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The Spatial-Numerical Association of Response Codes (SNARC) effect in highly math-anxious individuals: An ERP study

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ABSTRACT

The Spatial-Numerical Association of Response Codes (SNARC) effect was examined in highly (HMA) and low math-anxious (LMA) individuals performing a number comparison in an ERP study. The SNARC effect consists of faster latencies when the response side is congruent with number location in the mental number line (MNL). Despite the stronger SNARC effect in the HMA group, their responses in incongruent trials were slower than in congruent trials only for the largest numerical magnitudes. Moreover, HMAs showed a less positive centroparietal P3b component in incongruent trials than in congruent ones, but only for the largest magnitudes. Since the SNARC effect arises during response selection and P3b positivity decreases with the difficulty of decision, this result suggests that HMA individuals might find it more difficult than LMAs to control the conflict between the automatically activated location of numbers in the MNL and the response side, especially in more cognitively demanding trials.

1. Introduction

More than 25 years have passed since Dehaene, Bossini, and Giraux (1993) described for the first time the Spatial-Numerical Association of Response Codes (SNARC) effect. In their seminal paper, they found that in binary classification tasks such as parity and comparison judgments (e.g., deciding whether a number is larger or smaller than 5), classifications were faster for small/large numbers with the left/right response keys, respectively. Since then, this effect has been repeatedly reported (for reviews of the SNARC effect see Fias & Fischer, 2005, and Fischer & Shaki, 2014; for a meta-analysis see Wood, Willmes, Nuerk, & Fischer, 2008). Several explanations have been put forward to justify this effect, with the most accepted being based on the mental number line (MNL). Numbers are represented on a horizontal MNL spatially oriented from left to right in ascending order in Western cultures (e.g., Dehaene et al., 1993). Thus, small numbers (e.g., 1 or 2) are spatially associated with the left side and large numbers (e.g., 8 or 9) with the right side. Processing a number activates its corresponding spatial location on the MNL, even in tasks where numerical magnitude is not necessary such as parity judgments. Evidence supporting this hypothesis has been found in studies showing that the perception of a number involuntarily moves attention to the left or right space activated by that number on the MNL (Fischer, Castel, Dodd, & Pratt, 2003; Salillas, El Yagoubi, & Semenza, 2008). This automatic activation makes it harder to classify a number when there is an incongruity between the activated location on the MNL and the location of the button to respond with.

Although the SNARC effect has been extensively reported, there seem to be individual differences in its strength and it has been estimated that about a third of participants do not even show it (Wood et al., 2008). For example, a stronger SNARC effect has been found in (a) individuals who are slower and whose reaction time is more variable (Cipora & Nuerk, 2013), (b) those with poorer inhibition capacities (Hoffmann, Pigat, & Schiltz, 2014), (c) males (Bull, Cleland, & Mitchell, 2013), (d) individuals with less visuospatial ability in a 2D mental rotation task (Viarouge, Hubbard, & Mccandliss, 2014), and (e) those with higher levels of math anxiety (Georges, Hoffmann, & Schiltz, 2016). In this study, we focused on this last aspect.

Math anxiety refers to the negative emotional response that some individuals have in situations where they need to deal with numbers (for a review see Suárez-Pellicioni, Núñez-Peña, & Colomé, 2016). To our

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knowledge, only one study has investigated the relationship between math anxiety and the SNARC effect. Georges et al. (2016) found a positive correlation between math anxiety scores and the SNARC effect in a parity task, which they interpreted initially as a stronger reliance on the spatial component of the basic mental number representation in highly math-anxious (HMA) individuals. They supported this conclusion by citing some studies that consider the SNARC effect to be a measure of the spatial representation of numbers (Viarouge et al., 2014) and others that have reported a less precise numerical magnitude representation in HMA individuals (e.g., Maloney, Ansari, & Fugelsang, 2011; Núñez-Peña & Suárez-Pellicioni, 2014). However, Georges et al. (2016) also found that HMA individuals showed weaker inhibitory control than their low math-anxious (LMA) peers in a self-designed incompatibility task. This task consisted of asking the participants to judge the colour of a red/green arrow pointing to the left or right side, with the direction in which the arrow was pointing either compatible or incompatible with the side of the correct button to press. They found a negative relationship between the parity SNARC effect and inhibitory control in this task. Thus, although they initially concluded that their findings supported a basic numerical and spatial deficit in HMA individuals, Georges et al. (2016) also stated that "the greater susceptibility to distraction in HMA individuals might lead to greater interference of the irrelevant magnitude-associated spatial code during parity judgments, thereby resulting in stronger parity SNARC effects" (p. 12). This last suggestion in Georges et al.'s (2016) study is supported by the hypothesis of Hoffmann, Pigat et al. (2014) regarding the relationship between a stronger SNARC effect and weaker inhibitory control. The aim of present study was to explore this alternative explanation to Georges et al.'s results. Specifically, we were interested in studying whether HMA individuals' susceptibility to be distracted would make it harder for them to make a decision in incongruent trials.

