TOPICS
TOPICS IN COGNITIVE SCIENCE

Topics in Cognitive Science 5 (2013) 354–366

ISSN:1756-8757 print / 1756-8765 online
DOI: 10.1111/tops.12017

Singing Numbers… in Cognitive Space — A Dual-Task Study of the Link Between Pitch, Space, and Numbers

Martin H. Fischer,[a] Marianna Riello,[b] Bruno L. Giordano,[c,d] Elena Rusconi[e,f]

[a]*Division of Cognitive Sciences, University of Potsdam*
[b]*Center for Mind/Brain Sciences, University of Trento*
[c]*Department of Music Research, Centre for Interdisciplinary Research in Music Media and Technology, McGill University*
[d]*Institute of Neuroscience and Psychology, University of Glasgow*
[e]*Department of Neurosciences, University of Parma*
[f]*Department of Security and Crime Science, University College London*

Received 20 April 2011; received in revised form 14 March 2012; accepted 5 November 2012

Abstract

We assessed the automaticity of spatial-numerical and spatial-musical associations by testing their intentionality and load sensitivity in a dual-task paradigm. In separate sessions, 16 healthy adults performed magnitude and pitch comparisons on sung numbers with variable pitch. Stimuli and response alternatives were identical, but the relevant stimulus attribute (pitch or number) differed between tasks. Concomitant tasks required retention of either color or location information. Results show that spatial associations of both magnitude and pitch are load sensitive and that the spatial association for pitch is more powerful than that for magnitude. These findings argue against the automaticity of spatial mappings in either stimulus dimension.

Keywords: Auditory pitch; Dual task; Mental number line; SMARC; SNARC; Spatial coding

Cognitive activities can be more or less demanding, and our performance limitations under cognitive load reveal important principles of cognitive functioning. One such principle is to rely on physical space for problem solving. This spatialization strategy is evident in several domains of cognition. For example, in numerical cognition most Western adults associate small numbers with left space and larger numbers with right space. As a result, lateralized responses to classify digits as odd or even (the parity judgment task) show a preference for left response keys with small numbers and for right response keys

Correspondence should be sent to Martin Fischer, Division of Cognitive Sciences, University of Potsdam, Karl-Liebknecht-Str. 24/25 House 14, D-14476 Potsdam-Golm, Germany. E-mail: martinf@uni-potsdam.de

with large numbers. Similarly, in a magnitude comparison task the smaller of two numbers is faster identified with left-side responses and the larger of two numbers is faster identified with right-side responses. This Spatial-Numerical Association of Response Codes (SNARC effect: Dehaene, Bossini, & Giraux, 1993) has now been documented in a wide range of settings (Wood, Nuerk, Willmes, & Fischer, 2008) and across several cultures (Göbel, Shaki, & Fischer, 2011). Similarly, in auditory frequency discrimination, a preferential association between lower response keys and low pitch, and between upper response keys and high pitch, has been documented, also known as Spatial-Musical Association of Response Codes (SMARC effect: Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2005). The SMARC effect, although introduced more recently than the SNARC effect, has been reported in both Western and Asian participants (e.g., Beecham, Reeve, & Wilson, 2009; Nishimura & Yokosawa, 2009; Rusconi, Giordano, Casey, Umiltà, & Butterworth, 2006; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). Several authors had previously noticed that pitch and vertical space are associated in a very consistent way, and they pointed to regularities of the physical world as to the possible origin of such regularities (Stumpf, 1883). Others, like Pratt (1930), hypothesized that pitch–space associations originate in a physiological bias in the perception of spatial sound. As the auditory modality is not as well equipped as the visual modality for localization purposes, pitch height would act as an extra-clue in case of particularly defective localization (i.e., along the vertical meridian; see, e.g., Middlebrooks & Green, 1991). Accordingly, Roffler and Butler (1968) reported pitch-space associations along the vertical meridian in congenitally blind participants and young children. Also, pitch seems to be processed in the right hemisphere of the human brain (e.g., Alcock, Wade, Anslow, & Passingham, 2000).

Findings and hypotheses such as these suggest that we frequently rely on spatial representations for problem solving, even when the source domain of our problem has no spatial component. This study investigates whether the use of space in the cognitive representation of numbers and pitch is automatic, or whether it is under intentional control and resource dependent (Jonides, 1981). This distinction between automatic and controlled processing is of fundamental importance in psychology because it addresses the basic operating mechanisms of the human mind. Initial studies of the SNARC effect suggested that the number-to-space mapping requires no cognitive resources because it emerged even when number meaning was task irrelevant, as for speeded discrimination of the presence/absence of a particular phoneme sound in a number's name (e.g., Fias, Brysbaert, Geypens, & d'Ydewalle, 1996; see also Lammertyn, Fias, & Lauwereyns, 2002). However, cross-cultural differences in SNARC and the often flexible nature of the mapping between numbers and space, even within a culture, raised the possibility of a primarily strategic rather than automatic origin of the spatial mapping of numbers (STrategic Association of Response Codes or STARC; Fischer, 2006; see also Rusconi, Bueti, Walsh, & Butterworth, 2011 for consistent neuro-functional evidence regarding the SNARC effect in magnitude judgment). Supporting this hypothesis of cognitively demanding use of external space for problem solving, the SMARC effect is stronger in trained musicians than in novices (Rusconi, Kwan et al., 2006), and might thus reflect — completely or in part — learned spatial associations.

