Each of the 27 conditions was represented by 8 trials (i.e., 2 digit combinations × 2 physical combinations × 2 sides of the computer screen) that were repeated twice in a given block. Every experimental block was preceded by a block of 27 practice trials that were similar to the experimental trials. Except for the items mentioned earlier, all other conditions were identical to those in Experiment 2.

Results

We calculated the mean RT for every participant in each condition (for correct trials only). Only trials with RTs longer than 200 ms and shorter than 2,000 ms were considered correct (99.4% from all trials). These means were subjected to a four-way ANOVA with all variables within subjects.

All main effects were significant, all $Fs > 7.77$. Only three interactions were significant: relevant dimension and physical distance, $F(2, 26) = 54.06$, $MSE = 6{,}295$; relevant dimension and numerical distance, $F(2, 26) = 4.63$, $MSE = 6{,}123$; and relevant dimension and congruity, $F(2, 26) = 13.36$, $MSE = 5{,}913$. The nonsignificant four-way interaction is presented in Figure 5. To further understand the source of the two-way interactions, we analyzed the numerical and physical comparisons separately for each interaction.

Relevant Dimension × Physical Distance. For the numerical comparison, the physical distance was significant, $F(2, 26) = 3.82$, $MSE = 2{,}899$; RT decreased as distance increased: 810 ms (Distance 1), 795 ms (Distance 2), and 793 ms (Distance 4). The physical distance was highly significant for the physical comparison, $F(2, 26) = 100.82$, $MSE = 8{,}538$. RT decreased as distance increased: 661 ms (Distance 1), 555 ms (Distance 2), and 498 ms (Distance 4).

Relevant Dimension × Numerical Distance. For the numerical comparison, we found a numerical distance effect, $F(2, 26) = 7.67$, $MSE = 8{,}416$; RT decreased as distance increased: 823 ms (Distance 1), 799 ms (Distance 2), and 778 ms (Distance 4). As in Experiment 1 with verbal notation, the distance effect was due to a difference between Distance 1 and Distance 2, $F(1, 13) = 4.76$, $MSE = 7{,}636$, but the difference between Distance 2 and Distance 4 was not significant, $F(1, 13) = 2.16$, $MSE = 13{,}118$, $p > .17$. In contrast, the numerical distance was not significant for the physical comparison, $F < 1$.

Relevant Dimension × Congruity. The simple SCE for numerical comparison was significant, $F(2, 26) = 28.98$, $MSE = 5{,}967$. The congruity effect was interference and facilitatorily based; the 31-ms difference between incongruent (835 ms) and neutral (804 ms) trials, $F(1, 13) = 15.24$, $MSE = 3{,}849$, and the 43-ms difference between neutral and congruent trials (761 ms), $F(1, 13) = 22.18$, $MSE = 5{,}306$, were significant. For the physical comparison, we also found a congruity effect, $F(2, 26) = 13.87$, $MSE = 3{,}499$. Examination of the components of the congruity effect revealed a significant interference component of 39 ms, $F(1, 13) = 21.15$, $MSE = 4{,}568$, but a reverse facilitatory component of −22 ms, $F(1, 13) = 7.85$, $MSE = 3{,}873$. To find out whether the SCE was due to the difference between the neutral condition versus the congruent and the incongruent conditions, we excluded the neutral condition from the analysis. The SCE was still significant: $F(1, 13) = 9.05$, $MSE = 2{,}055$.

Error rates. The three-way interaction of Relevant Dimension × Size Distance × Congruity was significant, $F(4, 52) = 4.16$, $MSE = 0.0025$, $p = .005$. The pattern of results was similar to that produced in the RT analysis. A correlation analysis between RTs and error rates did not reveal any RT–accuracy trade-off ($r = .44$).

Discussion

In this experiment, we managed to find a P-SCE for the verbal numbers. However, the pattern of the SCE was different from what was found in the other experiments. That is, the SCE was neither modulated by numerical distance nor by physical distance. Most important, we found a negative facilitation.[3] Specifically, the neutral condition was processed faster than the congruent condition. This may be due to perceptual similarity between the two members of the pairs of stimuli, which was more salient in the current experimental design than in Experiment 1. This salient feature of the stimuli may have led to faster processing than expected. In contrast, when the stimuli in a given pair were not identical, it resulted in additional processing time, which yielded an extraction of the irrelevant numerical value.