The proposal that susceptibility to distraction among HMA individuals might underlie their low math achievement (Suárez-Pellicioni, Núñez-Peña, & Colomé, 2014; Suárez-Pellicioni, Núñez-Peña, & Colomé, 2015) was made as an extension of Ashcraft and colleagues' proposal (Ashcraft & Kirk, 2001; Ashcraft, Kirk, & Hopko, 2000; Ashcraft & Krause, 2007). Based on the Processing Efficiency Theory (PET; Eysenck & Calvo, 1992), Ashcraft and colleagues proposed that the anxious reaction would occupy cognitive resources of working memory that would no longer be available to solve the mathematical task, thus worsening performance in this task. Working memory is a system responsible for the control, regulation and active maintenance of a limited amount of information relevant to performing a task (Miyake & Shah, 1999). Thus, math anxiety would result in HMA individuals being faced with a dual task: on the one hand, the execution of the mathematical task (e.g., solving arithmetic operations) and, on the other hand, dealing with concerns related to the task (e.g., thoughts about the negative consequences of failure; Ashcraft & Kirk, 2001). Evidence supporting this proposal can be found in studies that show that HMA individuals are slower and make more mistakes than their LMA peers when solving complex arithmetic problems that load working memory (e.g., carrying additions), but not when solving simple problems (Ashcraft & Faust, 1994; Faust, Ashcraft, & Fleck, 1996). In the first case both tasks would compete for the limited resources of working memory, so performance in the arithmetic task would be hindered.

Suárez-Pellicioni et al. (2014, 2015) used the Attentional Control Theory (ACT; Eysenck, Derakshan, Santos, & Calvo, 2007) as the basis to extend Ashcraft and colleagues' proposal. The ACT, which was developed from the PET, assumes that anxiety increases the influence of stimulus-driven processing over goal-directed regulatory processes, decreasing processing efficiency by affecting two functions involving attentional control: inhibition and shifting. It should be noted that the PET and the ACT state that anxiety affects the processing efficiency (amount of cognitive or attentional resources invested in performing a task) more than the processing effectiveness (execution or result obtained in the task). Suárez-Pellicioni et al. proposed that HMA individuals have a deficit of attentional control that makes them more susceptible to distraction, which might explain their difficulties in numerical tasks, particularly the most difficult ones, which also demand more cognitive resources. These distractors can be internal (intrusive thoughts, concerns, etc.) or external (task irrelevant information).

Given that Georges et al. (2016) reported a stronger SNARC effect in HMA individuals than their LMA counterparts and that this effect could be explained in terms of more distractibility by the automatically activated number spatial code, we aimed to shed more light on this effect by using event-related brain potentials (ERPs). To our knowledge, no study has investigated ERP differences in the SNARC effect as a function of math anxiety, so we took advantage of the high temporal resolution of ERPs to study cognitive processes that cannot be inferred with behavioural measures (Luck, 2005). Specifically, examining the patterns of brain activity between the stimulus and the response can help us to better understand which cognitive process is affected by the higher distractibility.

Although there are very few studies on the SNARC effect using ERPs, one merits attention. Gut, Szumska, Wasilewska, and Jaśkowski (2012) studied the SNARC effect from the perspective of conflict processing. They asked their participants to perform a parity task on one of four digits (1, 2, 8 or 9) and found that the centroparietal P3b amplitude was less positive in incongruent trials compared to congruent trials[1] . Since its discovery in the mid-1960s, the meaning of the centro-parietal P3b has been a matter of considerable debate (for a review see Kok, 2001). The most long-standing interpretation of P3b is that its amplitude is related to context updating (Donchin, 1981; Kok, 2001). Most of the studies supporting this view used an oddball paradigm in which the P3b component indexed the revision or updating of the model of the environment in response to task-relevant, subjectively unexpected events. This updating process is strategic rather than tactical. However, this interpretation does not seem very suitable for a paradigm such as the one used by Gut et al. (2012), and they interpreted their P3b as reflecting "the decision concerning stimulus classification (Verleger, Jaśkowski, & Wascher, 2005) and/or the operation of memory storage when making a decision about the response (Polich, 2003)" (p. 13). Indeed, an alternative to the context updating account proposes that P3b might directly reflect the decision-making process for an immediate response to the current stimulus rather than some post-decision adaptation (e.g., Falkenstein, Hohnsbein, & Hoormann, 1994; Hillyard & Kutas, 1983). In this sense, Verleger et al. (2005) suggested that "P3b reflects a process that mediates between perceptual analysis and response initiation, possibly monitoring whether the decision to classify some stimulus is appropriately transformed into action" (p. 165), and less positive P3b amplitude has been suggested to be a sign of greater difficulty in decision processes (Linden, 2005) or an increase in cognitive workload (e.g., Ghani, Signal, Khan Niazi, & Taylor, 2020). It is worth noting that other electrophysiological studies aimed at discovering at which stage of processing the SNARC effect occurs have indicated that the locus is on the response selection stage (e.g., Keus, Jenks, & Schwarz, 2005), so the automatically activated magnitude information might cause interference during this stage, giving support to Gut et al.'s interpretation of their P3b results.

Given these findings, we considered that the P3b amplitude could be a useful measure to gain further knowledge on the stronger SNARC effect in HMA individuals. In the SNARC effect, a conflict occurs whenever a number (stimulus) spatially associated with the right/left side requires a response with the opposite hand, thus making the decision harder. In the present study, we selected two groups of participants with extreme

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[1] Gut et al.'s results were consistent with the study of Salillas et al. (2008), who measured the SNARC effect in the paradigm of Fischer et al. (2003), where numbers were used as cues for the detection of lateralized spatial targets. In this study, a more positive centro-parietal P3 was also found in congruent compared to incongruent trials.

scores in math anxiety and asked them to perform a comparison task, i.e., deciding whether a number presented on the screen (from 1 to 9, but excluding 5) was smaller or larger than 5. Based on a review of the literature, we hypothesized that the behavioural SNARC effect would be stronger in HMA participants than in their LMA peers. Thus, we expected to extend the findings of Georges et al. (2016) to a numerical comparison task. As for the SNARC effect on ERPs, we predicted a stronger P3b amplitude effect (i.e., less positive centroparietal P3b amplitude in incongruent trials compared to congruent trials) on HMA individuals than in their LMA peers, because the former are expected to be more distracted for the automatically activated spatial location linked to the mental representation of the number and, therefore, their decision would be more difficult. Moreover, we explored whether HMA individuals' difficulties would be stronger for the largest magnitudes in both the behavioural and ERP responses since anxiety is expected to influence processing efficiency to a higher degree under conditions of more cognitive load, according to the ACT. Differences in the processing of small and large numerical magnitudes have been reported in a non-anxious population (e.g., Moyer & Landauer, 1967). Moreover, small numbers are more frequently encountered than large ones (Dehaene & Mehler, 1992); thus, processing of small numerical magnitudes might be easier.