This study aimed to clarify the issue of automaticity of spatialization, and to assess the extent to which SNARC and SMARC effects demand similar cognitive resources. We combined, in a single stimulus, a numerical magnitude with a distinctive auditory pitch. This type of stimulus allowed us to assess the selectivity of cognitive processing when either one or the other stimulus attribute became task relevant.

The dual-task method is a powerful diagnostic tool to help us understand the cognitive resources required in a given task (e.g., Wickens, 2008). It relies on the following basic rationale: First, if task A performance deteriorates when performed together with task B then task A is not automatized and does require cognitive resources. Secondly, different well-understood secondary tasks can be combined with the primary task under investigation, so as to infer the underlying primary task processes from the pattern of interference (in the domain of numerical cognition, see, among many others, Lee & Kang, 2002; Rusconi, Galfano, Speriani, & Umiltà, 2004; Imbo, Vandierendonck, & Fias, 2011). For example, Lee and Kang (2002) measured multiplication and subtraction performance while their participants simultaneously performed one of two secondary tasks; they either repeatedly whispered a non-word or had to remember the shape and position of a visual figure. While accuracy was comparable in all four task combinations, multiplications took longer with simultaneous whispering and subtraction took longer with the simultaneous memory load. These results indicate that the two arithmetic operations rely on distinct working memory structures, with multiplication requiring the phonological loop and subtraction relying on the visuo-spatial sketchpad (cf. Baddeley, 2012, for a recent review of working memory).

Applying this dual-task rationale to the SNARC effect in a magnitude comparison task, Herrera, Macizo, and Semenza (2008) measured the strength of spatial-numerical associations under verbal and visuo-spatial secondary task conditions. They found that spatial but not verbal memory load reduced the SNARC effect, confirming that the spatial-numerical mapping relies on visuo-spatial resources. Following on from this study, Van Dijk, Gevers, and Fias (2009) recently showed that the SNARC effect disappears under verbal load in a parity judgment task but under spatial load in a magnitude comparison task. This pattern of dual-task results suggests that spatial codes can be either visuo-spatially or verbally mediated (see also Gevers et al., 2010). Using a similar dual-task logic, we investigated the relationship between the SNARC and SMARC effects and determined whether they are automatic or resource-demanding effects.

1. Method

1.1. Participants

Sixteen students (nine females, mean age: 22 years, all non-musicians, three left-handers) recruited at University College London participated in the experiment, in compliance with UCL ethics. They had no hearing impairments, were musically untrained, and were naïve as to the purpose of the experiment.

1.2. Tasks and materials

In the two main tasks (number magnitude and pitch comparison) stimuli consisted of five English number words (two, three, four, five, and six) sung by four different professional singers (two men and two women) at each of five equidistant pitches, ranging from B2 to G4. The central stimuli (number four and pitch A3) were references for magnitude comparison and pitch comparison, respectively. In the magnitude comparison task participants decided whether a sung number target was smaller or larger than the preceding fixed reference (number four sung at A3); in the pitch comparison task they decided whether the target was lower or higher in pitch than the preceding fixed reference (number four sung at A3). Responses were given by pressing one of two keys placed diagonally (i.e., they were displaced from one another both in the vertical and in the horizontal dimension) on a QWERTY keyboard (lower left V and upper right U). This layout allowed us to capture both the horizontal SNARC effect and the vertical SMARC effect at the same time. The experiment was run on a Toshiba SA50 laptop display with E-Prime Software (Schneider, Eschman, & Zuccolotto, 2002) and using Sennheiser HD 280 professional headphones.

1.3. Procedure

On each trial a fixation cross appeared in the center of the screen, which participants were asked to fixate up to response execution. After 200 ms, the auditory reference stimulus was played for 1,000 ms. It was immediately followed by the target, lasting for another 1,000 ms. Responses were recorded within 2,000 ms after target onset. At the end of each trial, a 300 ms feedback display showed a central fixation cross (if the response was correct), an exclamation mark (if it was wrong) or a question mark (if no response had been given).

Two concomitant short-term memory tasks (Luck & Vogel, 2007) required maintenance of either color or location information presented before each trial of the main task. In the color task, four squared concentric frames appeared in the center of the screen, and participants were asked to remember their colors. At the end of a trial, a single squared frame appeared on the screen and participants said aloud whether this color had been present in the previous memory display (Fig. 1, left panels). The experimenter coded the answer by clicking one of two mouse buttons. In the location task, participants remembered the position of four dots appearing simultaneously on the screen at different positions of an imaginary central circle (each of them in a different imaginary quadrant). At the end of a trial, a single dot appeared on the screen, at a position on the same imaginary central circle, and participants said whether it was part of the previous memory display (Fig. 1, right panels). In either concomitant task, the memory display remained visible for 150 ms, whereas the probe remained on screen until a response was entered.

