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Numerical Associations With Visual Space and Size Exist in Parallel

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Two Attributes of Number Meaning:

Numerical Associations with Visual Space and Size Exist in Parallel

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Abstract

Many studies demonstrated interactions between number processing and either spatial codes (effects of spatial-numerical associations) or visual size-related codes (size congruity effect). However, the interrelatedness of these two number couplings is still unclear. The present study examines the simultaneous occurrence of space- and size-numerical congruency effects and their interactions both within and across trials. In a magnitude judgement task physically small or large digits were presented left or right from screen centre. The reaction times analysis revealed that space- and size-congruency effects co-existed in parallel and combined additively. Moreover, a selective sequential modulation of the two congruency effects was found. The size-congruency effect was reduced after size incongruent trials. The space-congruency effect, however, was only affected by the previous space congruency. The observed independence of spatial-numerical and within-magnitude associations is interpreted as evidence that the two couplings reflect different attributes of numerical meaning possibly related to ordinality and cardinality.

Keywords: number processing, spatial-numerical associations, size congruity effect, shared magnitude representation, Gratton effect

It has been argued that number processing is based on a shared analogue system that processes a wide range of magnitude information for perception, action and cognition (Dehaene & Brannon, 2011; Walsh, 2003). Two distinct types of cognitive couplings between numerical and non-numerical information have been proposed to be driven by such a common cognitive metric for magnitudes: interferences between numbers and spatial locations (Dehaene, Bossini, & Giraux, 1993) and within-magnitude interferences between numbers and size-related visual (Henik & Tzelgov, 1982) or motor features (Lindemann, Abolafia, Girardi, & Bekkering, 2007). Although both interference effects have been investigated extensively in the last couple of years, their interrelatedness is still poorly understood and will therefore be subject of the present study.

Evidence for an association between numbers and spatial locations comes from the effect of spatio-numerical associations of response codes (SNARC effect), which refers to the tendency to react faster with the left response to small numbers and with the right response to large numbers (Dehaene et al., 1993). These interactions have been interpreted as evidence for a spatial coding of numerical magnitude in the form of a mental number line (Fias & Fischer, 2005). Effects of spatial-numerical associations exist not only for a wide range of motor responses (for a review see Hubbard, Piazza, Pinel, & Dehaene, 2005), but also emerge at the stimulus level. We henceforth refer to effects reflecting an interactions between stimulus and response features as *compatibility effects* and use the label *congruency effects* for interactions between different stimulus features (cf. Kornblum, Hasbroucq, & Osman, 1990; Hommel, 1997). For instance, Stoianov, Kramer, Umilta & Zorzi (2008) demonstrated that spatial stimulus features interact with number processing independent from the motor response. Moreover, Fischer, Castel, Dodd, & Pratt (2003) found an attentional priming of left or right space in a visual target detection task after subjects processed small or large digits respectively. However, there are also several studies suggesting that spatio-

numerical congruency effects are not as robust as the spatial number-response compatibility effects, such as the classical SNARC effect (Gevers, Caessens, & Fias, 2005; Mapelli, Rusconi, & Umilta, 2003; Fattorini, Pinto, Merola, D'Onofrio & Doricchi, 2016).

In contrast to effects of spatio-numerical associations, within-magnitude interference effects are characterized by a congruency between numbers and the size of visual stimuli (Henik & Tzelgov, 1982; Schwarz & Heinze, 1998) or a compatibility between numbers and size-related motor features such as grip-size (Lindemann et al., 2007) or response intensity (Krause, Lindemann, Toni, & Bekkering, 2014). For instance, in the classical size-congruity paradigm, two digits are simultaneously presented in different sizes and subjects are instructed to indicate the numerically (or physically) larger digit. The size-congruity effect then reflects the interference of physical size in numerical judgments (or numerical size in physical judgments). That is, congruent trials, in which the numerically larger digits is physically larger, are responded to faster than incongruent trials, in which this digit is physically smaller. Size congruity effects in both physical and number classification tasks reflect evidence for a cognitive association between numerical and physical magnitudes (Krause, Pratt, Bekkering, Lindemann, 2016; Schwarz & Heinze, 1998). In addition, the size-congruity effect in physical size classifications has often been used to investigate the automaticity of number magnitude processing (see e.g. Girelli et al., 2000).

The meaning of numbers is not only connected to a particular quantity or magnitude, that is, its cardinality. Each number also stands in a particular relation with all other numbers clearly defined by its unique position within the number sequence. The concept of ordinality refers to this sequential relation. Since also non-numerical sequences such as letters of the alphabet are known to be spontaneously mapped onto space (Gevers, Reynvoet, & Fias, 2003), it has been proposed that any sequential information is spatially coded (van Dijck & Fias, 2011). This implies that spatio-numerical associations reflect the processing of number ordinality. Evidence for this notion is

coming from the finding that participants, who memorize random number sequences, do not show the typical SNARC effect and instead associate the ordinal position of the numbers in the instructed sequence with space (van Dijck & Fias, 2011). It is plausible to assume that, in contrast to the spatial mapping of number order in memory, within-magnitude interferences, for instance between numerical and visual sizes, are not related to order and tap directly into the representation of numerical quantity processed within a shared magnitude system. The concept of number cardinality is linked to the size or magnitude of a number and is assumed to be cognitively represented in an analogue format (Dehaene, 2009). Since within-magnitude interferences are based on associations between analogue magnitude codes, this type of coupling might therefore be less mediated by the ordinality feature of a number and might there reflect the number cardinality.

