The Universal SNARC Effect

The Association between Number Magnitude and Space is Amodal

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Abstract. It is thought that number magnitude is represented in an abstract and *amodal* way on a left-to-right oriented mental number line. Major evidence for this idea has been provided by the SNARC effect (Dehaene, Bossini, & Giraux, 1993): responses to relatively larger numbers are faster for the right hand, those to smaller numbers for the left hand, even when number magnitude is irrelevant. The SNARC effect has been used to index automatic access to a central semantic and amodal magnitude representation. However, this assumption of modality independence has never been tested and it remains uncertain if the SNARC effect exists in other modalities in a similar way as in the visual modality. We have examined this question by systematically varying modality/notation (auditory number word, visual Arabic numeral, visual number word, visual dice pattern) in a within-participant design. The SNARC effect was found consistently for all modality/notation conditions, including auditory presentation. The size of the SNARC effect in the auditory condition did not differ from the SNARC effect in any visual condition. We conclude that the SNARC effect is indeed a general index of a central semantic and amodal number magnitude representation.

Keywords: amodal number magnitude representation, spatial representation, number processing, auditory and visual presentation, SNARC

Introduction

In 1993, Dehaene and colleagues published a seminal paper concerning the automatic activation of number magnitude, which they found to occur even when it was task-irrelevant. In parity (odd-even) judgment tasks, they found that responses to larger numbers were consistently faster for the right hand key, while responses to smaller numbers were faster for the left hand key. They termed this effect the SNARC (spatial numerical association of response codes) effect and concluded that it indicates automatic assessment of an analogue and *amodal* magnitude representation (see also Dehaene & Cohen, 1995, 1997; Dehaene, Piazza, Pinel, & Cohen, 2003). The modality-independence of the SNARC effect, however, has never been tested.

Although different pathways or conversion routes may lead to an abstract magnitude representation, virtually all current models of number processing assume the existence of such a magnitude representation (e.g., see Cohen & Dehaene, 2000; Dehaene, 1992; Dehaene & Cohen, 1995, 1997, for the triple code model and its functional-anatomical successors; McCloskey, 1992; McCloskey, Caramazza & Basili, 1985; McCloskey & Macaruso, 1995, for a model with one central symbolic semantic magnitude representation; Cipolotti & Butterworth, 1995, for an extension of the McCloskey model; but see Campbell, 1994; Campbell & Clark, 1992, for a contrasting view with regard to amodal magnitude representation in their encoding complex model). Although the centrality of a magnitude representation is disputed, no model – to our knowledge – assumes this magnitude representation to be notation- or modality-specific. However, there are very few studies that have used modalities other than the visual modality in elementary numerical tasks. Zorzi, Priftis, and Umiltà (2002) have tested neglect patients with a number bisection task (what is the middle between 1 and 9?) using auditory presentation. They found that the answers were systematically shifted to the right. Thus, at least in these neglect patients, the spatial representation of the mental number line was also modulated systematically when the stimuli were presented in an auditory rather than a visual modality.

The SNARC effect has been found to be relatively consistent over a wide range of experimental manipulations and participant groups (see Fias & Fischer,