Last, in addition to the absence of overlap in the RTs between the physical and numerical dimensions (a difference of 229 ms in discriminability), the standard deviation (i.e., temporal spread in Schwarz & Ischebeck's [2003] terminology) was small (78 ms for verbal notation and 113 ms for Arabic notation). Hence, such a result contradicts the relative speed account, which assumes that under these conditions, the faster dimension does not interfere with the slower dimension (Schwarz & Ischebeck, 2003).

General Discussion

We start by summarizing the significant results: (a) The SCE was found across conditions. Moreover, the N-SCE had both interference and facilitatory components, while the P-SCE, which appeared for Arabic notation, was interference based. In addition to interference, in the P-SCE for verbal notation, a reverse facilitatory component was observed. (b) In numerical comparisons, the distance effect was indicated by faster mean RTs for a large numerical distance between members of the pair relative to a small numerical distance. This effect interacted with notation and was more moderate for verbal notation. (c) Regarding the interaction between numerical distance and congruity, it is important to note that such an interaction was obtained for Arabic numbers regardless of comparison (physical or numerical[4]). The nature of this interaction was opposite for numerical and physical comparisons; P-SCE increased with augmented numerical distances, while

[3] Since this result is rather surprising, we ran a replication for the physical comparison with 13 new participants. Again, RT for the neutral condition was significantly slower than for the congruent and incongruent conditions.

[4] We did not obtain an interaction between numerical distance and congruity for numerical comparison in Experiment 1. However, when we looked specifically at the Arabic notation, the interaction between distance and congruity approached significance, $F(4, 60) = 2.20$, $MSE = 808$, $p = .08$. However, this was not the case for verbal notation, $F(4, 60) = 0.18$, $MSE = 1{,}258$, $p = .94$.

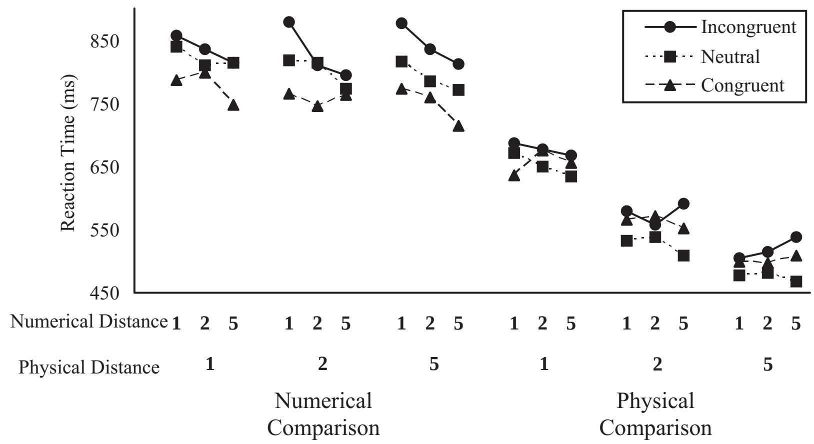

Figure 5. Reaction time as a function of relevant dimension, physical distance, numerical distance, and congruity in Experiment 4.

N-SCE decreased with the increase in numerical distance. In the case of verbal numbers, this interaction was absent for both physical and numerical comparisons. (d) In contrast to the suggestion that discriminability and variability might modulate N-SCE and P-SCE, neither effect was affected by these variables in Experiment 2. (e) A P-SCE was observed for verbal numbers. However, the SCE was atypical and was obtained only when RT was substantially increased, despite the big difference in discriminability. By and large, current models of number processing cannot accommodate these results, and, as we will later elaborate, some modifications are required in order to fit in the data.

Implications for Models of Number Processing

In the numerical comparison, N-SCE and distance effects were obtained for both notations. However, the pattern of the N-SCE and the distance effect for both notations was different: the distance effect was smaller for the verbal notation than for the Arabic notation, and the N-SCE of the Arabic notation was larger and explained a larger portion of the variance than did the N-SCE of the verbal notation. In what way are models in numerical processing compatible with, or challenged by, these results?