Based on the hypothesis that spatial and within-magnitude interferences reflect different attributes of numerical concepts, it is expected that space and size congruency or compatibility effects emerge simultaneously and independently from each other. Crucially, however, many theoretical models of number cognition seem to be in conflict with this notion, because they implicitly assume that both spatio-numerical and within- magnitude interferences reflect very similar functional associations and are thus driven by the same cognitive mechanisms of numerical processing (see Dehaene & Brannon, 2011; Walsh, 2003). This would in turn suggest an alternative hypothesis and predicts the presence of an interaction between space and size-based interferences effects.

To test the dependence of spatio-numerical and within-magnitude associations, we instructed participants to classify small and large digits, which were presented in six different visual sizes and at six different horizontal locations and this way allowed a simultaneous and independent variation of number congruency with respect to stimulus position and stimulus size. Responses were given verbally to avoid spatial stimulus-response compatibilities (Lu & Proctor, 1995). If

number associations with visual space and size reflect different attributes of the underlying conceptual representations, the space and size-congruency effects should not interact and emerge additively (cf. Sternberg, 1969).

An additional test of the dissociation of spatio-numerical and within-magnitude interactions is provided by the well-described phenomenon that interference effects are reduced after incompatible trials (Gratton, Coles, & Donchin, 1992). This so-called Gratton-effect occurs for a variety of behavioral compatibility effects (e.g., Stürmer, Leuthold, Soetens, Schröter & Sommer, 2002) including spatial-numerical interferences (Pfister, Schroeder, & Kunde, 2013). Since cognitive control can act specifically for a certain type of conflict while leaving other cognitive interferences unresolved (Egner, 2008), we examined the sequential modulation of space and size congruency effects. If the two types of interferences reflect independent mechanisms of number processing, they are expected to be reduced following an incongruency of the same type but not if the preceding incongruency was of the different type.

Method

Participants

Forty-four students from the Radboud University Nijmegen (33 female, mean age of 22.71 years) took part in the experiment, in return for course credits.

Materials and Stimuli

Experimental software, raw data and analysis scripts are available online via the Open Science framework (OSF): http://osf.io/t54xv.

Number stimuli were presented on a gray background (viewing distance 70 cm) and consisted of the Arabic digits 1 to 9 (except 5). To ensure a maximum consistency in the perceived location and size of the stimuli, digits were presented in white font on top of black dots, which

scaled linearly with the digit size. Numbers appeared at six horizontal positions (-10°, -6°, -3°, 3°, 6°, 10° of visual angle from screen center). Likewise, stimuli were presented in six sizes (diameters of approximately 1.00°, 1.40°, 2.00°, 3.80°, 5.40° & 7.50°). Stimulus diameters were varied exponentially to ensure that consecutive small or large number stimuli were twice/half the size of each other and the size discriminability thus held constant. See figure 1 for an illustration of the experimental stimuli.

Figure 1 about here.

Procedure

Each trial started with a blank screen for 1,000 ms. Afterwards, the fixation dot appeared for 500 ms followed by the number stimulus with a random inter-stimulus interval of 250 to 500 ms. The participants' task was to indicate as fast as possible whether the number was smaller or larger than 5 by saying either /ti:/ or /to:/. We used utterances that begin with the identical phonemes to avoid onset difference in the automatised voice onset detections. The number stimulus disappeared as soon as the response was given or after a maximum interval of 1,500 ms. Verbal responses were recoded by a microphone as well as online classified by the experimenter. After each 36 trials, a feedback on average speed and accuracy of the last responses was provided and participants were given the opportunity to take a short break.

Space and size congruency

Due to systematic variation of spatial location, visual size and numerical magnitude, a continuous measurement of the congruency between the number and spatial position as well as the congruency between the number and visual size could be calculated for each trial. To do so, each stimulus location and size was coded with the values -3, -2, -1, +1, +2, +3, where -3 represented the most left location or smallest size and +3 the most right location or largest size. Space congruency,

SpC, and size congruency, SiC, which varied from -1 (maximally incongruent) to 1 (maximally

congruent) were defined as follows:

$$SpC = \frac{l}{3} \cdot \frac{m-5}{4} = \frac{l(m-5)}{12}, \quad (1)$$

$$SiC = \frac{s(m-5)}{12}, \qquad\qquad (2)$$

were l represents the stimulus location, s the stimulus size and m the number magnitude. SpC and

SiC were calculated for each trial n as well as the preceding congruency in trial n-1, P-SpC and P-

SiC.

Design

The experiment consisted of two blocks with all combinations of the 8 number stimuli, 6 sizes

and 6 locations each, resulting in a total of 576 trials. The mapping of verbal responses changed in

the middle of the experiment. The order of the mapping was counterbalanced across participants.