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2005; Gevers & Lammertyn, in press, for reviews about the SNARC effect). In their first paper, Dehaene and colleagues demonstrated the effect for Arabic numbers and – albeit somewhat weaker – for number words, for both highly skilled and less skilled individuals, and for both left- and right-handers (Dehaene et al., 1993). Moreover, the SNARC effect can be found for different notations, such as negative numbers (Fischer, 2003; Fischer & Rottmann, in press; Nuerk, Iversen, & Willmes, 2004), number words (Fias, 2001, Nuerk et al., 2004), and for different kinds of stimuli such as letters, months, or days (Gevers, Reynvoet, & Fias, 2003; but see letter judgment in Dehaene et al., 1993, Exp. 4, for a null effect). Recently, a SNARC effect for Arabic numbers, number words, and German number signs was observed in German signers (Iversen, Nuerk, & Willmes, 2004; Iversen, Nuerk, & Willmes, submitted). For Arabic numbers (although not necessarily for other notations), the effect can be found across different tasks, such as phoneme detection (Fias, 2001; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996), symmetry judgment (Huha, Berch, & Krikorian, 1995), parity judgment (Dehaene et al., 1993; Fias et al., 1996), as well as magnitude comparison (e.g., Dehaene, Dupoux, & Mehler, 1990; Nuerk, Bauer, Krummenacher, Heller, & Willmes, in press). Interestingly, the simple use of Arabic numbers as a fixation point already leads to SNARC-specific variations, which might be interpreted as spatial shifts of attention induced by a simple perceptual encounter with numbers (Fischer, Castel, Dodd, & Pratt, 2003). In addition to eye movement (Fischer, Warlop, Hill, & Fias, 2004) and RT data, reliable SNARC effects have also been observed for error data (Nuerk et al., 2004). Thus, the SNARC effect is a stable and replicable effect across different stimulus materials, tasks, and dependent variables. However, it appears to be most stable for Arabic notation. For other notations, such as number words, the SNARC effect may depend more strongly on the particular task demands. Arabic notation may thus be the stimulus notation that most automatically activates number magnitude.

In all SNARC experiments that have been conducted so far the stimuli were visual. This is surprising because an abstract semantic and *amodal* magnitude representation is supposed to be responsible for the SNARC effect, i.e., it indexes automatic access to magnitude and its spatial orientation for visual and auditory input alike. However, this modality independence assumption has never been tested. Is there an automatic pathway from auditory input to magnitude representation? And if so, how does it differ from the automaticity present in the different visual pathways. Given that the pathway from Arabic input notation to the magnitude representation seems to be more automatic than for verbal material, at least five hypotheses can be postulated:

1. The SNARC effect is a visual effect: No SNARC effect should be found for auditory input.
2. Auditory input is a verbal input and as such comparable to number words: Therefore, the SNARC effect for auditory input should be similar to number words but smaller than for Arabic notation.
3. Auditory input is comparable to the default visual input (which is Arabic notation in our culture): Therefore, the auditory SNARC effect should be comparable to the SNARC effect for Arabic numbers.
4. Whereas different visual inputs (Arabic, number words, but also Roman numbers or dice dot patterns) project to the same analogue magnitude representation and thus the different visual pathways may interfere with one another, the pathway from auditory input to analogue magnitude representation is unique (at least within one language). Therefore, auditory input may lead to a stronger SNARC effect than any visual input.
5. The SNARC effect is independent of modality (and notation). The SNARC effects for different modalities and notations do not differ in any way.

In the current experiment, these hypotheses were examined by comparing the SNARC effect for auditory input with visual Arabic input, visual number word input, and – as a visual control notation – with dice dot patterns. In contrast to many previous studies, we compared the notations within participants and with a larger sample size to enhance the power of the SNARC comparisons.

Methods

Participants

Thirty-two German students and research staff of the University Hospital Aachen (16 female, mean age 25 yrs., range 18–37 yrs.) participated in this study. All of them had normal or corrected-to-normal vision and were right-handed. Participants were not informed about the purpose of the study.

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Parity Decision Task

Numerical stimuli were presented in four different formats (see Figure 1): Arabic numbers (AN), visual number words (NW), auditory number words (AW) and dice dot patterns (DI). Numbers in different formats were presented in separate blocks of trials. Numbers from 0 to 9 were presented 10 times each (100 valid trials) in each block plus 10 practice trials. The order of presentation for different stimulus formats were balanced across participants in a Latin-square design, resulting in four different sequences (AN/NW/AW/DI, NW/AW/DI/AN, AW/DI/AN/NW and DI/AN/NW/AW).