The coalescence model. This model assumes no differences between verbal and Arabic numbers. However, the nonlinear relation between the drift rate and RT can lead to nonadditive RT effects in the case of different RTs between the notations. Therefore, the interaction between notation and SCE can be explained by this model. Rather than assuming that the SCE is due to general speed of processing (discriminability according to Algom et al., 1996; Pansky & Algom, 1999, 2002), Schwarz and Ischebeck (2003) assumed that the degree of the SCE depends upon the saliency of irrelevant and relevant dimensions. In this respect, the shallower processing of verbal numbers (as indicated by the smaller distance effect) reduces the chance of interference from the irrelevant physical size, therefore leading to a smaller SCE in the case of verbal numbers. Nevertheless, this type of explanation for the interaction between notation and congruity supports the argument for a difference in the processing of Arabic and verbal numbers. Moreover, assuming that verbal and Arabic numbers are processed similarly, one finds that the coalescence model cannot explain the absence of the interaction between numerical distance and the N-SCE in the verbal notation, nor the interaction between notation and numerical distance as we observed. That is, in a case of interaction between notation and distance, the dimension with the smaller drift rate (i.e., verbal numbers) should yield a larger or equivalent distance effect to that of the dimension with the larger drift rate (i.e., Arabic numbers). In the current study, verbal numbers yielded a smaller distance effect. We replicated the same interaction in a different study (R. Cohen Kadosh, 2008b). To accommodate the current data, the model should assume that different notations (e.g., Arabic and verbal numbers) are processed differently by notation-dependent mechanisms (R. Cohen Kadosh, K. Cohen Kadosh, Kaas, et al., 2007) and thus have different parameters such as the drift rate (as the distance effect is indicated in the model) and the degree of automaticity (see next section).

In addition, the coalescence model predicts that the SCE will be composed of a larger interference component than a facilitatory component. However, while this pattern was sometimes reversed for the N-SCE (Experiments 1 and 4), the P-SCE was composed only of an interference component. Moreover, the model cannot provide an explanation of the negative facilitatory component under P-SCE with verbal numbers (however, we are not familiar with any other model that can do so).

The triple-code model. This model assumes that the different numerical notations are converted into a single notation-independent abstract representation (Dehaene, 1992). Therefore, the model implies no distinction between verbal and Arabic notations in the pattern of the N-SCE and the distance effect. Hence, the interactions between notation and congruity and between notation and numerical distance contradict the central idea of the model. Even the later modification of the triple-code model (Koechlin et al., 1999), which assumes the existence of specific representations of quantity for different notations that converge at a later stage, cannot explain the current results; such separate notation-specific representations can be revealed only under an extreme temporal condition (e.g., subliminal priming), a condition that did not apply to our study. Moreover, Dehaene (1996) has explicitly argued that the distance effect originates independently of the physical or notational characteristics. Therefore, this model cannot explain the interaction between congruity and numerical distance that was obtained here, indicating that congruity (physical characteristics) does influence the distance effect. Thus, the distance effect cannot be independent from physical characteristics of the stimulus.

The encoding complex hypothesis. In contrast to the hypothesis by Dehaene (1992), the encoding complex hypothesis introduced by Campbell and colleagues (Campbell, 1994; Campbell & Epp, 2004) can explain the differences between the notations because they presume that number processing is mediated by modality-specific processes and not by an abstract code. Therefore, this model can explain the interactions between congruity and notation and between notation and numerical distance, results that the triple-code model would have not predicted. However, the encoding complex hypothesis predicts that the distance effect will be larger for the less-practiced notation. In contrast, in the current study, we found the opposite pattern: that the distance effect was larger for the more-practiced Arabic notation and smaller for the less-practiced verbal numbers. The discrepancy between our results and the results in Campbell and Epp (2004), who found a smaller distance effect for Arabic numbers compared with Mandarin numbers, could be due to several reasons. First, our study used Hebrew verbal numbers, which are phonetic, while Mandarin numbers are logographic. Second, in Campbell and Epp's (2004) study, both notations were presented in a mixed design. Since Mandarin and Arabic numbers are logographic, it might be that the perceptual similarity, or sharing of similar brain areas during the perceptual stages, caused some confusion and interference that affected the numerical processing, especially in the case of less-practiced Mandarin numbers. Independent of the exact pattern of the interaction between notation and distance effect, both studies strongly indicate that numerical magnitude is format dependent.