Trials in each block were presented in a pseudo-randomized order. To interpret the potential

impact of the congruencies in trial n-1 on the congruencies in trial n, the randomization algorithm

(see supplementary material in the OSF repository) ensured that no digit was presented twice in a

row and that the number of transitions between space congruent (SpC>0), space incongruent

(SpC<0), size congruent (SiC>0) and size incongruent (SiC<0) trials was balanced across trials.

Each participant received a different randomized order of trials.

Analysis

Anticipation responses (i.e. RTs faster than 250 ms; 0.27 % of the trials), slow responses (i.e.

RTs slower than 1500 ms; 0.21% of the trials) and trials with incorrect responses (2.18 % of the

trials) were excluded from further statistical analyses. Due to the low error rates, analyses of the response accuracies were omitted.

Three main analyses were performed on the data. First, effects of the congruencies on the RTs and interactions as well as their interaction with the congruencies in trial *n*-1 were analysed using linear mixed effects models (Bates, Maechler, Bolker, & Walker, 2015). Second, to examine the temporal characteristics of the congruency effects, mixed models were extended and the impact of the factor reaction time bin was tested. Third, to get a better insight in the pattern of effects of the preceding congruencies, we employed a linear regression analysis for repeated measures data (Lorch & Myers, 1990, Method 3) on the residual RTs after accounting for the control factors stimulus position, visual size and numerical distance.

Statistical analyses were performed in R with the software libraries lme4 (Bates et al., 2015) and lmerTest (Kuznetsova, Brockhoff, & Christensen, 2016). The *p*-values for mixed models were calculated using the Satterthwaite approximation for degrees of freedom.

Results

Linear mixed effects analysis of the congruencies

A linear mixed effects model tested for the effect of the space and size congruencies SpC and SiC and their interactions. In this model, sequential modulation across trials is reflected by an interaction between a particular type of congruency (SpC or SiC) in trial *n* and the congruency, P-SpC or P-SiC in the preceding trial, *n*-1. Thus, the model comprised the following fixed factors of theoretical interest: SpC, SiC, P-SpC and P-SiC and the interaction SpC:SiC, as well as the sequential modulations SpC:P-SiC, SpC:P-SpC, SiC:P-SiC, SiC:P-SpC, and all high-level interactions. To control for the numerical distance effect in number comparison tasks (Moyer & Landauer, 1967) as well as for differences due to stimulus eccentricity and saliency, we furthermore

included the Numerical Distance, (ND), between the number and the comparison standard,

Stimulus Location (Loc) and Visual Size (VS) as fixed effect. The participant was the only random

main effect in our initial model.

To select a parsimonious but sufficient random effect structure (cf. Barr, Levy, Scheepers, &

Tily, 2013; Bates, Kliegl, Vasishth, & Baayen; in press), we fitted a linear mixed effects model with

the described fixed factors and the by-participant random intercept only and added in a stepwise

manner the random slopes for all factors. χ^2-squared tests of the log likelihoods of the previous

model and the model containing the additional random slope were calculated to determine whether

a random slope was entered in the model or not (Baayen, Davidson, & Bates, 2008). Only the

random slope for ND improved the model fit significantly, $\chi2(2) = 16.74$, $p < .001$. The by-

participant adjustments for VS, $\chi2(3) = 4.60$, $p = .20$, Loc, $\chi2(3) = 3.11$, p = .37, SiC, $\chi2(2) = 1.58$,

$p = .66$, SpC, $\chi2(2) = 3.34$, $p = .34$, P-SiC, $\chi2(2) = 1.05$, $p = .79$, and P-SpC, $\chi2(2) = 1.94$, $p = .58$,

didn't improve the model substantially. The resulting random effect structure of the final model thus

comprised only the random slopes for the intercept and ND.

The results for the linear mixed effects model are summarized in Table 1. As expected,

magnitude classification depended strongly on the numerical distance with shorter RTs for

comparisons with larger numerical distance (see Figure 2). RTs were also substantially affected by

stimulus size. That is, responses were facilitated for large compared to small stimuli. The analysis

revealed that both expected main effects, the effect of SpC and SiC occurred simultaneously

without affecting each other. That is, there was a significant negative linear relationship between

space congruency and response times reflecting that participants responded faster if the numbers

were presented at more congruent positions such as small numbers presented left or large numbers

right. Moreover, the negative linear relationship between size congruency and response time

indicated that participants responded faster when numbers were presented in a congruent size such

as small numbers printed in small and large numbers in large size. Importantly, the interaction of both effects (SiC:SpC) did not reach the level of significance demonstrating that the effect of space congruency was not affected by the level of size congruency and vice versa and therefore suggests that both effects reflect independent numerical associations.

Figure 2 about here.

Moreover, our hypothesis received further support by the analysis of the sequential effects of the preceding congruency. That is, the mixed model revealed the presence of two highly selective Gratton effects. The space congruency effect was modulated by preceding space congruency (SpC:P-SpC) but not by the previous size congruency (SpC:P-SiC). The strength of the size congruency effect, in turn, was only affected by preceding size (SiC:P-SiC) but not space congruency (SiC:P-SpC). The three and four-way interactions were not significant.

