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Vertical spatial representation of numbers across two cultures*

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There is strong evidence that numbers are spatially represented. However, much of the research has been concerned with investigating number representation within the horizontal rather than the vertical dimension. It has been suggested that the organisation of the writing system, by rows or by columns, plays a pivotal role in shaping the mental number representation. We investigated the vertical number representation in British and Japanese participants, who were asked to randomly generate numbers after turning their heads up or down. Previous works showed that this method facilitated the access to the corresponding portions of the horizontal mental number representation. We found that neither group seemed to be affected by the up/down head turns. These results are discussed in terms of cultural crossover, differences in the horizontal vs. vertical spatial and numerical representation, and sensitivity of the random number generation task.

Key words: Mental number line, number representation, spatial representation, culture

Highlights:

- The directionality of a writing system affects horizontal (h) numeric representation.
- Is it the same for vertical (v) numeric representation? Two writing systems were tested.

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- British and Japanese participants randomly generated numbers at each up/down head turn.
- The randomly generated number should be affected by the direction to which one's head is turned.
- Cultural crossover and differences in h/v representation may explain the negative results.

Numerous studies have reported that numbers tend to be spatially represented. More specifically, it has been shown that numbers are represented along the so-called *mental number line* where smaller numbers are represented on the left hand side, while larger numbers are represented on the right hand side (Bonato, Fabbri, Umiltà, & Zorzi, 2007; Dehaene, Bossini, & Giraux, 1993; Fischer, 2003; Schwarz & Keus, 2004). The behavioural evidence reported by the abovementioned studies has also been corroborated by imaging studies showing that spatial and numeric functions share the same neural circuitries within the parietal lobe (Bueti & Walsh, 2009; Montefinese, Turco, Piccione, & Semenza, 2017; Göbel, Calabria, Farnè, & Rossetti, 2006; Zorzi, Priftis, & Umiltà, 2002).

The *main* source of evidence for the existence of a link between spatial and numeric representations comes from the investigations using the Spatial-Numerical Association of Response Code (SNARC; Bonato et al., 2007; Dehaene et al., 1993; Fischer, 2003; Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006b; Schwarz & Keus, 2004) paradigm. In typical SNARC experiments, participants respond to numeric stimuli in tasks such as parity judgement. Those experiments have consistently shown that performance is more accurate and rapid when the physical positions of the production of responses to the numeric stimuli match the positions of the numeric stimuli within the mental representation of numbers (i.e., faster and more accurate judgement regarding larger numbers when the right hand is used to respond and vice versa). By using the SNARC paradigm, the spatial representation of numbers was observed not only for integer numbers (Dehaene et al., 1993), but also for fractional numbers (Bonato et al., 2007), negative numbers (Fischer, 2003), and even musical notes (Prpic et al., 2016). The mechanism underlying spatial-numerical associations is still debated (Gevers et al., 2010; Proctor & Cho, 2006; Van Dijck, Gevers, & Fias, 2009).

It should be noted that not all studies investigating the links between space and numbers employed the SNARC task. For example, several studies have employed the random number generation task, which consists of rapidly uttering a series of randomly generated numbers (Loetscher & Brugger, 2007; Pasqualotto, Taya, & Proulx, 2014; Seno, Taya, Ito, & Sunaga, 2011). The principal difference between SNARC and random number generation tasks is the levels of cognitive process required, which might account for the variation in the experimental results obtained using different methods. Whereas the classic SNARC task requires participants to detect stimuli, process them and produce the correct motor response, the random number generation task requires

monitoring the generated numbers to keep them *random*, thus involving the central executive attentional component of the working memory (Brugger, 1997). Additionally, when articulation of numbers is coupled with alternate left and right head turns, performance in the random number generation task tends to be affected by the direction participants are facing (Loetscher, Schwarz, Schubiger, & Brugger, 2008). When participants turn their heads to the left, they are more likely to generate smaller numbers, whereas when participants turn their heads to the right they are more likely to generate larger numbers. These results were explained by the effect that posture has on the deployment of attention (Fischer, Castel, Dodd, & Pratt, 2003; Longo & Lourenco, 2007). In other words, turning the head to the left focuses attention towards the left side of the mental number line, where smaller numbers are located. On the other hand, turning the head to the right focuses attention towards the left side of the mental number line, where larger numbers are located.

Thus far, the overwhelming majority of these studies has focused on investigating the link between numbers and the *horizontal* dimension of space. In fact, little is known about the spatial representation of numbers within the vertical dimension compared to the spatial representation of numbers within the horizontal dimension. Amongst the very few studies that investigated the spatial representation of numbers within the vertical dimension, Schwarz and Keus (2004) tested Dutch participants using the SNARC paradigm and found that numbers are spatially represented in an ascending order, with smaller numbers in the lower half of the space and larger numbers in the upper half. This suggests that there is a vertical mental number line that represents numbers from bottom to top, much like the horizontal mental number line, along which numbers are represented from left to right.