The experiment was divided into two sessions to avoid fatigue and was completed on two different days by each participant. Each session comprised of an initial training with the color and location tasks alone. Then baseline data were collected for one of the main

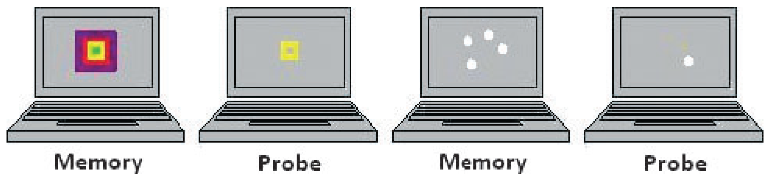

Fig. 1. Sample memory and probe displays in the color task (left-side panels, "yes" trial) and the location task (right-side panels, "no" trial).

tasks (single-task condition, first half), followed by the same task with both concomitant tasks, and finally by another baseline (single-task condition, second half). On each session a different main task was tested. Order of main and concomitant tasks was fully counterbalanced between participants to cancel out any practice or tiredness effects.

2. Results

The main tasks were performed with mean accuracy of 93% in the single-task condition and with mean accuracies of 93% and 92% in the color and location dual-task conditions, respectively. These figures show that participants were able to perform our tasks, both alone and in combination. Both mean correct reaction times (RTs) and arcsine-transformed accuracy scores were submitted to repeated measures analyses of variance (ANOVAS) to evaluate the effects of Condition (single-task, color dual-task, location dual-task), SMARC (compatible, incompatible), SNARC (compatible, incompatible), and Task (magnitude comparison, pitch comparison) on performance.

2.1. Reaction times

The analysis on RTs revealed a main effect of Condition, $F(2,30) = 13.396$, $p < .001$, indicating that the single-task was performed faster than either dual-task condition (single-task: $M = 747$ ms, $SE = 35$ ms; color dual-task: $M = 864$ ms, $SE = 33$ ms; location dual-task: $M = 870$ ms, $SE = 27$ ms). Paired t-tests confirmed significant differences between single-task and both dual-tasks, $t(15) = 4.35$, $p < .001$ and $t(15) = 5.21$, $p < .001$ for color and location, respectively, and no difference between dual-tasks ($t < 1$). The main effect of Task was also significant, $F(1,15) = 10.695$, $p < .01$, with faster RTs in magnitude comparison than in pitch comparison (magnitude: $M = 775$ ms, $SE = 22$ ms; pitch: $M = 878$ ms, $SE = 40$ ms). The main effect of SMARC was highly significant, $F(1,15) = 9.808$, $p < .01$, and the main effect of SNARC showed a tendency toward significance, $F(1,15) = 3.459$, $p < .10$. Thus, while both spatial mappings of interest were present, they were expressed with different strength in our data. Following the dual-task logic outlined in our introduction, the pattern of interactions was inspected next to investigate possible explanations for this result.

There were reliable SMARC × Task, $F(1,15) = 5.245$, $p < .05$, and SNARC × Task, $F(1,15) = 9.346$, $p < .01$, interactions, which were further qualified by a significant three-way SMARC × SNARC × Task interaction, $F(1,15) = 5.850$, $p < .05$. This very informative interaction is depicted in Fig. 2 and is explained in more detail next, by looking at the data pattern in each task. In the magnitude comparison task (Fig. 2, left panel) there was a significant SNARC effect, $t(15) = 3.09$, $p < .01$; SNARC compatible trials: $M = 758$ ms, $SE = 20$ ms; SNARC incompatible trials: $M = 793$ ms, $SE = 26$ ms, in the absence of a significant SMARC effect ($p > .10$; SMARC compatible trials: $M = 772$ ms, $SE = 22$ ms; SMARC incompatible trials: $M = 779$ ms, $SE = 23$ ms). Thus, our participants performed magnitude comparisons by mapping numbers onto space but were at the same time able to ignore the spatial association of pitch.

In the pitch comparison task (Fig. 2, right panel) there was a significant SMARC effect, $t(15) = 2.74$, $p < .05$; SMARC compatible trials: $M = 847$ ms, $SE = 38$ ms; SMARC incompatible trials: $M = 910$ ms, $SE = 45$ ms, in the presence of a significant but reverse SNARC effect in SMARC incompatible trials only, $t(15) = 3.08$, $p < .01$; SNARC compatible trials: $M = 928$ ms, $SE = 48$ ms; SNARC incompatible trials: $M = 892$ ms, $SE = 43$ ms. Thus, our participants performed pitch comparisons by mapping frequency onto space but were at the same time able to block the typical spatial mapping of numbers. We will discuss possible reasons for the reversal of SNARC further below after inspecting the accuracy scores to safeguard our interpretation of the results against possible speed-accuracy trade-offs.