Analyses of the interaction between reaction time bin and congruency effects

A possible reason for the lack of interaction between space and size congruencies might be that space and size congruency effects emerge at different stages of cognitive processing. In order to exclude this alternative explanation, we examined whether the strength of the congruency effects varied across different bins of the reaction time distribution. To do so, the RTs of each participant were divided into five reaction time bins. The fixed factor RT-Bin was included to the control factor model with the fixed effects ND, VS and Loc, the random effect Subject and the by-subject variation for the intercept and ND. We afterwards compared this model with models including the interactions between the RT-bin and the two factors SiC and SpC.

Importantly, neither the interaction between RT-Bin and SiC, $\chi^2(4)=0.76, p=.94,$ nor the interaction between RT-Bin and SpC, $\chi^2(4)=1.53, p=.82,$ improved the model fit significantly

suggesting that both the size and the space congruency effect were present equally strong in each reaction time bin and did not emerge at different stages of cognitive processing.

Analysis of the individual congruency slopes

To get a better insight in the pattern of the effects and to visualize the impact of the preceding congruencies, we analyzed the individual linear effects of space and size congruency after congruent and incongruent trials (see Figure 3). To do so, we applied a regression analysis for repeated measures data (Lorch & Myers, 1990, Method 3). Trials with P-SpC > 0 were classified as preceding space congruent and trials with P-SiC > 0 as preceding size congruent. Trials with P-SpC < 0 or P-SiC < 0 were classified as space or size incongruent respectively. We then computed the individual linear effects of space and size congruency after congruent and incongruent trials using regression analyses for repeated measures data.

Since only numerically very small or large digits can have an extreme congruency value, ND is correlated with SpC and SiC. Consequently, we needed to account for the variance related to ND in the analysis on the congruency slopes. To do so, the residuals of the reaction times after accounting for all control factors in the linear mixed effects model above, that is, the fixed effects ND, VS and Loc and the random by-subject variation of intercept and ND, were determined.

For each participant, linear regressions between the residual response time and SpC and SiC were calculated. Note, the size of the negative regression coefficient (-1*b) in this model represents the strength of the expected individual linear congruency effect. These estimates of the individual space and size congruency effects were then submitted to separate 2x2 repeated measures analyses

of variance (ANOVA) with the factors Type of Preceding Congruency (Space, Size) and Preceding

Congruency (congruent, incongruent).

Figure 3 about here.

The mean regression coefficients b are depicted in figure 3. For the position congruency

effect, the ANOVA revealed an impact of the previous position congruency, $F(1,43) = 11.87$, p

$< .01$, $\eta_p^2 = .22$, reflecting that the position congruency effect was stronger following space

congruent (b = -18.76) as compared to incongruent (b = -3.58) trials. Importantly, the position

congruency was not modulated by the previous size congruency, $F(1, 43) = 1.43$ (b = -14.01 vs. b =

-8.33). As expected, the analysis of the size-congruency effects showed the exact opposite pattern of

effects. That is, the size congruency effect was affected by the previous size congruency, $F(1, 43) =$

9.73, $p < .01$, $\eta_p^2 = .18$, but not by the previous space congruency, $F(1, 43) < 1$ (b = -3.14 vs. b = -

4.38). To be precise, size congruency effects were present after size congruent trials (b = -10.72)

and vanished following size incongruent trials (b = 3.20). The interactions in both ANOVAs did not

reach significance, both Fs < 1.

Post-hoc power analyses demonstrated that the non-significant main effects in both

ANOVAs---that is, the lack of impact of the previous size congruency on the position congruency

effect and lack of impact of the previous position congruency on the size congruency effect---were

probably not the result of an insufficient power. Assuming an $\alpha = .05$ and a to-be-detected Gratton

effect, $\eta_p^2 = .17$, that is somewhat smaller the smallest influence of the previous congruency

observed in the present study, the power to detect sequential modulation in the slope analyses was

$(1-\beta)=0.83$. In sum, this pattern of effects confirms the presence of two selective Gratton effects and the independence of the effects of space and size congruencies.

Discussion

The present study examined the relationship between spatio-numerical and within-magnitude couplings and provides converging evidence suggesting that space- and size-congruency effects have different cognitive origins. First, as demonstrated by the linear mixed effects analysis, space and size congruency co-existed in parallel and did not interact. Second, the analysis of the reaction times as well as the analysis of the space and size congruency regression slopes revealed a double dissociation of the sequential modulation of the space and size congruency effect by the type of cognitive conflict in the preceding trial.

The additivity of the space and size congruency effect suggests that the two effects emerge independent from each other and reflect different underlying processes. Including reaction time bin to the statistical model demonstrated that both congruency effects are not modulated by response speed and excludes that the lack of interaction between the effects was caused by a temporal separation of the two cognitive interactions. Consequently, it can be concluded that both effects indeed occurred simultaneously and that space and size congruency effects are driven by different attributes of the number representation.