In our study, we formed our groups by controlling for trait anxiety to rule out the possibility that our group differences were due to this variable, since according to the ACT, increased trait anxiety leads to decreased attentional control (Eysenck et al., 2007). Moreover, only women were selected as participants because previous studies have shown gender differences in the SNARC effect (Bull et al., 2013). We selected women instead of men because there is usually an association between math anxiety and gender, with females showing greater math anxiety than males (Hembree, 1990).

2. Methods

2.1. Participants

Forty female students from the University of Barcelona participated in this study. They were part of a larger sample whose math and trait anxieties had been previously assessed within the framework of a larger project. Two groups were formed based on the math anxiety scores on the Shortened Mathematical Anxiety Rating Scale (sMARS) (Alexander & Martray, 1989). The LMA group was formed by twenty participants who had scored below the first quartile[2] in the sMARS (score range = 34–52; mean = 44.7, SD = 5), while the HMA group comprised twenty participants who had scored above the third quartile (range = 77–101; mean score = 85.4, SD = 6.7). As expected, the groups showed significant differences in their math anxiety scores ($t(38) = 21.69$, $p < .001$). By contrast, they did not significantly differ in age ($t(38) = 1.66$, $p = .10$). The ages of the participants in the LMA group ranged from 19 to 25 years (mean age = 21.6, SD = 1.3), while those in the HMA group ranged from 19 to 32 years (mean = 23, SD = 3.38). The groups also did not differ in handedness ($\chi^2(1) = .36$, $p = .55$). There were 19 right-handed participants in the LMA group and 18 in the HMA group. The two groups did not differ in their scores on the trait anxiety scale of the State-Trait Anxiety Inventory (STAI) (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983) ($t(38) = 1.20$, $p = .23$). Scores ranged from 6 to 40 in the LMA group and 6–49 in the HMA group (means (SD) were 21.25 (8.96) and 24.95 (10.37), respectively). All the participants provided signed written informed consent and received a monetary compensation for their participation.

2.2. Materials

2.2.1. Shortened Mathematics Anxiety Rating Scale (sMARS) (Alexander & Martray, 1989)

Math anxiety was measured with this questionnaire, which asked participants to report their level of anxiety in 25 situations that may induce it (e.g., being given a homework assignment with many difficult problems that is due in the next class). The 25 items of the questionnaire are scored on a Likert scale, where 1 indicates no anxiety and 5 represents high anxiety. Hence, the total score ranges from 25 to 125. We used the Spanish version of sMARS (Núñez-Peña, Suárez-Pellicioni, Guilera, & Mercadé-Carranza, 2013), which has strong internal consistency (Cronbach's alpha = .94) and high 7-week test-retest reliability (intra-class correlation coefficient = .72).

2.2.2. The State-Trait Anxiety Inventory (STAI) (Spielberger et al., 1983)

Although this questionnaire has two scales that measure state and trait anxiety, only the trait anxiety scale (STAI-T) was used. It consists of 20 items describing different emotions and is used to measure a general and relatively stable tendency to respond with anxiety. Participants are asked to report how they feel "in general" by giving each of the items a score ranging from 0 (almost never) to 3 (almost always). We used the Spanish version of the test (Spielberger, Gorsuch, & Lushene, 2008), which has shown good to excellent internal consistency (Cronbach's alpha = .95) and adequate 20-day test-retest reliability with college students (r = .86).

2.2.3. Comparison task

The stimuli in the comparison task were all Arabic digits from 1 to 4 and from 6 to 9 and were presented in white Arial font centered on a black screen. We created four blocks and each number was randomly presented on fourteen occasions in each block, giving a total of 448 trials.

2.3. Procedure

Participants were seated in an individual electrically-shielded, sound-attenuating recording chamber, with an electro-cap and independent electrodes placed on them. They were asked to decide whether the number on the screen was smaller or larger than five by pressing one of the two mouse buttons with the corresponding thumb. In two consecutive blocks, they had to click the left button if the number displayed was smaller than five and the right button if it was larger (congruent trials). The response rule was reversed in the next two blocks (incongruent trials). Half of the participants in each group received the blocks in the order described above, while the other half began with the blocks in which the larger numbers were answered with the left mouse button. At the beginning of each block in which a new rule was used, participants received eight training trials: each stimulus was presented once and the response feedback was provided. Each experimental trial had the following structure. A white fixation dot was presented at the center of the screen for 500 ms. Immediately after this, a digit was displayed until the participants responded or for a maximum of 2000 ms. Finally, a black screen was shown for 500 ms between the trials. E-prime 2 (Psychology Software Tools Inc., Sharpsburg, PA, USA) was used to display the stimuli and record the responses. The distance to the computer screen (NEC MultiSync FE770-bk monitor, with a pixel resolution of 1024 × 768 and a vertical refresh rate of 59.8 Hz) was 150 cm. Stimuli subtended a visual angle of 1.48° vertically and 1.03° horizontally.