Participants had to decide if a numerical stimulus was odd or even by pressing the right or the left response key. The assignment of which hand was to respond to even or to odd numbers first was balanced across participants. After stimuli were presented in all formats in the first 4 blocks, the Parity × Response Hand assignment was changed (from even-right/odd-left to even-left/odd-right or vice versa). The experiment comprised 8 blocks (= 8 × 100 trials). Participants responded using two keys at a distance of 26 cm from each other, positioned in front of them on the left and right side. Arabic numbers from 0 to 9 comprised a visual angle of 2.5° vertically and 2° horizontally from a viewing distance of 50 cm and number words a visual angle of 2.5° vertically and on average 3.5° horizontally. Dice patterns were presented inside of a squared frame subtending a visual angle of 4° vertically and horizontally. All visual stimuli were presented on a computer screen for a maximum duration of 1,500 ms. After each visual stimulus a fixation cross was presented for 500 ms. Auditory number words were recorded from a male voice uttered in normal speed and were presented via sound boxes positioned below the computer screen at the same rate as the visual stimuli. In auditory trials a fixation cross was presented during the whole block and participants were instructed to fixate. For all stimulus formats reaction time (RT) was recorded for a maximum of 1,500 ms from the beginning of stimulus presentation. Presentation of stimuli and registration of RT were controlled using the Presentation software (www.nbs.com).

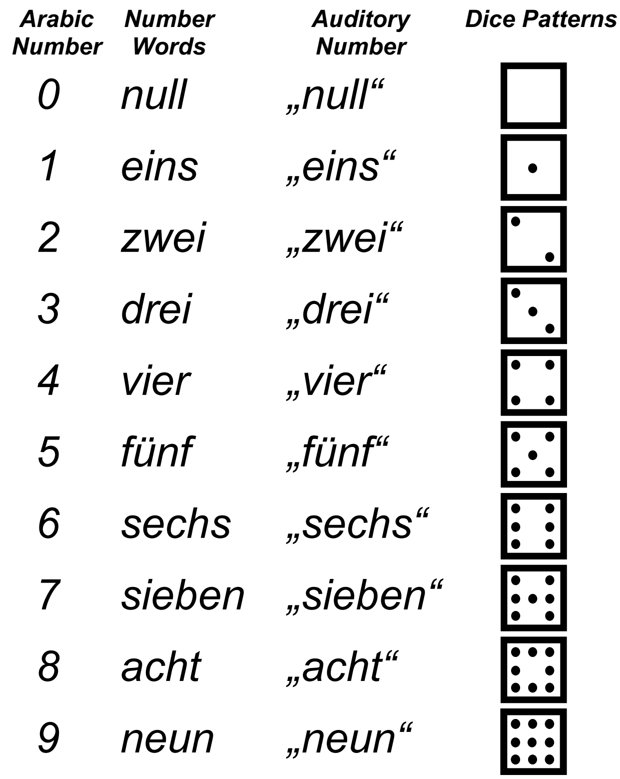

Figure 1. Stimuli presented.

Results

Of trials, 7.1% were excluded from the analysis due to wrong responses, anticipations (RT faster than 200 ms) or RT outside ±3 standard deviations from the individual mean. There was no trade-off between mean RT and error rate ($r = -.331$; $p > .05$). We carried out two analyses with our data: First we performed a 2 × 2 × 4 × 4 ANOVA on mean individual RT across correct responses. The design comprised responding hand (left/right), parity (odd/even), magnitude (with pairs of numbers 1–2, 3–4, 5–6, and 7–8 merged together) and stimulus format (AN, NW, AW, DI) as within-subject factors. We had to exclude numbers 0 and 9 because one participant responded at random to zero in auditory and dice dot pattern presentation. Second, as a complementary analysis, we analyzed SNARC regression slopes for individual participants in the four stimulus formats (method adapted by Fias et al., 1996 based on Lorch & Meyers, 1990). Finally, in order to study the time course of the SNARC effect, we conducted a median-split analysis of RT.