In addition to these analyses, we tested the independence of the two congruency effects by examining how a particular conflict in one trial affects the conflict in the subsequent trial (Gratton et al., 1992, Stürmer et al., 2002). Importantly, two independent Gratton effects were observed. That is, the reduction of cognitive interference following high-conflict trials was selective for the space and size congruency effect. The space congruency effect was diminished after a space incongruent trial, but not after a size incongruent trial. The size congruency, however, was merely affected by

the preceding trial size congruency. This double dissociation provides additional evidence for the

hypothesis that the two associations of numbers with space or visual size are processed

independently. Even though it can not be exclude that rather small Gratton effects between space-

and size-incongruences exist that are not detectable with the achieved statistical power, all analyses

clearly suggest that sequential modulations within each congruency domain are substantially larger

than possible between-domain Gratton effects. Taken together, the present findings make a strong

case for the idea that inherently different mechanisms are driving spatio-numerical and within-

magnitude couplings and that these two numerical associations are related to distinct attributes of

number meaning.

Previous research suggests that numerical knowledge is associated with space (Dehaene et

al., 1993; Hubbard et al., 2005) and magnitude-related information in perception (Henik & Tzelgov,

1982; Krause et al., 2016) and action (Lindemann et al., 2007). Several models of number

processing assume that number cardinality is represented by an analogue representation that is

subserved by associations between magnitudes, quantities and space (e.g., Dehaene & Brannon,

2011; Hubbard et al., 2005; Umiltà, Priftis, & Zorzi, 2009; Walsh, 2003). These theoretical accounts

assume a single approximate number system that is spatial in nature and imply that spatio-

numerical and within-magnitude couplings are the result of similar functional mechanisms. For

instance, Walsh (2003) argued explicitly for a common origin of spatial and within-magnitude

associations and proposed that space and size congruencies originate from a shared cognitive metric

coding for numbers and space. Importantly, the absence of an interaction between space- and size-

congruency effects in the current study is in conflict with a common mechanism for spatio-

numerical and within-magnitude associations, and the data rather suggest that associations with space and sensorimotor magnitudes reflect different aspects of number concepts.

The idea that spatio-numerical associations reflect a mechanism independent from associations between numbers and sensorimotor magnitudes, such as visual size, is further corroborated by recent research on the neural correlates of number-response compatibility effects. Krause and colleagues (2014), for instance, investigated the relation between grey matter density in parietal cortex and spatio-numerical associations as well as within-magnitude associations between numbers and continuous non-spatial response features such as response force. They found that only within-magnitude interferences but not the SNARC effect was correlated with structural differences in number related brain areas. Similar support for a different origin of space and size congruency effect is also coming from functional neuroimaging studies. While interference between numerical and visual magnitudes are known to emerge from representations in intra-parietal cortex (Cohen Kadosh et al. 2007), spatial-numerical conflicts are not accompanied by changes in neural activity in parietal areas (Weis, Estner, Krick, Reith, & Lachmann, 2015).

The stimulus features manipulated in the present study, spatial extent and location, belong, according to Stevens and Galanter (1957), to different classes of continua referring to either prothetic and metathetic dimensions. Prothetic dimensions such as stimulus extent are characterized by an additive process at the physiological level and thus a continuous quantitative relation between stimulus intensity and perceived magnitude. In contrast, differences along the metathetic dimension---here spatial location---are the result of substitutive processes and thus do not represent quantitative but qualitative differences in sensory excitation. Taking into account this dissociation of perceptual qualities, the independence of space- and size-related numerical interferences shows that mappings of numbers with the metathetic continuum spatial location and mappings with the

prothetic information visual size have to be understood as two functionally different cognitive mechanisms (Lindemann & Fischer, 2015).

If spatial-numerical associations and within-magnitude interferences have different origins, do these effects relate to different attributes of conceptual representations of numbers? While the important role of the ordinality attribute for spatial-numerical associations is well in the literature established (e.g., van Dijck & Fias 2011), we do not fully understand the origin of within-magnitude associations. One might however hypothesize that the clear dissociation of characteristics of the number interferences with prothetic and metathetic stimulus features correspond to the distinction of cardinality and ordinality of number meaning.

That is, spatio-numerical associations have been shown to be driven by the representation of number ordinality, that is, its position in the counting sequence. Recent research suggests that any representation of sequential information in long-term (Gevers et al., 2003) and short-term memory (van Dijck & Fias, 2011) are mapped onto space. For instance, van Dijck and Fias (2011) showed that participants who memorized a sequence of objects responded to items early in the sequence faster with the left compared to the right hand and slower with the left hand to later items. Importantly, this effect generalizes to random digit sequences and suppresses the emergence of the typical left-to-right mapping of numbers onto space. In contrast to the fact that spatial-numerical associations are best characterized by a coupling of the ordinality of numbers with metathetic stimulus or response features, size congruity clearly represents a non-spatial coupling between prothetic dimensions that represent per definition continuous quantitative differences. It is therefore plausible to assume that this within-magnitude interference is primarily related to the representation of analogue quantity information, that is, number cardinality.