How are notational dependence and verbal numbers represented and processed? We suggest that the default representation of numerical magnitude is not abstract, and such a representation is detectable via unintentional tasks. In line with the interactive specialization approach to functional brain and cognitive development (K. Cohen Kadosh & Johnson, 2007), we suggest that due to the interaction with other brain areas needed for the processing of each notation, separate but highly interconnected subassemblies of neurons for each notation emerge during development. In line with this idea, verbal numbers and Arabic numbers are affected by the left hemisphere due to the need for language (Wiese, 2003). In contrast, Arabic numbers (but not verbal number) are affected by the right hemisphere due to visuospatial abilities (Göbel, Calabria, Farne, & Rossetti, 2006). Therefore, the left parietal lobe is capable of processing Arabic numbers as well as verbal numbers due to its role in language. In contrast, the right parietal lobe is limited in its capacity to process verbal numbers. This of course does not imply that the left parietal lobe represents numbers in an abstract fashion, at least not as a default, as it seems that the left parietal lobe is more limited, in comparison to the right parietal lobe, in its capacity to process other numerical notations (e.g., dots). This idea gains some support from neuropsychological (Colvin, Funnell, & Gazzaniga, 2005) and neuroimaging (R. Cohen Kadosh, K. Cohen Kadosh, Kaas, et al., 2007; Piazza, et al., 2007) studies.

We did not discuss the set of results involving the P-SCE in relation to the various models. Apart from the coalescence model (Schwarz & Ischebeck, 2003), all the other models mentioned focus on relevant numerical processing and ignore irrelevant numerical processing. We now turn to discuss these results.

Effects of Numerical Values on Physical Comparisons (P-SCE)

It is interesting that only under relatively long mean RT (~600 ms), an irrelevant verbal number managed to be processed. Under shorter mean RT, other irrelevant semantic dimensions (i.e., Arabic numbers) managed to be processed and to interfere. This gives additional support for the disparity in processing and the difference in automaticity between Arabic and verbal numbers. An event-related potential (ERP) study showed that under intentional processing, extraction of semantic information from Arabic numbers—compared with verbal numbers—differs only by a few milliseconds (Dehaene, 1996). In contrast, in the current study, it appears that it takes much more time for a verbal number to exert its influence under unintentional processing. This finding supports the idea of weak automatic activation for verbal numbers in contrast to Arabic numbers. Such a weaker automatic activation for verbal numbers might also explain the smaller N-SCE for verbal numbers versus Arabic numbers. In this respect, it might be that the physical size affected the verbal numbers less than the Arabic numbers because the verbal numbers were less automatic and therefore recruited more resources to be processed, even when they were processed intentionally. This in turn left fewer resources to process the irrelevant physical dimension in comparison to the Arabic numbers. This idea is in line with neuroimaging data that showed smaller modulation of the parietal lobes by verbal numbers than by Arabic numbers (R. Cohen Kadosh, K. Cohen Kadosh, Kaas, et al., 2007). This idea also corroborates other neuroimaging and behavioral studies in other domains that show that there are fewer resources to process the irrelevant dimension as task difficulty increases (for a review, see Lavie, 2005). It would be interesting to find out whether other null effects of unintentional processing, as was discussed in the introduction, would have turned out to be significant if RT had been increased extensively, as in the current study (up to ~600 ms). For example, the null P-SCE in the case of Kana numbers in the study by Ito and Hatta (2003) could be attributed to the faster RT for the physical size comparison (~300 ms) that did not allow for the Kana script to be processed.

Another conclusion that can be derived from our results is that autonomous processing of verbal numbers, compared with Arabic numbers, might result in a quantitative or maybe even qualitative difference in intraparietal sulcus activation. Indeed, in a recent functional magnetic resonance imaging (fMRI) study, we showed that Arabic numbers are processed by both the left and right parietal lobes, while verbal number processing is limited only to the left parietal lobe (R. Cohen Kadosh, K. Cohen Kadosh, Kaas, et al., 2007). A TMS study showed that the right, but not the left, parietal lobe is crucial for the SCE with Arabic numbers (R. Cohen

Kadosh, K. Cohen Kadosh, Schuhmann, et al., 2007). We believe that this asymmetry in the processing between the SCE and the verbal numbers helps us to uncover the differences in notational representations. This suggestion of reduced interference due to asymmetry of neuronal mechanisms is in line with previous studies that showed that the irrelevant and relevant dimensions interfere with one another if processing of these two dimensions involves a shared brain structure (the neuronal overlap theory, Fias, Lauwereyns, & Lammertyn, 2001; see also Posner, Sandson, Dhawan, & Shulman, 1990).