ANOVA

The statistical effects for RT and error rates were quite similar, therefore we will only report the results for RT. Number format had a significant effect on RT, $F(3, 93) = 298.65$; $p < .001$. Arabic numbers were responded to fastest (487 ms) followed by dice dot patterns (538 ms), number words (574 ms), and auditory numbers (909 ms). The large RT difference be-

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tween auditory presentation and the other formats is due to the duration of the auditory stimuli, as RT was always registered from stimulus onset on.

Response hand had no effect on RT, $F(1, 31) < 1$; *ns*. However, the Interaction Hand × Magnitude interaction was significant, $F(3, 93) = 5.55$, $p = .002$, characterizing the SNARC effect. The Hand × Magnitude × Format interaction was not significant: In the ANOVA, the SNARC effect was comparable in all number formats.

The main effect of parity was also significant, $F(3, 93) = 5.91$; $p = .02$, revealing an odd effect. Odd numbers (620 ms) were responded to more slowly than even numbers (612 ms). The main effect of magnitude was also significant, $F(3, 93) = 13.14$; $p < .001$.

Some other interactions also reached significance: the two-way interactions Format × Magnitude, $F(9, 279) = 26.72$; $p < .001$, Magnitude × Parity, $F(3, 93) = 11.08$; $p < .001$, and the three-way interaction Format × Magnitude × Parity, $F(9, 279) = 36.65$; $p < .001$. Mostly, these interactions are related to particularly slow responses to single numbers in a particular notation rather than to systematic trends. Therefore, we will not interpret them in detail. However, in Appendix A and Appendix B, all mean RTs and standard deviations for all conditions are reported to provide the reader with a full overview of the data and the possible sources of these interactions.

SNARC Slopes

More interesting than the ANOVA results were the analyses of the individual SNARC slopes. SNARC slopes were calculated as suggested by Fias and colleagues (1996, see above). For each participant and each single number, mean RT for the left hand response was subtracted from mean RT for the right hand response. For each individual, a linear regression was computed in which this RT difference was predicted by number magnitude and in which the regression slope was estimated for each individual separately. More negative slopes represent larger SNARC-effects (see Figure 2). We examined further the validity of these results by testing the individual SNARC slopes for each condition against 0. All SNARC slopes were significantly smaller than 0. We compared number formats for differences in these individual SNARC slopes. There was no indication of any difference (all $t(31)$ between .10 and .50; all p values $>$ .610 uncorrected).

In order to study the time course of the SNARC effect, we conducted an RT median-split. We calculated the median for each participant in each condition of the experimental design. Then we estimated the individual SNARC slopes for responses below and above the median separately. All responses equal to the median were excluded from the analysis. We calculated a 4 × 2 ANOVA with number format slow/