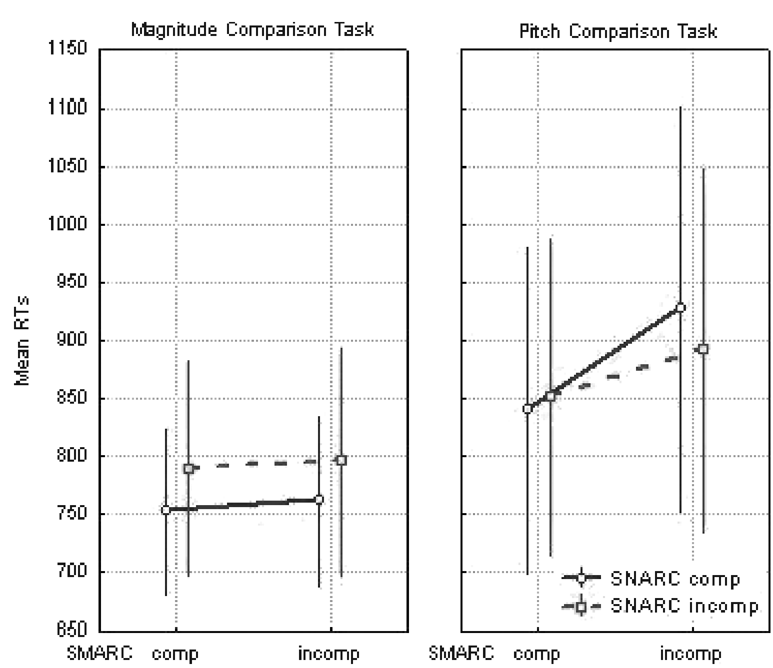

Fig. 2. Response speed results. Magnitude comparison (left panel) showed a 35 ms SNARC effect but no SMARC effect. Pitch comparison (right panel) showed a 63 ms SMARC but a 36 ms *reverse* SNARC effect in *SMARC*-incompatible trials. Bars: 95% confidence intervals.

2.2. Accuracy

The analysis on accuracy revealed statistically reliable main effects of SMARC, SNARC and Task, $F(1,15) = 14.813$, $p < .01$, $F(1,15) = 7.851$, $p < .05$ and $F(1,15) = 36.776$, $p < .001$, respectively, that are consistent with the RT results. Also in close agreement with the RT results, the SMARC × Task and the SMARC × SNARC × Task interactions were significant, $F(1,15) = 11.876$, $p < .01$, and $F(1,15) = 7.861$, $p < .05$, respectively. They indicated the presence of a significant SNARC effect, $t(15) = 2.74$, $p < .05$; SNARC compatible trials: $M = 1.48$, $SE = 0.02$; SNARC incompatible trials: $M = 1.41$, $SE = 0.02$, with concomitant absence of a SMARC effect in magnitude comparison ($t < 1$; SMARC compatible trials: $M = 1.45$, $SE = 0.02$; SMARC incompatible trials: $M = 1.44$, $SE = 0.02$). This result is consistent with the RT findings in showing that our participants mapped numbers onto space when performing the number-related task and were at the same time able to ignore the spatial mapping of pitch. The SMARC effect was instead significant in pitch comparison, $t(15) = 4.73$, $p < .001$; SMARC compatible trials: $M = 1.35$, $SE = 0.03$; SMARC incompatible trials: $M = 1.24$, $SE = 0.03$, where a reverse SNARC effect was also significant in SMARC compatible trials only, $t(15) = 3.14$, $p < .01$; SNARC compatible trials: $M = 1.40$, $SE = 0.03$; SNARC incompatible trials: $M = 1.30$, $SE = 0.04$, thus again confirming and complementing our RT results: Participants were able to map frequency onto space when performing the pitch-related task and were at the same time able to largely ignore the spatial mapping of numbers.

Of further interest for this study, the Condition factor (single-task, color dual-task, location dual-task) was involved in a two-way interaction with SNARC, $F(2,30) = 5.413$, $p < .05$, and a three-way interaction with SMARC and Task, $F(2,30) = 4.000$, $p < .05$. Again following the dual-task logic outlined above, let's now look at each of these two results in more detail to understand how numbers, pitch, and space interact.