2.4. Electrophysiological recording

EEG signals were recorded and digitised (500 Hz) with the Scan 4.5 hardware and software (Copyright (C) 2009, Compumedics Neuroscan, Inc., Herndon, VA). We used 32 electrodes mounted in an elastic electro-

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[2] Quartiles were calculated in a sample of 1,547 students at the University of Barcelona (78% females and 22% males) with a mean age of 21.92 years (SD = 5.15).

cap, according to the 10/10 International System: eight electrodes were placed on the midline at the Fpz (placed on every participant at 10 % of the nasion-inion distance), Fz, FCz, Cz, CPz, Pz, POz and Oz locations, along with 12 lateral pairs of electrodes that were placed on standard sites at the prefrontal (FP1/FP2), frontal (F3/F4, F7/F8), frontocentral (FC3/FC4), frontotemporal (FT7/FT8), central (C3/C4), temporal (T7/T8), centroparietal (CP3/CP4), temporoparietal (TP7/TP8), parietal (P3/P4, P7/P8) and occipital (O1/O2) positions. An independent reference electrode was placed on the nose and the ground, between FPz and Fz. The horizontal and vertical electrooculogram movements were controlled respectively by two other independent electrodes, one situated at the outer canthus of the right eye and the other below the left eye. Finally, two independent electrodes were placed on the mastoids for re-referencing. Electrode impedance was kept below 5 kΩ throughout the experiment.

2.5. *Data analysis*

2.5.1. *Behavioural data*

In an initial analysis, medians of response times for correctly solved trials were assessed with a multifactorial ANOVA, using Magnitude (very small, small, large and very large numerical magnitudes) and Congruency (congruent vs incongruent trials) as the within-subject factors and Group (LMA vs HMA) as the between-subjects factor. We collapsed response times for four magnitudes (1–2: very small, 3–4: small, 6–7: large, 8–9: very large) to control for possible Markedness Association of Response Codes (MARC) effects, i.e., faster left-/right-hand responses to odd/even numbers (Nuerk, Iversen, & Willmes, 2004). As for the Congruency factor, this referred to the congruency or incongruency between the location activated by the number on the MNL and the location of the response button, e.g., the number 9 answered with the right hand (congruency) vs the number 9 answered with the left hand (incongruency). Greenhouse-Geisser correction for sphericity departures was applied when appropriate. The F value, the uncorrected degrees of freedom, the probability level following correction, the ε value and the η_p^2 effect size index (Kirk, 1996) are reported. Pairwise comparisons were conducted using t-tests whenever a main effect reached significance and tests of simple effects were conducted whenever an interaction reached significance. The Bonferroni correction was used to control for the increase in type I error for multiple comparisons. Only significant p-values are reported for these last analyses.

We also measured the SNARC effect according to Fias, Brysbaert, Geypens, and d'Ydewalle (1996). We first calculated the dRT (difference in latencies with right and left hands) by subtracting the median RT for responses performed with the left hand from that of the right hand. Afterwards, we performed a regression analysis for the dRTs of each participant, using magnitude as a predictor. Negative regression slopes indicated faster responses to small numbers with the left hand and to large numbers with the right hand, indicating a SNARC effect. We performed t-tests to check whether the regression slopes of the whole sample as well as of each group deviated significantly from zero. Finally, we used an independent t-test to compare slopes between the groups.

2.5.2. *EEG data*

The EEG data were pre-processed with EEGLAB 14.1.1, a toolbox of the MATLAB 9.1.0.441655 (R2016b) software (Copyright (C) 1994–2020, The MathWorks, Inc). They were filtered using a band-pass filter from 0.5 to 30 Hz and then re-referenced with the data from the mastoids. After removing non-stereotypical signal fragments, we ran an independent components analysis (Delorme & Makeig, 2004), using the binica algorithm provided by EEGLAB (Mozaffar and Petr, 2002) to better eliminate the noise generated by eye movement and some other muscle artifacts. Next, epochs for each participant and each experimental condition were averaged relative to a pre-stimulus baseline of 100 ms, using ERPLAB (Lopez-Calderon & Luck, 2014). Only accurate trials were used to determine the average ERP. The number of epochs included in each average ERP for each participant varied between 37 and 56.

To study the P3b component, an ANOVA was performed, using the mean amplitude in the 300–400-ms window at nine electrodes (C3, Cz, C4, CP3, CPz, CP4, P3, Pz, and P4) as the dependent variable. These electrodes were chosen because P3b has its maximum amplitude in the centro-parietal area (e.g., Polich, 2007). We selected the 300–400 ms interval because, although the latency of this component varies notably depending on factors such as the task (e.g., Polich, 2007), P3b is often elicited in this window (e.g., Barceló & Cooper, 2018), and visual inspection of our ERP waveforms showed that amplitude differences were maximum at this latency. Magnitude (very small, small, large and very large), Congruency (congruent vs incongruent), Frontality (central, centroparietal and parietal) and Laterality (left, midline and right) were the within-subject factors in the ANOVA, while Group (LMA vs HMA) was the between-subjects factor. Statistical analyses were performed as described for the behavioural data.