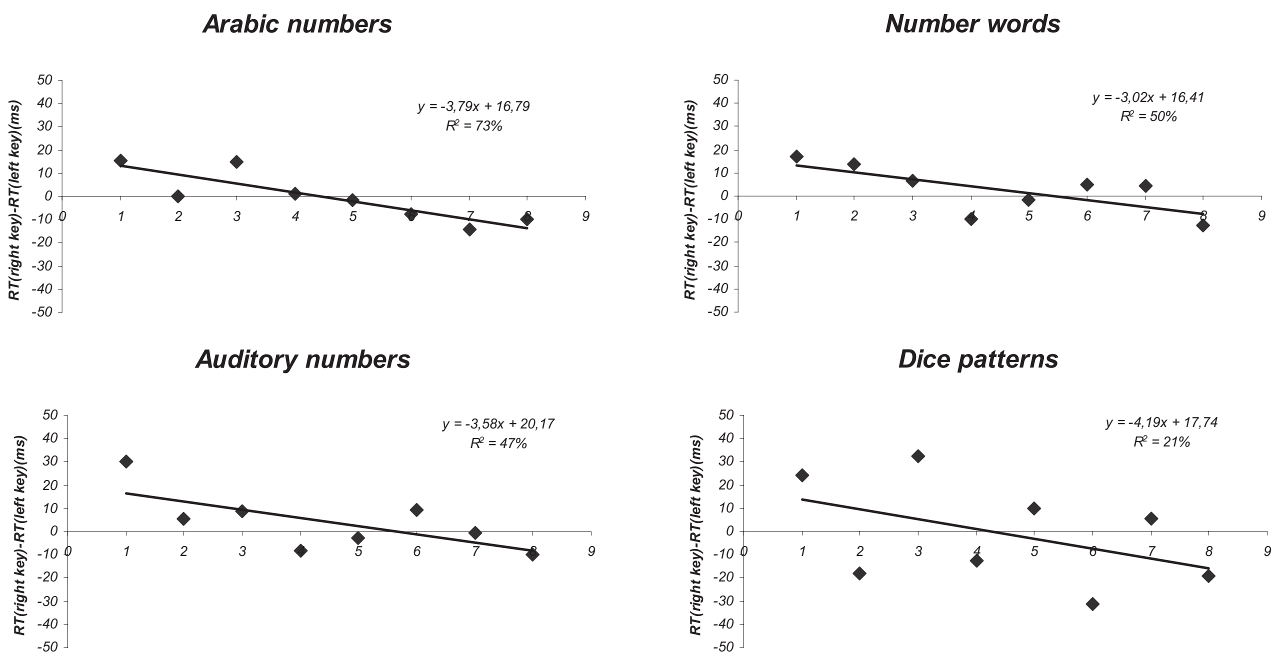

Figure 2. The SNARC effect was significant (tested one-sided) in four different presentation formats: Arabic numbers ($p < .01$), number words ($p < .05$), auditory numbers ($p < .05$), dice dot patterns ($p < .05$).

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fast responses as factors with the SNARC slope as dependent variable. Only the main effect slow/fast response reached significance, $F(1, 31) = 10.97$; $p = .002$: the SNARC slopes were significantly larger when responses were slower (–5.75 ms) than when they were faster (–2.17 ms). Neither the main effect of number format, $F(3, 93) < 1$; *ns*, nor the interaction with slow/fast responses, $F(3, 93) < 1$; *ns*, reached significance. These results show that the SNARC effect increased with processing time and that this increase does not depend on number format or modality. In particular, there was no indication that the SNARC slope for auditory presentation differed from the SNARC slopes in other presentations in any analysis.

Discussion

The SNARC Effect is Amodal

The results indicate that the SNARC effect is not a visual effect. For the auditory as well as for the visual modality, the SNARC effect indexes the existence of an automatic pathway to an *amodal* semantic magnitude representation. For visual stimuli, a SNARC effect was found for Arabic numbers, number words, and dice dot patterns. It is important to note that the SNARC effect for auditory stimuli in our study was not different from the SNARC effect for Arabic numbers or number words or dice dot patterns. Thus, we have found no indication that visual (Arabic) numbers possess more direct and automatic access to the abstract semantic magnitude representation than auditory numbers. In sum, only Hypothesis 5 of the Introduction is corroborated by the results of this study.