The SNARC × Condition interaction signaled a significant SNARC effect in the color dual-task condition only, $t(15) = 3.43$, $p < .01$; SNARC compatible trials: $M = 1.45$, $SE = 0.02$; SNARC incompatible trials: $M = 1.31$, $SE = 0.03$, and no SNARC in either the single-task or the location dual-task (both ts < 1; see Fig. 3). This result suggests that spatial associations of numbers were invoked only as long as spatial processing was not overloaded, to improve dual-task performance. This interpretation is supported by the observation that accuracy was higher for SNARC compatible trials in the color dual-task condition compared to both the single-task and the location dual-task conditions, $t(15) = 2.37$, $p < .05$ and $t(15) = 3.13$, $p < .01$, respectively. SNARC incompatible trials were instead made less accurate by the color dual-task manipulation when compared with the single-task, $t(15) = 3.05$, $p < .01$, but not when compared with the location dual-task, $t < 1$.

We now turn to a more detailed inspection of the three-way SMARC × Task × Condition interaction. In magnitude comparison, the SMARC compatible condition was significantly less accurate in the color dual-task than in the single-task condition, $t(15) = 2.25$, $p < .05$, whereas in pitch comparison it became significantly more accurate both in the color and the location dual-task condition compared to the single-task

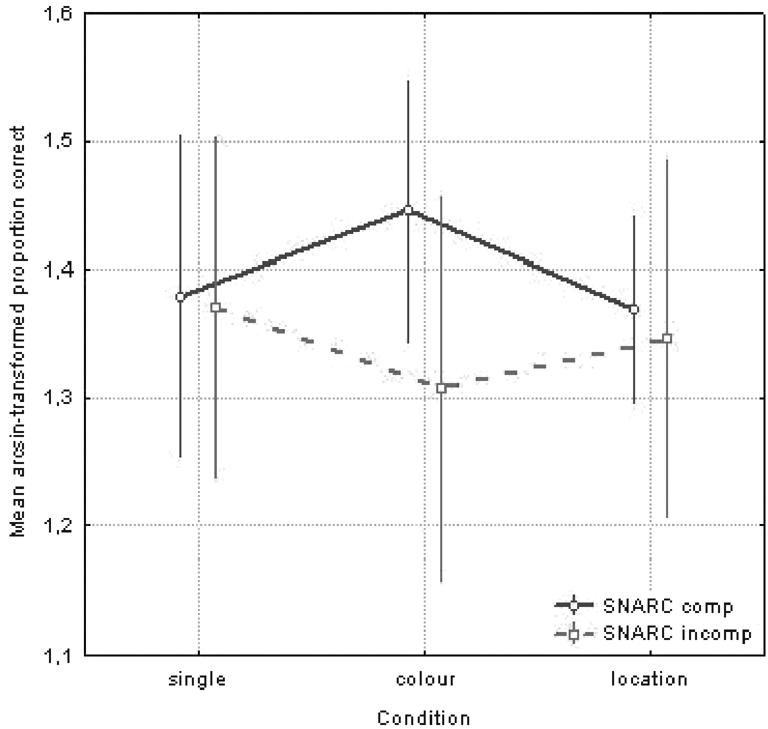

Fig. 3. Response accuracy results, showing the SNARC × Condition interaction in arcsine-transformed proportion correct. Conventions as in Figure 2.

condition, $t(15) = 2.65$, $p < .05$ and $t(15) = 2.35$, $p < .05$, respectively, thus indicating a general dual-task benefit for pitch processing. Overall, the SMARC effect was not significant in any condition during magnitude comparison, whereas it was significant in both dual-task conditions during pitch comparison, $t(15) = 4.19$, $p < .001$ and $t(15) = 2.92$, $p < .05$, respectively; see Fig. 4. This outcome clearly signals a strategic use of spatial representations of sound frequencies.

3. Discussion

In this study, we adopted the established dual-task methodology to investigate the extent to which the processing of numerical magnitudes and auditory pitch relies on automatized spatial mappings. To manipulate intentionality and load dependence of spatial processing (e.g., Jonides, 1981), we asked participants to discriminate sung numbers either by magnitude or by pitch while ignoring the irrelevant dimension, that is, pitch or magnitude, respectively. We measured the extent to which the two stimulus dimensions interacted on spatial performance.