3. Results

3.1. *Behavioural measures*

ANOVA of the response times showed a significant main effect of Congruency ($F(1,38) = 5.58$, $p = .023$, $\eta_p^2 = .13$), with responses being slower in incongruent trials than congruent trials. However, this effect was modulated by Group and Magnitude, as revealed by the significant Congruency x Group interaction ($F(1,38) = 4.13$, $p = .049$, $\eta_p^2 = .10$) and Congruency x Magnitude interaction ($F(3,114) = 6.09$, $p = .001$, $\eta_p^2 = .14$). To study these interactions in more detail, separate ANOVAs were performed for each group, with Magnitude and Congruency as the within-subject factors. Regarding the LMA group, only the main effect of Magnitude was significant ($F(3,57) = 14.11$, $p < .001$, $\varepsilon = .72$, $\eta_p^2 = .43$). Both the main effect of Congruency ($F(1,19) = .05$, $p = .826$, $\eta_p^2 = .003$) and the Magnitude x Congruency ($F(3,57) = 2.25$, $p = .109$, $\eta_p^2 = .13$) interaction failed to reach significance. Paired comparisons for the effect of Magnitude showed that response times were slower for small numerical magnitudes than for very small ($t(19) = 5.58$, $p < .001$) and very large magnitudes ($t(19) = 6.67$, $p < .001$). They were also slower for large than for very small ($t(19) = 3.13$, $p = .006$) and very large magnitudes ($t(19) = 5.46$, $p < .001$), reflecting the distance effect (Moyer & Landauer, 1967) in the LMA group. Importantly, for the HMA group, the main effects of both Congruency and Magnitude as well as their interaction were significant (Congruency: $F(1,19) = 10.75$, $p = .004$, $\eta_p^2 = .36$; Magnitude: $F(3,57) = 16.97$, $p < .001$, $\eta_p^2 = .47$; and the Congruency x Magnitude interaction: $F(3,57) = 4.25$, $p = .009$, $\eta_p^2 = .18$). Paired comparisons for the main effect of Magnitude revealed the same pattern of responses as those described for the LMA group: response times were slower for the small than very small ($t(19) = 7.79$, $p < .001$) and very large magnitudes ($t(19) = 3.90$, $p = .001$), and they were also slower for the large than very small ($t(19) = 5.59$, $p < .001$) and very large magnitudes ($t(19) = 4.25$, $p < .001$). Thus, the distance effect was also observed in this group. As for the interaction, simple effects analysis revealed that the response times were slower in the incongruent trials than in the congruent trials in the HMA group only for the large ($t(19) =$

Table 1
Means and standard errors of the means (SEM; in brackets) for the LMA and HMA groups in the congruent and incongruent trials for each numerical magnitude.

	LMA		HMA	
	Congruent	Incongruent	Congruent	Incongruent
Very small	426 (16.4)	418 (18.6)	440 (19.6)	452 (18.7)
Small	441 (17.0)	441 (18.9)	468 (19.9)	483 (19.6)
Large	432 (16.4)	448 (22.3)	465 (24.6)	498 (21.6)
Very large	416 (17.2)	416 (17.5)	437 (21.0)	469 (17.1)

3.36, p = .003) and very large magnitudes (t(19) = 3.59, p = .002). Table 1 shows the means and SEMs for the LMA and HMA groups in each experimental condition.

As for the analysis of the regression slopes, we found some evidence of a general SNARC effect in the whole sample (mean unstandardised slope = −3.46; t(39) = 2, p = .052). When analysing each group separately, only the HMA participants showed a SNARC effect (mean unstandardised slope = −7.40; t(19) = 3.29, p = .004). In the LMA group, the mean unstandardised slope was .48 and t(19) < 1. As expected, the difference between the regression slopes of the two groups was significant (t(38) = 2.41, p = .02). Fig. 1 shows the linear regression lines that best predict the dRTs, using magnitude as a predictor for each of the groups.

3.2. ERP measures

The analyses performed on the mean amplitude in the 300-400-ms window revealed that neither the main effect of Magnitude (F(1,38) = 1.18, p = .322, η_p^2 = .03) nor that of Congruency (F(1,38) = 1.05, p = .312, η_p^2 = .03) reached statistical significance. However, the effect of Group was marginally significant (F(1,38) = 3.88, p = .056, η_p^2 = .09), with HMA individuals showing less positive amplitudes than their LMA peers. Furthermore, significant interactions for Magnitude x Frontality (F(6,228) = 3.01, p = .03, ε = .54, η_p^2 = .07) and Magnitude x Congruency x Laterality (F(6,228) = 4.16, p = .006, ε = .57, η_p^2 = .10) were observed.

A more detailed analysis of these interactions was performed because we were interested in studying differences in the congruency effect in HMA and LMA individuals depending on the magnitude. Thus, we undertook separate ANOVAs for each magnitude at the three laterality levels considering Congruency and Frontality as the within-subject factors and Group as the between-subjects factor. As for the left hemisphere, no effect was significant for any of the numerical magnitudes (all p-values ≥ .1). Concerning the midline sites, there were no significant effects for the very small and small magnitudes (all p-values ≥ .1); however, importantly, very interesting effects emerged for the large and very large magnitudes. For the large magnitude, the Congruency x Group interaction (F(1,38) = 4.22, p = .047, η_p^2 = .10) and the main effect of Group (F(1,38) = 4.47, p = .041, η_p^2 = .11) were significant. For the very large magnitude, a main effect of Group was found (F(1,38) = 5.25, p = .027, η_p^2 = .12). When looking at each group separately, the effect of Congruency was significant in the HMA group for the very large magnitudes (F(1,19) = 4.99, p = .038, η_p^2 = .21), where the amplitude was less positive for incongruent than congruent trials. Although the effect of Congruency did not reach statistical significance in the HMA group for the large magnitudes (F(1,19) = 3.13, p = .093, η_p = .14), the results showed a similar trend, with amplitude being less positive for incongruent than for congruent trials. In the LMA group, there was no effect of congruency.