An alternative account to the understanding of the independence of the effects of spatial- and within-magnitude associations might be differences in the involvement of working

memory resources. As demonstrated by a recent tDCS study of Schroeder, Pfister, Kunde, Nuerk & Plewnia (in press), an inhibition of working memory circuits eliminates the presence of a SNARC effect providing strong evidence for the claim that the linkage of number and space is shaped in working memory. Since within-magnitude couplings are assumed to rely on direct access to long term memory (Dehaene, 2009), the current finding of an independence of the two couplings might be also explained by different working memory requirements for the mapping of numbers with space or analog magnitude information.

The analyses of the congruency effects in the different reaction time bins reveal that the strength of size- and space-congruency effects was not modulated by the processing time. This finding argues against the idea that the two effects emerged at different stages of cognitive processing and rather suggests that size- and spatial associations are driven by distinct features of the numerical representations.

However, a possible alternative explanation for the independence of spatial and within-magnitude associations might be seen in the different stimulus-response relations. That is, participants indicated verbally the numerical size of the digit (i.e., /ti:/ for small or /to:/ for large). As a consequence, size-congruent trials might also be conceived as semantically congruent with respect to the relation between physical size and the verbal response (Kornblum et al., 1990). Since spatial stimulus congruencies were orthogonal to these stimulus-response compatibilities, response priming mechanisms could have contributed only to the size congruency effect, which in turn might account for the observed independence of the size- and space congruency effects. However, this explanation assumes that the two effects emerge at different processing stages. This notion is however not supported by the bin analyses. Previous research has shown that stimulus-stimulus congruencies and stimulus-response compatibilities exhibit different temporal dynamics (cf. Hommel, 1997). That is,

while interactions at the stimulus level tend to increase with response time, stimulus-response compatibility effects are reduced for slow responses. The bin analysis renders an explanation by different processing stages as unlikely since it revealed no evidence for a modulation of the two congruency effects by response time. Moreover, electrophysiological research clearly suggests that interferences between numerical and physical size emerge early during the encoding of numerical meaning and not while later processes of response selection (Schwarz & Heinze, 1998; Szucs & Soltész, 2007).

Previous research on cognitive control mechanisms suggests that a conflict adaptation between two tasks is more likely to occur when response compatibilities in both tasks are based on the same type of stimulus information. For instance, Notebaert and Verguts (2008) found a transfer between a spatial stimulus-response compatibility effect (i.e., SIMON effect) and SNARC effect. They only observed a Gratton effect between the SIMON and SNARC task---that is, a reduced SIMON effect following a SNARC incongruent trial and vice versa---, if both tasks were based on the same stimulus feature and not if the tasks required the processing of a different stimulus characteristics (e.g. stimulus colour and font). Importantly, in line with this finding, conflict adaptation was observed while all trials comprised the same type of task-relevant (i.e., numerical magnitude) and task-irrelevant information (i.e., size and position). Nevertheless, it has to be noted, that the Gratton effect between size- and spatial congruencies reported here is incommensurable with the notion that conflict adaptation between two tasks depends on the overlap of the task-relevant information, because conflict adaptation was examined only within a single task. Moreover, an additional crucial difference to the study of Notebaert and Verguts (2008) is that the current study does not only examine stimulus-response compatibility effects but also stimulus-stimulus congruencies. The findings reported here therefore demonstrate now that conflict adaptation in number processing also

occurs after processing of conflicting stimulus features independently from any required motor response.

To summarize, the present study investigated the interrelatedness of spatio-numerical and within-magnitude couplings. Our results provided dissociations between both couplings within trials, since both effects did not interact, and across trials, as shown by a selective Gratton effect. Together, these results are in line with the hypothesis that spatio-numerical and within-magnitude mappings are independently related to the two numerical attributes ordinality and cardinality.

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Acknowledgments

Tables

Table 1

Estimates of the fixed effects (ms) for response times.

Effect	Estimate	SE	t	df	p
Intercept	654	12,26	53,33	44	<.001
ND	-14,35	1,31	-10,98	44	<.001
VS	-7,68	0,47	-16,27	12220	<.001
Loc	0,42	0,47	0,88	12220	0.38
SiC	-4,47	2,06	-2,16	12221	<.05
SpC	-8,47	2,06	-4,11	12220	<.001
P-SiC	0,16	2,07	0,08	12243	.94
P-SpC	-0,29	2,06	-0,14	12241	.89
SiC:SpC	0,40	3,34	0,121	12220	.90
SiC:P-SiC	-13,68	4,41	-3,11	12253	<.01
SiC:P-SpC	6,59	4,38	1,50	12255	.13
SpC:P-SiC	-6,97	4,41	-1,58	12250	.11
SpC:P-SpC	-8,64	4,35	-1,99	12249	<.05
P-SiC:P-SpC	-0,39	3.34	-0,12	12249	.91
SiC:SpC:P-SiC	-7,13	7,33	-0,97	12258	.33
SiC:SpC:P-SpC	-4,59	7,16	-0,64	12257	.52
SiC:P-SiC:P-SpC	6,97	7,31	0,95	12260	.34
SpC:P-SiC:P-SpC	-3,77	7,22	-0,52	12256	.60
SiC:SpC:P-SiC: P-SpC	-10,89	12,14	-0,90	12260	.37

Note. ND = Numerical distance; VS = Visual size; Loc = Stimulus location; SiC = Size congruency; SpC = Space congruency; P-SiC = Preceding size congruency; P-SpC = Preceding space congruency

Figure Captions

Figure 1. Illustration of 4 examples from the 36 possible combinations of different space (SpC) and size (SiC) congruencies. Number were presented in 6 different size at 6 different locations.