A Word on the MARC Effect

We would like to discuss briefly our findings with regard to the MARC effect (Nuerk et al., 2004), which was not the core interest of this study. The MARC effect describes an association between stimulus (parity) and response (left hand/right hand) attributes that are linguistically marked or unmarked, respectively (see Nuerk et al., 2004, for details). Markedness-congruent stimulus response pairs (even number and right hand response/odd number and left hand response) are usually responded to faster than markedness-incongruent trials (even–left; odd–right; Nuerk et al., 2004, see also Berch, Foley, Hill, & McDonough, 1999). Previously we had observed the strongest MARC effect for number words. In this study, we did not observe any main MARC effect (all $t(31)$ between .12 and 1.34; all p values $> .190$ uncorrected). However, closer inspection of the data revealed that the MARC effect depended strongly on the permutation of stimulus notation. For number words, the usual MARC effect was replicated when participants started the experiment with Arabic notation, $t(31) = 3.50$, $p = .01$). However, when the experiment was started with dice dot patterns, a tendency was seen for a reverse MARC effect for number words, $t(31) = 2.13$; $p = .07$, two-sided, resulting in a null overall MARC effect. In our previous research, we had two Arabic notations (positive and negative Arabic notation) and observed an overall MARC effect (Nuerk et al., 2004). In this research, we also observed a MARC effect for number words, but only when the experiment started with the Arabic notation (which was one of four possible notations).

Thus, it would seem that the coupling between the markedness of stimulus attribute (odd/even) and response (left hand/right hand) operates in a flexible and task-dependent way. The SNARC effect is known to be task- and range dependent. When the number range is [0, 5], the numerals 4 and 5 are responded faster to with the right hand, because they are the largest numbers in the available range while the same numerals are responded faster to with the left hand when the number range is [4, 9] and they are the smallest numbers in the range. In a similar way, the markedness association between stimulus and responses seems to depend on the associations triggered by the experimental setting.

Deaf signers, for instance, showed a very reliable MARC effect, which was, however, the reverse of that seen for hearing participants. Future research needs to specify under which conditions and in which participants the markedness association between stimulus and responses operates in its task-specific and possibly participant-specific way.

Magnitude Representation May Be Amodal but its Spatial Association not

In a study with the intriguing title "A SNARC in the dark," Fischer and Hill recently investigated the SNARC effect in a dark room with auditory stimulation. They observed a SNARC effect only when the response hands were crossed, but not in the usual response hand allocation parallel to the respective response key (i.e., the right hand on the right response key and the left hand on the left; Fischer & Hill, 2004). This result contrasts with the findings in our study in which we obtained an ordinary SNARC effect with the parallel response hand allocation.

The integration of these two findings may offer interesting insights about the nature of the spatial association with number magnitude. Our study suggests that the modality of the stimulus input may not be important for an observation of the SNARC effect. However, the built-up of a response-based spatial reference frame that could be associated with number magnitude seems to depend on its visual perception. If the participant does not visually perceive his/her hands as being on the right or left side of space, he/she may not be able to build up a spatial reference frame for the responses and, consequently, he/she might not be able to produce a spatial-numerical stimulus-response association, namely the SNARC effect. Fischer and Hill suggested that the results may be different with crossed hands, because the stronger tactile and proprioceptive stimulation induced by the experimental setting of hand crossing may partially substitute for the lack of visual perception and help to build up a spatial reference frame for responses, which can then be associated with number magnitude again. Thus, while the modality of stimulus input seems to be irrelevant for the activation of number magnitude, its association with space may critically depend on strong external (visual or tactile) feedback from the response-based spatial frame of reference.

From a more general perspective, these findings are also interesting with respect to the issue of spatial stimulus-response associations as indexed by the Simon effect (Simon, 1969). Like the SNARC effect, the Simon effect tends to prevail at the same response key positions (at least in choice reaction tasks, see Anzola, Bertoloni, Buchtel, & Rizzolatti, 1977) with visual stimulation even when participants respond with crossed hands or crossed tools (Riggio, Gawryszewski, & Umiltà, 1986; Wallace, 1971, Wascher, Schatz, Kuder & Verleger, 2001, but see Roswarski, & Proctor, 2003a, 2003b, for comments on the latter study). For auditory stimulation the Simon effect is mostly replicated with parallel hand position; however, the results for crossed hands tend to be more variable then (Simon, Hinrichs & Craft, 1970; Wascher et al., 2001; Roswarski, & Proctor, 2003b). The integration of our results with those of Fischer and Hill also seems to suggest that the existence (or nonexistence) of visual or tactile spatial feedback might be a factor that contributes to the variability of spatial stimulus-response congruity effects in the auditory modality.