Finally, regarding the right hemisphere, there was again no significant effect for the very small and small magnitudes (all p-values ≥ .1). Crucially, the Group effect (F(1,38) = 4.56, p = .039, η_p^2 = .11) and the Congruency x Group interaction (F(1,38) = 4.54, p = .04, η_p^2 = .11) were significant for the large magnitude. A significant main effect of Congruency (F(1,38) = 9.50, p = .004, η_p^2 = .20) as well as a marginally significant effect of Group (F(1,38) = 3.65, p = .064, η_p^2 = .09) were also observed for the very large magnitude. A separate analysis by group showed that amplitude was less positive for the incongruent than congruent trials only in the HMA individuals for large (F(1,19) = 5.99, p = .024, η_p^2 = .24) and very large (F(1,19) = 8.58, p = .009, η_p^2 = .31) magnitudes. No congruency effect was found in the LMA group for any of the magnitudes (all p-values ≥ .1). Fig. 2 shows the grand average ERPs for the very large magnitude in the congruent and incongruent trials in both groups recorded with the centroparietal electrodes.

4. Discussion

The aim of this study was to gain further knowledge on the relationship between math anxiety and the SNARC effect by studying brain activity in a comparison task. Georges et al. (2016) showed that HMA individuals had a stronger behavioural SNARC effect than their LMA counterparts in a parity task and suggested that it could be explained by HMA's stronger reliance on the spatial component of the basic mental number representation or by their greater susceptibility to distraction, which might lead to greater interference by the irrelevant magnitude-associated spatial code during parity judgments. A stronger SNARC effect has already been explained by greater sensitivity to the interference that the automatically activated location on the MNL has on the location of the response button (e.g., Hoffmann, Pigat et al., 2014). Moreover, according to the ACT, anxiety reduces processing efficiency by affecting attentional control (Eysenck et al., 2007), and several studies have reported that HMA individuals are more susceptible to distraction when performing numerical tasks (e.g., Suárez-Pellicioni et al., 2014). Consequently, in this study, we sought to examine whether HMA individuals would be more distracted by the spatial magnitude code associated with digits in the comparison task, making it more difficult for them to make a decision in incongruent trials.

There were two major findings in this study. First, we extended the behavioural results of Georges et al. (2016) to a comparison task. A stronger SNARC effect was found in the HMA group than in the LMA group. Importantly, when looking at these data in more detail, we found that only the HMA group showed a SNARC effect and that they were slower in incongruent trials than in congruent trials, specifically for the largest numerical magnitudes (large and very large). Thus, the number–space conflict in HMA individuals seems to be especially serious with these numerical magnitudes. It is worth adding that we controlled for trait anxiety in our study. Hence, we can rule out the possibility that our group differences were explained by this factor, which positively correlates with deficits in attentional control (e.g., Pacheco-Unguetti, Acosta, Lupiáñez, Román, & Derakshan, 2012).

Our second finding was that the groups also differed in their brain responses in the incongruent trials. Changes in the P3b amplitude depending on congruence were only found in the HMA group. This effect was centroparietally distributed and right-lateralized: P3b was less positive for incongruent trials than for congruent trials in this group, only for the very large magnitude at the midline and for the large and very large magnitudes in the right hemisphere. Previous studies suggested that the centroparietal P3b might be a marker of the decision-making process for an immediate response to the current stimulus (e.g., Falkenstein et al., 1994; Hillyard & Kutas, 1983; Verleger, Baur, Metzner, & Śmigasiewicz, 2014), and a less positive P3b amplitude has been considered a sign of greater difficulty in decision-making processes (Linden, 2005) or an increase in cognitive workload (e.g., Ghani et al., 2020). Moreover, some studies have provided evidence that the automatically activated magnitude information causes interference in the SNARC effect on the response selection stage (e.g., Keus et al., 2005). Taken together, our results suggest that it might be harder for HMA individuals to select their response in incongruent trials than for their LMA counterparts, because of the difficulty HMAs have in controlling the interference of the automatically activated spatial dimension of numbers on the MNL. As regards the P3b's relationship with aspects of the decision process, Verleger's (2020) paper presented an interesting revision of findings for these response-related effects. In previous work, Verleger and colleagues (e.g., Verleger, Grauhan, & Śmigasiewicz, 2016; Verleger et al., 2005) proposed that the P3b forms a 'bridge' from stimulus (S) to response (R), and so its amplitude increases when a well-established S-R link is reactivated (i.e., the *S–R link reactivation* account).

The worse interference control in HMA individuals had been previously reported in different Stroop tasks (numerical and emotional Stroop tasks, e.g., Suárez-Pellicioni et al., 2014), and it was interpreted