This representation is likely not to be ubiquitous, because it has been shown that the number representation is affected by sensory experience (e.g., visual experience vs. blindness, Crollen, Dormal, Seron, Lepore, & Collignon, 2013; Pasqualotto et al., 2014) and the specific cultural practices people are exposed to (Göbel, Shaki, & Fischer, 2011; Núñez, 2011). For example, those who grew up in cultures where written scripts are read from right to left possess a spatial representation of numbers that proceeds in the same direction (Göbel et al., 2011; Zebian, 2005). Effects of the writing system on the numeric representation might arise from the extensive practice with writing and reading following a particular direction, which results in perceptual and motor biases (Göbel et al., 2011; Kazandjian & Chokron, 2008). To use a metaphor, professional tennis players, for example, have more developed muscles in one arm in comparison to those in the other arm due to extensive practice. Likewise, extensive practice with writing and reading from left to right produces a left-to-right numerical representation. Additionally, some studies examining the effects of the writing system on the horizontal numeric representation suggests that those who are accustomed to *both* the left-to-right *and* the right-to-left writing systems showed no clear spatial representation of numbers within the vertical dimension (Rashidi-Ranjbar, Goudarzvand, Jahangiri, Brugger, & Loetscher, 2014; Shaki, Fischer, &

Petrusic, 2009). For example, Israeli who are exposed to both writing systems do not seem to possess a clear spatial representation of numbers, most likely because influences of two opposite writing systems seem to *cancel* each other (Shaki et al., 2009). Again, this illustrates how important is the role the writing system plays in forming the horizontal spatial representation.

We know that the spatial representation of numbers within the horizontal dimension is affected by culture, but it remains unclear whether this is the case for the vertical dimension because of the limited literature. Therefore, this study investigated whether horizontal and vertical numerical representations are equivalent, and whether they share the same underlying mechanisms. To better understand the effect of cultural practices on the vertical number representation, we tested British and Japanese participants, which are two populations whose writing systems differ in terms of direction in which the text is written (left-to-right vs. top-to-bottom, respectively). We chose to use the random number generation task, which is a more recently proposed and potentially more informative method to investigate the role of culture on the deployment of attention and spatial-numerical associations along the vertical dimension (Fischer et al., 2003; Longo & Lourenco, 2007).

Because of the shared writing system in the UK and the Netherlands, we predicted our results to substantially replicate the findings by Schwarz and Keus (2004) for British participants. These authors tested Dutch participants and found that small numbers are represented at the bottom and large numbers are represented at the top (i.e., bottom-to-top representation). In contrast, although they also use the left-to-right writing system, in Japan the writing system is traditionally column-based and the written scripts read from top to bottom. Hung, Hung, Tzeng, and Wu (2008) used a SNARC task and tested Taiwanese participants. Their results indicate that the Taiwanese possess a top-to-bottom numeric representation that follows the direction of their writing system, which is consistent with that of Japanese traditional writing system. Yet, another SNARC study by Ito and Hatta (2004) with Japanese participants found that their numeric representation is organised from bottom to top thus not following the direction of the Japanese traditional writing system. The primary aim of our experiments was to clarify these inconsistencies. Should the same rules as those for the Dutch apply to the Japanese, the results *should* indicate a numerical representation proceeding from top to bottom, as opposed to the bottom-to-top representation in the British.

Method

Participants

A total of thirty-two participants (16 males and 16 females), 16 recruited amongst the students of the Queen Mary University of London (UK) and the other 16 recruited amongst the students of Kyoto University (Japan) were tested. Their average age was 23.19 years ($SD = 3.28$). British participants were born and raised in the UK or the rest of Europe, while Japanese participants were born and raised in Japan. All participants signed the consent form approved by a respective local ethics committee.

Apparatus and procedure

British and Japanese participants were instructed to utter, in a random order, numbers from 1 to 100. One random number was uttered each second while participants were being recorded with a Dell™ Latitude E5510 laptop (UK) or a Sony IC recorder (Japan). Later, recordings were encoded and used for data analysis. An electronic metronome (www.tabguitarlessons.com) emitting one click per second was used to help participants keep the pace at one number per second during the random number generation. As in previous studies (Loetscher et al., 2008; Pasqualotto et al., 2014), participants wore a blindfold during the entire experiment. Each participant undertook two counterbalanced blocks: in the *baseline* block participants looked straight ahead and uttered one random number per second for 40 seconds, and in the *head-turn* block participants *alternately* turned their heads up and down every second and uttered one random number after each turn¹. The block where participants turned their heads up and down lasted 80 seconds. Participants were instructed to keep the pace with the metronome as much as possible and to generate numbers in a manner as random as possible. In sessions where participants were not able to follow these instructions, the session was terminated, and they started a new session. The experiment consisted of a mixed design, with Culture (British vs. Japanese) as the between-subjects variable and Heading (baseline vs. up vs. down) as the within-subjects variable. The entire experiment lasted for about 15 minutes.