Conclusions

It has often been assumed that the SNARC effect indexes an automatic association from (visual or auditory) number input to a semantic (amodal) number magnitude representation, but this has never been tested. This study employing a within-participant design and a rather large sample size shows that the SNARC effect does not differ for auditory input from other visual inputs such as Arabic notation, number words or dice dot patterns. This is good news for researchers studying the spatial representation of numbers: the SNARC effect is indeed an index for a general and amodal magnitude representation of numbers and thus allows for general and modality-independent conclusions about the nature of number representations.

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Appendix A

Descriptive statistics for RT in all experimental conditions.

Modality	Hand		Number Magnitude							
		RT (ms)	1	2	3	4	5	6	7	8
Arabic	Right	Mean	494.2	472.8	488.1	470.0	481.1	479.6	475.0	465.1
		SE	13.1	11.2	16.0	11.7	12.0	11.6	14.9	12.4
	Left	Mean	478.7	473.1	473.2	469.0	482.5	487.1	489.5	475.0
		SE	14.0	14.1	13.0	12.5	10.9	14.0	12.3	11.8
Words	Right	Mean	579.0	541.5	536.2	528.3	532.8	552.7	546.0	522.3
		SE	14.7	14.0	12.2	13.7	12.7	14.4	12.2	11.9
	Left	Mean	561.8	527.6	529.5	538.1	534.7	547.9	541.4	535.0
		SE	17.9	14.1	16.3	14.0	12.4	12.6	15.2	11.5
Auditory	Right	Mean	870.0	907.4	867.6	917.2	980.7	908.5	909.7	821.0
		SE	18.6	19.6	22.3	18.1	19.9	15.1	22.2	19.5
	Left	Mean	839.8	901.9	859.0	925.5	983.4	899.2	910.1	830.6
		SE	16.7	18.9	20.9	19.2	16.0	19.1	19.8	18.2
Dice	Right	Mean	551.7	523.8	549.3	511.5	542.1	524.4	589.9	587.4
		SE	21.4	18.6	24.8	21.4	26.3	21.1	32.9	31.3
	Left	Mean	527.4	542.0	517.0	524.2	532.1	555.7	584.1	606.6
		SE	21.9	19.9	19.7	23.2	26.4	25.4	33.0	30.4

Appendix B

Descriptive statistics for error rates in all experimental conditions.

Modality	Hand		Number Magnitude							
		errors (%)	1	2	3	4	5	6	7	8
Arabic	Right	Mean%	12.2	9.1	4.4	7.8	5.9	7.2	6.3	4.1
		SE%	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.1
	Left	Mean%	4.7	7.2	7.2	1.3	5.3	9.1	6.3	7.2
		SE%	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2
Words	Right	Mean%	17.5	8.8	5.9	3.8	6.6	5.6	5.3	2.8
		SE%	0.3	0.1	0.1	0.1	0.2	0.1	0.2	0.1
	Left	Mean%	10.3	6.3	3.8	6.6	4.7	9.1	6.3	7.2
		SE%	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.2
Auditory	Right	Mean%	12.5	7.8	5.6	5.0	7.5	3.4	8.4	5.0
		SE%	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.1
	Left	Mean%	4.1	4.1	2.2	3.8	6.9	8.4	2.8	6.3
		SE%	0.2	0.1	0.1	0.2	0.2	0.1	0.2	0.2
Dice	Right	Mean%	10.9	15.0	7.8	3.1	7.5	5.0	10.3	10.9
		SE%	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.2
	Left	Mean%	7.8	2.2	5.6	2.8	4.4	5.9	5.9	13.1
		SE	0.2	0.3	0.2	0.1	0.1	0.1	0.2	0.2

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