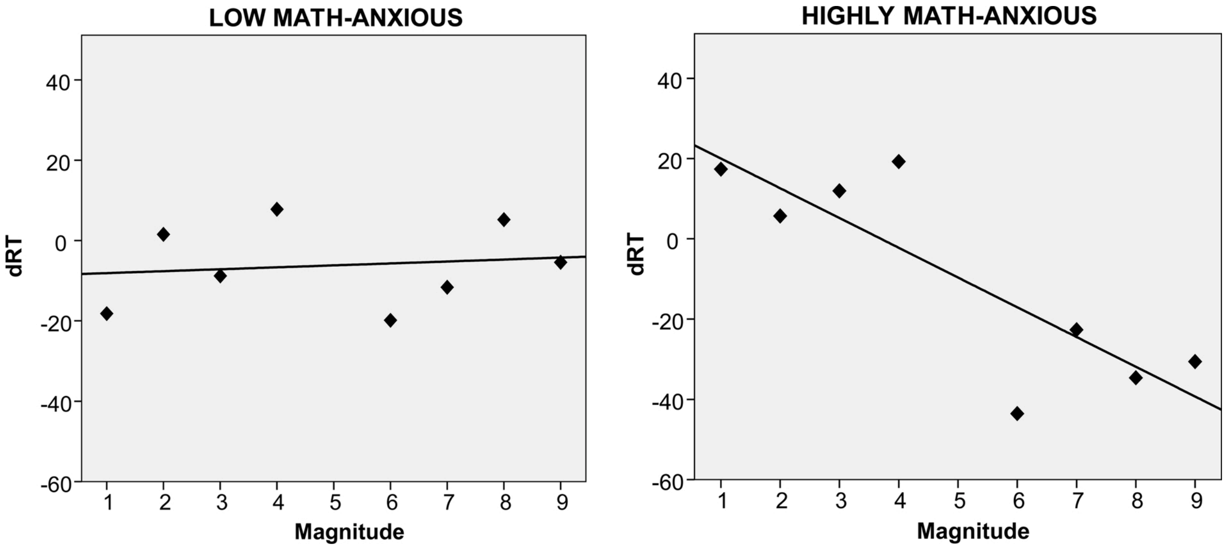

Fig. 1. The SNARC effect presented as a linear regression line that best predicts the differences in latencies between the right and left hand (dRT) as a function of numerical magnitude. Regression lines for each of the groups are shown.

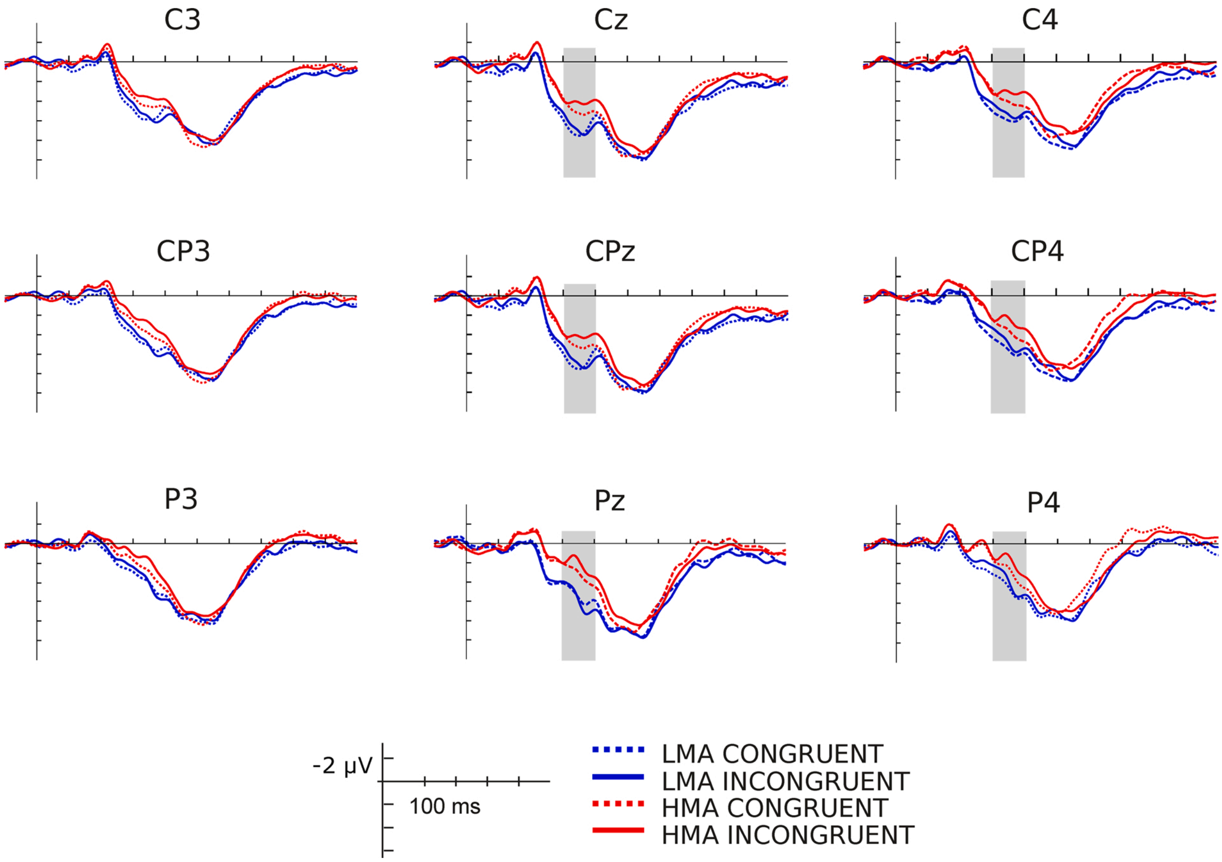

Fig. 2. Grand average ERPs in the congruent and incongruent trials for the very large magnitudes in both groups. The time interval for significant effects is shaded. The effect of Congruency was significant for these magnitudes in the HMA group in midline and right sites.

according to the ACT (Eysenck et al., 2007) as a stronger susceptibility to distraction in highly-anxious individuals. Similar modulations of the P3b amplitude to the ones we found in the present study have been reported in other interference paradigms. In an Attention Network Test that included a flanker task using arrows[3] (Eriksen & Eriksen, 1974), Neuhaus et al. (2007), Neuhaus et al. (2010) found a less positive P3 amplitude at parietal electrodes in incongruent trials when compared to congruent trials (see also Oelhafen et al., 2013). Neuhaus et al. (2010) suggested that "parietal P3 may mirror both increased difficulty of target detection as well as inhibition per se" (p. 78). Thus, their reduced parietal P3 (i.e., less positive) may reflect worse suppression of the activation of the distracting flankers (see similar findings in Kałamała, Szewczyk, Senderecka, & Wodniecka, 2018). Attenuation in P3b amplitude has also been found in task switching paradigms, where target-locked switch trials elicit a less positive centroparietal P3 relative to repeat trials; this is consistent with smaller P3b amplitude reflecting greater difficulty in decision processes (e.g., Barceló, Periáñez, & Nyhus, 2008).