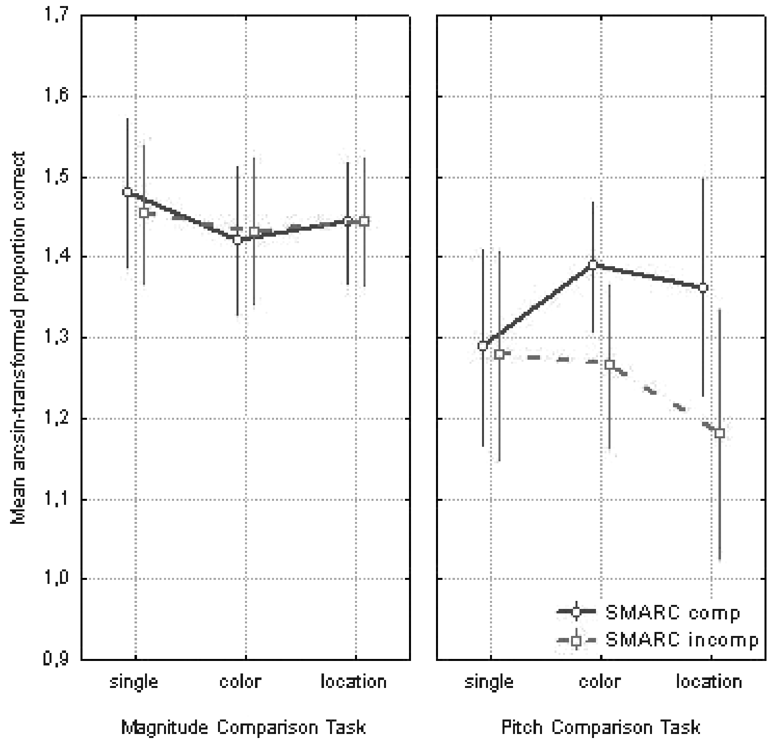

Fig. 4. Response accuracy results. Relative to single-task, SMARC suffered from dual-tasks in magnitude comparison (left panel), whereas it improved in dual-tasks during pitch comparison (right panel). Conventions as in Fig. 2.

Our novel method yielded several clear-cut results. First, we note that our single-tasks were overall easier to perform than the dual task combinations, as is required by the dual-task logic. Secondly, magnitude comparison was easier than pitch comparison, which probably reflects the over-learned use of number symbols combined with the fact that our participants were musically untrained. This aspect of our results relates to the recent theoretical proposal that knowledge might be hierarchically represented as grounded, embodied, and situated concepts (Fischer & Brugger, 2011). According to this view, grounding captures universal aspects of knowledge, such as the vertical orientation of magnitude and pitch associations, whereas horizontal associations, such as the typical SNARC, are culture-specific and thus situation dependent and easily modifiable through experience. Future studies must explore the learning gradients of various such mappings (cf. Fischer, 2012).

More interestingly for the present purpose of assessing the automaticity of spatial representation of pitch and magnitude, we found that both the speed and the accuracy results indicate that attending to magnitude induced a SNARC effect without inducing a SMARC effect; while attending to pitch induced a SMARC effect without inducing a regular SNARC effect (in the incompatible condition it was actually detrimental to the SNARC effect). This clear top-down modulation of both effects by task instruction argues against a fully automatic spatial mapping of either stimulus dimension and instead supports Fischer's (2006) proposal of a cognitive strategy that uses space to deal with discrimination along another, non-spatial dimension (the STARC hypothesis).

This important conclusion can be further elaborated on the basis of our present results. We found that only pitch discrimination, but not number discrimination, showed an overall spatial mapping. This result suggests that the SMARC effect is more robust or consistent than the SNARC effect, a claim that agrees with the considerable flexibility and cultural variability of SNARC effects and the supposed universality of SMARC. For example, Shaki, Fischer, and Petrusic (2009) showed that SNARC had different directions in three adult populations with different reading habits: Canadian participants, who read both text and numbers from left to right, exhibited the typical magnitude-to-space association we described above and also found in this study; Palestinian participants, who read both text and numbers from right to left, had a reverse SNARC effect, thus associating smaller numbers with right space and larger numbers with left space; and finally, Israeli participants, who read Hebrew text from right to left but numbers from left to right, showed no spatial mapping strategy, presumably because they regularly experienced a directional conflict when processing alphanumerical information. Incidentally, this latter observation should not be taken to imply that Hebrew readers do not use space at all: Shaki and Fischer (2012) recently showed a SNARC effect in Israeli participants once the directional conflict was removed by placing response keys in the vertical dimension. Similarly, Fischer, Shaki, and Cruise (2009) reported a rapid change in the strength of SNARC within individuals as a result of reading a single word.

In contrast to this variability and flexibility of SNARC (reviewed in Fischer, 2012), there might be a culture- or language-free predisposition underlying the association between pitch and space (e.g., Pratt, 1930; Roffler & Butler, 1968; Rusconi et al., 2005; Rusconi, Giordano et al., 2006; Rusconi, Kwan et al., 2006; Stumpf, 1883). It is undeniable that in Westernized countries musical pitches are referred to as either high or low, and descriptions of musical sequences often denote a vertical component of an actual movement in space (e.g., *ascending* and *descending*, *rising* and *falling*). This linguistic link between pitch and vertical displacements in space does not appear to reflect a lawful relationship between the pitch of musical tones and the spatial nature of the actions of a performer, due to their extreme variability (Ashley, 2004). It could not reflect (only) the way we read and write music in Western countries, because pitch to space associations have been reported in non-musicians (e.g., Pratt, 1930), young children, and congenitally blind adults (Roffler & Butler, 1968). Several hypotheses have thus been put forward such as embodiment (e.g., when singing, low-pitched sounds are perceived to come from the chest, and high-pitched sounds are perceived to come from the head), regularities in the physical world (e.g., larger objects are usually located at ground position and tend to produce lower pitches when struck, while smaller objects are less frequently located at ground position and tend to produce higher pitches when struck), or a compensation mechanism in the human central nervous system (e.g., as sound source localization is particularly challenging along the vertical dimension, pitch height would be used as a heuristic), all suggesting a universal character of the pitch-space association along the vertical (Rusconi, Giordano et al., 2006).