Figure 2. Mean response onset as a function of absolute numerical distance between the standard (digit 5) and the presented digit, stimulus position and stimulus size. Error bars represent the 95% within-subject confidence intervals (cf. Morey, 2008).

Figure 3. Average regression space and size coefficients b multiplied by -1 as a function of space- and size-congruency on the previous trial. Error bars represent the 95% within-subject confidence intervals.

size congruent
(SiC > 0)
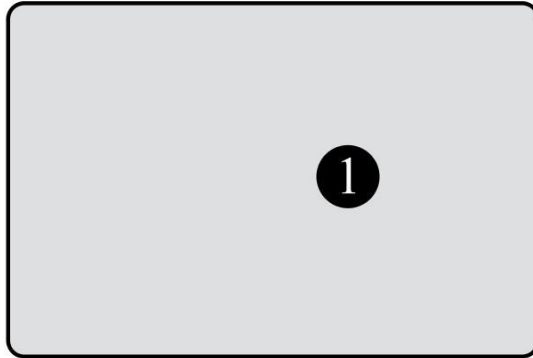
size incongruent
(SiC < 0)

space congruent
(SpC > 0)

space incongruent
(SpC < 0)
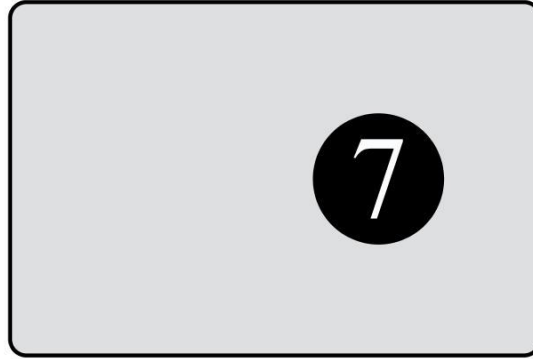
SpC = 0.33, SiC = 0.50
(digit = 7, location = 2, size = 3)
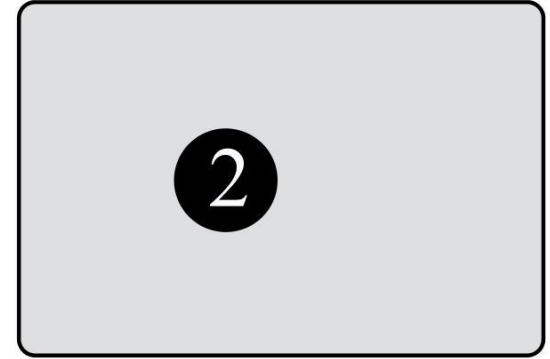
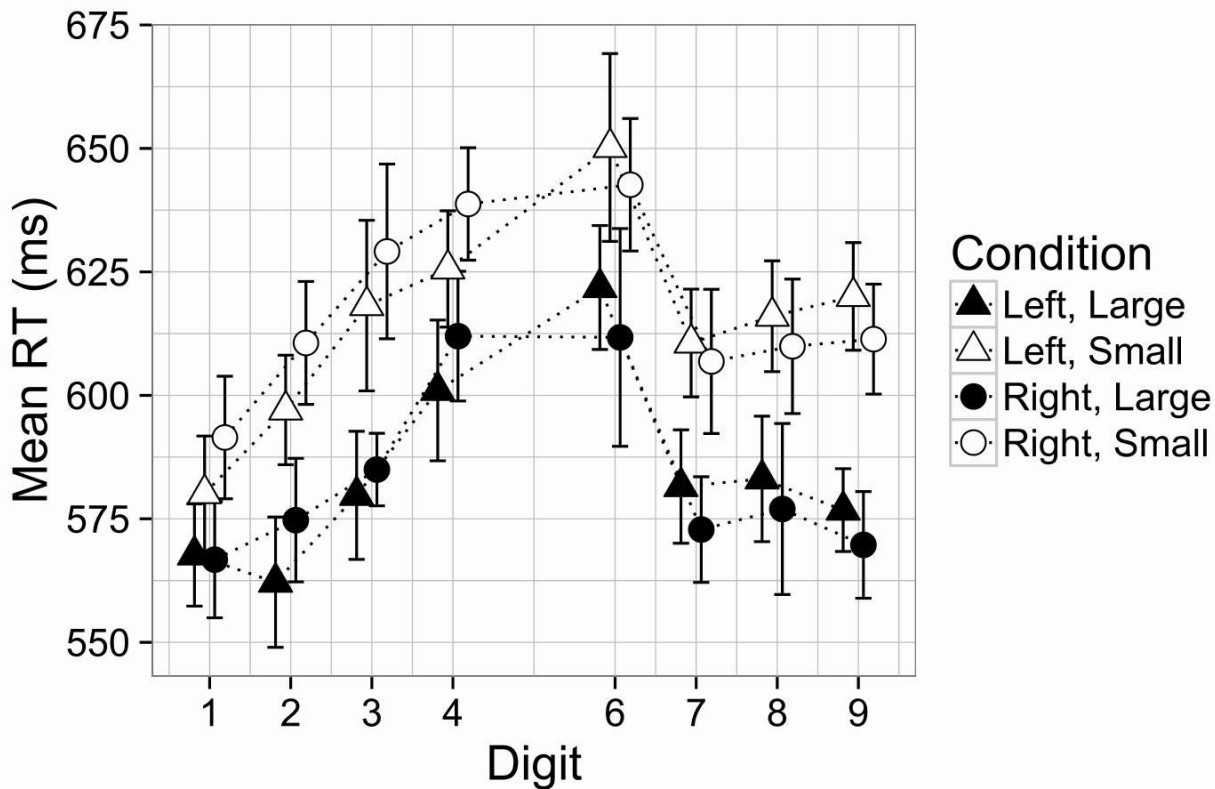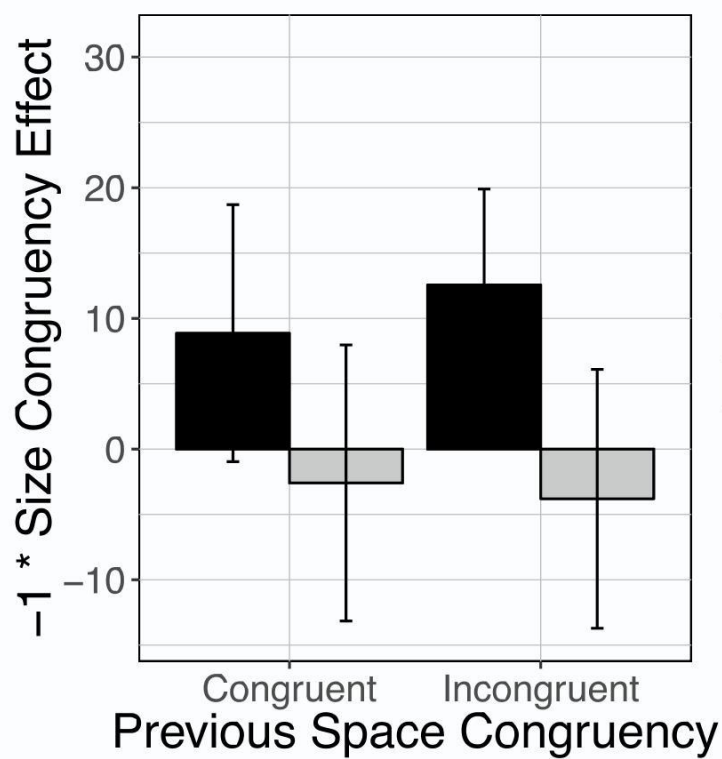SpC = 0.50, SiC = -0.50
(digit = 2, location = -2, size = 2)
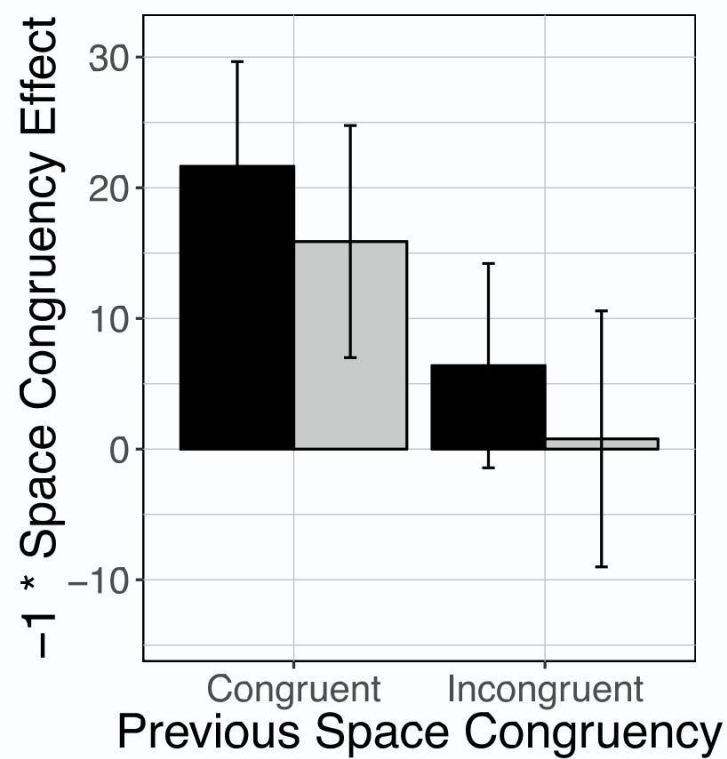
SpC = -0.33, SiC = 0.67
(digit = 1, location = 1, size = -2)

SpC = -1, SiC = -1
(digit = 9, location = -3, size = -3)