Our ERP results were consistent with the differences in the response times we found in our study. In both measures, a greater interference effect was observed in the HMA group than in the LMA group for the largest numerical magnitudes. But why were differences between the congruent and incongruent trials only found for the large and very large magnitudes in the HMA group? Several studies have reported that the processing of large numerosities is harder than the processing of small ones. First, the size effect (Moyer & Landauer, 1967) is a well-established phenomenon in numerical comparison tasks, where it is easier to compare low magnitude (1–2) than large magnitude digits (8–9) for number pairs with equivalent distance. Second, Núñez-Peña and Suárez-Pellicioni (2014) reported a tendency for a larger size effect in HMA individuals than in their LMA peers. Overall, the better performance when dealing with small numerosities compared to large ones has often been explained by the increased familiarity with the former (Dehaene & Mehler, 1992), which would lead to more automatic processing and, therefore, be less cognitively demanding.

In the field of anxiety, the ACT (Eysenck et al., 2007) predicts that the negative effects of anxiety on performance in cognitive tasks are due to the impaired use of attentional control mechanisms, which is more detrimental in tasks placing more demands on cognitive resources. Indeed, the role of cognitive load in the negative relationship between math anxiety and mathematical performance is a phenomenon that has been reported several times (e.g., Ashcraft, 2002). In the present study, the stronger SNARC effect in HMA individuals for the largest magnitudes could be explained by their susceptibility to distraction (i.e., interference from the activated location on the MNL) being greater for these less familiar magnitudes.

Our behavioral results are consistent with those of Gut et al. (2012), who found a Congruency x Magnitude interaction in their parity task. They reported that although people were generally slower in deciding on the parity of high compared to low magnitudes, this difference was larger in incongruent trials than in congruent trials. Although they did not include a comparison between incongruent and congruent stimuli for each magnitude in their analysis like we did, Fig. 2 in their paper suggests that this difference was larger for the high magnitudes than the low ones. They interpreted this effect in terms of greater familiarity and the automatic processing of low magnitudes, since digits like '1' or '2' are more frequently found in everyday life. Moreover, they reported less positive P3 amplitudes at centroparietal sites in incongruent trials compared to congruent trials for high numerical magnitudes in the right hemisphere, as we found in the present study.

Before concluding we would like to mention a few limitations of our study. First, the most obvious was that all the participants were women and, therefore, generalization to the male population should be made with caution. Although a weaker SNARC effect has been reported in women than in men (Bull et al., 2013), we observed a stronger SNARC effect in females with high math anxiety. Future studies aiming to compare the SNARC effect between genders might want to consider math anxiety as a variable to take into account. Second, the SNARC effect has been linked to mathematical proficiency, being weaker in arithmetically skilled individuals (Hoffmann, Mussolin et al., 2014; Kramer, Bressan, & Grassi, 2018). Mathematical proficiency also negatively correlates with math anxiety (e.g., Ashcraft & Krause, 2007). Thus, the stronger SNARC effect found in the present study in HMA individuals might also be due to these individuals being less skilled in mathematics compared to their LMA peers. However, the relationship between the SNARC effect and mathematical ability is far from clear. Cipora, He, and Nuerk (2020) recently revised research on the association between the SNARC effect and mathematical skills, reporting that the majority of studies have not found a significant relationship. Moreover, Hoffmann et al. stated that they could not rule out that other factors, such as inhibition deficits or mathematical anxiety, could influence differences in the SNARC effect depending on the level of mathematical proficiency. Also, although in our study we did not control for math ability, no group differences were found for congruent trials in the comparison task, suggesting that HMA and LMA individuals did not differ in math tasks of this type. Third, a greater SNARC effect has also been associated with lower visuospatial abilities (Viarouge et al., 2014) and HMA individuals perform worse than their LMA peers in spatial tasks (e.g., Ferguson, Maloney, Fugelsang, & Risko, 2015; Núñez-Peña, González-Gómez, & Colomé, 2019). Hence, the stronger SNARC effect in our HMA individuals could be explained by their lower spatial ability. However, the fact that the differences between the congruent and incongruent trials were not only found in the response times, but also in the centroparietal P3b makes it more plausible that the differences we found were due to greater susceptibility to distraction in HMA individuals. Moreover, in both measures, the SNARC effect was significant only in the more demanding conditions, as predicted by the ACT for the effect of anxiety on performance (Eysenck et al., 2007), which is difficult to explain in terms of a lower spatial ability in the more anxious group. Finally, a less positive P3b amplitude has been reported in externalizing (e.g., delinquency and impulsivity) and internalizing (e.g., depression and anxiety) disorders, and so it has been suggested that this amplitude modulation might reflect a general psychopathology factor (Bernat, Ellis, Bachman, & Hicks, 2020). Although in the present study the groups were formed in such a way that they did not differ in trait anxiety, we did not control for other types of psychopathologies that might have affected P3b amplitude.

In summary, the present study provides further evidence that individuals with high math anxiety might have a deficit in attentional control that does not allow them to prevent their attentional resources from deviating to irrelevant aspects during numerical task performances. These difficulties in suppressing the processing of irrelevant properties of the stimuli might hinder their decision processes and hamper their performance in numerical tasks, particularly in the more cognitively demanding.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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[3] In their flanker task, participants were asked to decide on the direction (left/right) a central arrow was pointing to. This arrow appeared in the middle of a horizontal line containing five stimuli. The four flanking stimuli were lines (neutral condition) or arrows pointing to the same direction (congruent trials) or the opposite direction (incongruent trials) as that of the central arrow.

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