Consider now the effect of different secondary tasks on the use of spatial mappings. We found that the SNARC effect was absent when the concomitant task imposed a spatial working memory load. This result is consistent with the previous study of Herrera et al. (2008) and Van Dijk et al. (2009) reviewed above, and it is not due to increased task difficulty (which was comparable in the color task). The finding suggests that both spatial mapping of numbers and memorizing locations use a common process. One such candidate process could be the rapid successive deployment of spatial attention to all four probe locations to assign and maintain their coordinates during a trial. Such attentional rehearsal in working memory can take place covertly (i.e., without observable body movements) or overtly (e.g., with eye movements). Covert attention deployment as a support mechanism for spatial memory was documented by Awh and Jonides (2001) who found better detection performance at memorized locations. Overt attention deployment as a support mechanism for spatial memory was recently demonstrated by Apel et al. (2011), who recorded eye movements in a complex assembly task and found that participants refixated to-be-used objects and locations, apparently rehearsing their forthcoming actions.

The STARC hypothesis (Fischer, 2006) predicts that strategic deployment of spatial attention is used to reduce the cognitive resources available for associating numbers to spatial locations, but that such strategic deployment of spatial attention would not be required to maintain verbal labels (color names) in working memory (cf. Baddeley, 2012). This proposal might also account for the reversed SNARC while participants intentionally focused on pitch under incongruent SMARC mappings. For example, pressing a low button to categorize a high pitch generated an incongruent spatial code but also yielded faster responses for high magnitudes. Given the relevance of pitch, this result probably reflects the flexibility of mapping the irrelevant magnitude dimension of our compound stimuli: The assigned response coordinates linked high magnitude via high pitch. A similar transfer of response mappings across tasks has been reported by Notebaert, Gevers, Verguts, and Fias (2006).

Finally, the stronger SMARC effect under both dual-task conditions might reflect the cost of incompatible SMARC mappings, rather than the benefit of compatible SMARC mappings. Thus, even under conditions of cognitive load it remained relatively easy for our participants to associate high pitches with high keys, but it became harder to impose a reversal of this natural mapping. A replication with trained musicians might be a useful extension of this study, especially when repeated measurements can be taken throughout the process of skill acquisition.

Overall, this dual-task study with sung numbers documented a task-dependent spatial mapping of both number magnitude and auditory pitch, and also found some evidence for the use of common cognitive resources during both tasks. It also suggests that the spatial mapping of pitch is more powerful than that of magnitude, which is consistent with its putative ontogenetically earlier acquisition and universal cultural occurrence.

Acknowledgments

MHF was supported by EPSRC under the Cognitive Foresight Program (EP/F028598/1). ER was supported by EC (MERG-CT-046511) and MIUR (FIRB-RBFR08EHZT). We thank Maro Machizawa for stimulating discussions about short-term memory tasks, and Stephen McAdams for granting us access to the facilities of the Music Perception and Cognition Laboratory to record the sound stimuli used in this study.

References

Alcock, K. J., Wade, D., Anslow, P., & Passingham, R. E. (2000). Pitch and timing abilities in adult left-hemisphere-dysphasic and right-hemisphere-damaged subjects. *Brain and Language*, *75*, 47–65.

Apel, J. K., Revie, G. F., Cangelosi, A., Ellis, R., Goslin, J., & Fischer, M. H. (2011). Attention deployment during memorizing and executing complex instructions. *Experimental Brain Research*, *214*(2), 249–259.

Ashley, R. (2004). Musical pitch space across modalities: Spatial and other mappings through language and culture. In S. D. Lipscomb, R. Ashley, R. O. Gjerdingen, & P. Webster (Eds.), *Proceedings of the 8th International Conference on Music Perception and Cognition*. (pp. 64–71). Adelaide, SA, Australia: Casual Productions.

Awh, E., & Jonides, J. (2001). Overlapping mechanisms of attention and spatial working memory. *Trends in Cognitive Sciences*, *5*(3), 119–126.

Baddeley, A. (2012). Working memory: Theories, models and controversies. *Annual Review of Psychology*, *63*, 1–29.

Beecham, R., Reeve, R. A., & Wilson, S. J. (2009). Spatial representations are specific to different domains of knowledge. *PLos One*, *4*, 1–5.

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

Fias, W., Brysbaert, M., Geypens, F., & d'Ydewalle, G. (1996). The importance of magnitude information in numerical processing: Evidence from the SNARC effect. *Mathematical Cognition*, *2*, 95–110.

Fischer, M. H. (2006). The future for SNARC could be stark. *Cortex*, *42*(8), 1066–1068.