The Relative Speed Account of the SCE

Increase in mean RT of the physical comparison with verbal numbers produced a SCE that deviated from the classic effect (i.e., RT for incongruent trials > neutral trials ≥ congruent trials). In Experiment 4, the neutral trials were processed faster than the congruent trials. Independent of indicating differences in the processing between Arabic and verbal numbers, the appearance of the SCE in Experiment 4 uncovered an extreme condition under which the irrelevant dimension might not be processed. Algom and colleagues (Algom et al., 1996; Pansky & Algom, 1999; 2002) proposed that the SCE might disappear if the discriminability and variability between the irrelevant and relevant dimensions are matched. However, Experiments 1 and 2 produced the same SCE for Arabic numbers, independent of variability and discriminability. In contrast, Experiment 4, with a bias in discriminability,[5] produced an SCE. This suggests that the critical aspect might not be variability or discriminability but the processing time of the relevant dimension.

Aside from the lack of facilitation, the P-SCE results can be explained by the coalescence model (Schwarz & Ischebeck, 2003), again if one assumes independent processing of notations at the comparison stage. Although the coalescence model also needs to be changed in order to be able to explain the mismatch in the facilitatory and interference components, we prefer this model over the others due to its broad theoretical framework that can explain numerical comparison under intentional and unintentional processing. Future models dealing with number processing need to take into account processing of numerical information not only when people attend to the information (intentional processing) but also when they do not (automatic processing).

Abstract and Nonabstract Representations in Other Notations

The current study focused on Arabic numbers and verbal numbers. One might argue that the current results are the exception rather than the rule. With other notations such as Roman numerals or numerosity, one might find results that are perfectly in line with abstract models (e.g., the triple-code model). An implied support for this suggestion might come from a recent study by Ganor-Stern and Tzelgov (2008) who concluded that numbers are abstractly represented. They conducted two experiments: one with a same–different task and another with the size congruity paradigm. The same–different experiment was similar to Dehaene and Akhavein's (1995) study but with Indian numbers (a different notation for numbers that is used mostly in Arabic-speaking countries) instead of verbal numbers. In the physical comparison task, they were not able to replicate the distance effect for Arabic numbers, Indian numbers, or mixed notation. However, they argued that numbers were still processed automatically by finding what they called the *value interference effect*; processing the numbers' numerical value impaired participants' "different" responses to different-notation pairs with the same numerical values (e.g., 8 in Arabic notation vs. 8 in Indian notation) compared with those with different numerical values (e.g., 8 in Arabic notation vs. 2 in Indian notation). However, we would like to emphasize that this effect does not indicate semantic processing, and it can be due to asemantic transcoding (e.g., due to phonological representation). In this case, the Arabic number 8 and the Indian number 8 were recognized as representing the same numbers, even though the numerical representation was not accessed (see Dehaene & Akhavein, 1995, for a discussion on this scenario). Indeed, the lack of distance effect in Ganor-Stern and Tzelgov's (2008) experiment supports the idea that numerical information did not reach the level of the semantic representation. In another experiment, they found a P-SCE for Arabic numbers, Indian numbers, and mixed notation (Arabic and Indian numbers). Again, they argued that this effect indicates abstract representation. However, one should note that the P-SCE interacted with notation and with the numerical distance. Stated differently, the P-SCE was affected by the notation and the distance effect, therefore providing a result that cannot be explained by assumption of an abstract representation. Ganor-Stern and Tzelgov's work led them to a totally different conclusion than ours; however, examination of the details of their results seems to support our view that numerical representation is notation dependent. We believe that further work is needed in order to examine how numbers are represented without assuming the fast and most common conclusion that numbers are abstract.

Conclusions

This article shows that with relatively small modification, it is possible for the current cognitive architecture to be more comprehensive in explaining additional phenomena in the area of number processing. One fundamental conclusion derived from this study is that Arabic and verbal numbers are processed in a notation-dependent manner. This, in turn, adds a strong behavioral support for a neuroimaging study (R. Cohen Kadosh, K. Cohen Kadosh, Kaas, et al., 2007), which suggests that under certain conditions the separate representations of Arabic and verbal numbers can be revealed.

[5] Note that in Experiment 4, we also had equal variability. In contrast, in Experiments 1 and 3, the variability in the physical dimension was much smaller than the variability in the numerical dimension. According to Algom and colleagues (1996), the greater the variability of stimuli along an irrelevant dimension, the more difficult it becomes to ignore. Accordingly, in Experiments 1 and 3, there should have been a large effect of the irrelevant numerical dimension on processing of the relevant physical dimension, whereas the irrelevant physical dimension should have had little or no effect on the relevant numerical processing. Note that in Experiment 4, we reduced the number of the verbal numbers to six stimuli, and we still observed the effect.

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