Fischer, M. H.. (2012). The spatial mapping of numbers — its origin and flexibility. In Y. Coello & A. Bartolo (Eds.), *Language and action in cognitive neurosciences.* (pp. 225–242). London: Psychology Press.

Fischer, M. H., & Brugger, P. (2011). When digits help digits: Spatial-numerical associations point to finger counting as prime example of embodied cognition. *Frontiers in Psychology*, 2.260. doi: 10.3389/fpsyg.2011.00260.

Fischer, M. H., Shaki, S., & Cruise, A. (2009). It takes only one word to quash the SNARC. *Experimental Psychology*, *56*(5), 361–366.

Gevers, W., Santens, S., Dhooge, E., Chen, Q., Van den Bossche, L., Fias, W., & Verguts, T. (2010). Verbal-spatial and visuospatial coding of number-space interactions. *Journal of Experimental Psychology: General*, *139*(1), 180–190.

Göbel, S. M., Shaki, S., & Fischer, M. H. (2011). The cultural number line: A review of cultural and linguistic influences on the development of number processing. *Journal of Cross-Cultural Psychology*, *42*, 543–565.

Herrera, A., Macizo, P., & Semenza, C. (2008). The role of working memory in the association between number magnitude and space. *Acta Psychologica*, *128*(2), 225–237.

Imbo, I., Vandierendonck, A., & Fias, W. (2011). Passive hand movements disrupt adults' counting strategies. *Frontiers in Cognition*, *2*, 201.

Jonides, J.. (1981). Voluntary vs. automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 187–203). Hillsdale, NJ: Lawrence Erlbaum Publishers.

Lammertyn, J., Fias, W., & Lauwereyns, J. (2002). Semantic influences on feature-based attention doe to overlap of neural circuits. *Cortex*, *38*, 878–882.

Lee, K.-M., & Kang, S.-Y. (2002). Arithmetic operation and working memory: Differential suppression in dual tasks. *Cognition*, *83*(3), B63–B68.

Luck, S. J., & Vogel, E. K. (2007). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281.

Middlebrooks, J. C., & Green, D. M. (1991). Sound localization by human listeners. *Annual Review of Psychology*, *42*, 135–159.

Nishimura, A., & Yokosawa, K. (2009). Effects of laterality and pitch height of an auditory accessory stimulus on horizontal response selection: The Simon effect and the SMARC effect. *Psychonomic Bulletin & Review*, 2009; *16*(4), 666–670.

Notebaert, W., Gevers, W., Verguts, T., & Fias, W. (2006). Shared spatial representations for numbers and space: The reversal of the SNARC and the Simon effect. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 1197–1207.

Pratt, C. C. (1930). The spatial character of high and low tones. *Journal of Experimental Psychology*, *13*, 278–285.

Roffler, S. K., & Butler, R. A. (1968). Localization of tonal stimuli in the vertical plane. *The Journal of the Acoustical Society of America*, *43*, 1260–1266.

Rusconi, E., Bueti, D., Walsh, V., & Butterworth, B. (2011). Contribution of frontal cortex to the spatial representation of number. *Cortex*, *47*, 2–13.

Rusconi, E., Galfano, G., Speriani, V., & Umiltà, C. (2004). Capacity and contextual constraints on product activation: Evidence from task-irrelevant fact retrieval. *Quarterly Journal of Experimental Psychology*, *57A*, 1485–1511.

Rusconi, E., Giordano, B., Casey, A., Umiltà, C., & Butterworth, B. (2006). *Horizontal and vertical dimensions in the spatial representation of pitch*. Bologna, Italy: IX ICMPC (International Conference on Music Perception and Cognition).

Rusconi, E., Kwan, B., Giordano, B. L., Umiltà, C., & Butterworth, B. (2005). The mental space of pitch height. *Annals of the New York Academy of Sciences*, *1060*, 195–197.

Rusconi, E., Kwan, B., Giordano, B. L., Umiltà, C., & Butterworth, B. (2006). Spatial representation of pitch height: The SMARC effect. *Cognition*, *99*, 113–129.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime user's guide*. Pittsburgh, PA: Psychology Software Tools, Inc..

Shaki, S., & Fischer, M. H. (2012). Multiple spatial mappings in numerical cognition. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 804–809.

Shaki, S., Fischer, M. H., & Petrusic, W. M. (2009). Reading habits for both words and numbers contribute to the SNARC effect. *Psychonomic Bulletin and Review*, *16*(2), 328–331.

Stumpf, C. (1883). *Tonpsychologie*. Leipzig, Germany: Verlag S. Hirzel.

Van Dijk, J. P., Gevers, W., & Fias, W. (2009). Numbers are associated with different types of spatial information depending on the task. *Cognition*, *113*, 248–253.

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*(3), 449–455.

Wood, G., Nuerk, H.-C., Willmes, K., & Fischer, M. H. (2008). On the cognitive link between space and number: A meta-analysis of the SNARC effect. *Psychology Science Quarterly*, *50*(4), 489–525.