Results

Transcriptions of participants' performance were coded in terms of *smaller* (1–50 interval) and *larger* (51–100 interval) numbers. The frequencies were converted into percentages and are reported in Table 1. Since smaller and larger numbers are complementary, we performed a 2x3 factorial ANOVA on the percentage of smaller numbers with Culture (British vs. Japanese) as the between-subjects factor and Heading (Baseline vs. Up vs. Down) as the within-subjects factor. We found no significant effect of Culture ($F(1, 30) = 0.06, p = .81, \eta^2 = .001$), but a significant effect of Heading ($F(2, 29) = 5.99, p = .004, \eta^2 = 0.06$), suggesting that in one of the head orientations participants generated smaller numbers more often than in others. The Bonferroni post-hoc comparison yielded that smaller numbers were generated more frequently in the baseline condition (i.e., looking straight ahead) compared to the other two conditions (i.e., head turned up and turned down, $p = .005$ and $p = .037$, respectively), while there was no significant difference between looking up and looking down ($p = 1$). The Culture by Heading interaction was not significant ($F(4, 27) = 1.05, p = .35, \eta^2 = 0.01$).

Since the baseline condition (i.e., looking straight ahead) seemed to promote the generation of smaller numbers, this *preference* was further investigated using one-sample *t*-tests comparing the baseline performance with

1 The initial positioning of participants in this block was counterbalanced, so that one half of participants started the block with their heads turned up whereas the other half down. They uttered the first random number in the original position before they tuned their heads to the opposite direction (either down or up) following the 'click' of the metronome and uttered another random number. This sequence was repeated following the sound of the metronome.

the chance level (i.e., 50%). We found that, in the baseline condition, smaller numbers were generated significantly more frequently than expected by chance by both British participants ($t(15) = 4.21, p = .001, \eta^2 = 0.54$), and Japanese participants ($t(15) = 2.83, p = .01, \eta^2 = 0.35$). These results regarding the random number generation performance while looking straight ahead replicate previous findings (Loetscher et al., 2007; Pasqualotto et al., 2014), thus validating our experimental setup and methods.

Table 1

Percentage of small (1–50) and large (51–100) numbers generated by British and Japanese participants in the three head orientations (baseline, up, and down). Standard deviations are presented in parentheses.

Culture	Baseline		Looking up		Looking down	
	1–50	51–100	1–50	51–100	1–50	51–100
British	60.72 (10.19)	39.28 (10.19)	51.44 (12.09)	48.56 (12.09)	54.21 (11.37)	45.79 (11.37)
Japanese	58.59 (12.14)	41.41 (12.14)	55.00 (9.17)	45.00 (9.17)	55.00 (10.25)	45.00 (10.25)

Discussion

We investigated the number representation within the *vertical* dimension using the random number generation task across two cultures with two writing systems emphasising different spatial dimensions (i.e., horizontal vs. vertical). Most of the previous studies on the spatial representation of numbers employed SNARC tasks, and were more concerned with the number representation within the horizontal dimension and within a given culture (e.g., Bonato et al., 2007; Dehaene et al., 1993; Ito & Hatta, 2004; Gevers, et al., 2006b).

Here, we found that being exposed to different writing systems (left-to-right in the UK vs. top-to-bottom in Japan) did not affect participant's performance in the random number generation task that required participants to turn their heads along the vertical dimension. Based on the available literature (Gevers, Lammertyn, Notebaert, Verguts, & Fias, 2006a; Schwarz & Keus, 2004), we expected that British participants would exhibit a bottom-to-top representation of numbers as it was previously found for the Belgian and the Dutch (Gevers et al., 2006a; Schwarz & Keus, 2004, respectively), who share the same writing system as the British. A bottom-to-top numerical representation is most likely the result of *implicit* correspondences between concepts such as *more*, *bigger*, *higher*, and *top*', which have been reported within and across sensory modalities (Brown & Proulx, 2013; Etzi, Spence, Zampini, & Gallace, 2016; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006). However, our results did not indicate any coherent spatial representation of numbers along the vertical dimension in the British sample.

We also found that participants who were exposed to a writing system emphasising columns over rows were not affected by up and down head turns

either. Our results for Japanese participants indicated neither a bottom-to-top numerical representation as reported in the Taiwanese, who also use the column-based writing system (Hung et al., 2008) nor a top-to-bottom representation as reported in the Japanese (Ito & Hatta, 2004).

Therefore, it seems that, across the two cultures we considered here, looking up and down did *not* facilitate the access to the corresponding portions of the mental number representation. This contrasts with the findings of previous studies using this method in order to investigate the numerical representation within the *horizontal* dimension (Loetscher et al., 2008; Pasqualotto et al., 2014). It is important to note here that this study is the first application of the random number generation task in investigating the *vertical* representation of numbers. Thus, we might speculate that this method is *not* sufficiently sensitive to detect the link between space and numbers along the vertical dimension, although its ability to detect the link between space and numbers along the horizontal dimension has been well-established. This may be due to a weaker or poorer spatial representation of numbers along the vertical dimension.

Several studies have reported that memory of vertically explored environments is poorer than that of horizontally explored environments (Hölscher, Meilinger, Vrachliotis, Brösamle, & Knauff, 2006; Jeffery, Jovalekic, Verriotis, & Hayman, 2013; Pasqualotto & Proulx, 2013; Thibault, Pasqualotto, Vidal, Droulez, & Berthoz, 2013). It is possible that a weaker spatial representation indicated, for example, by a poorer memory within the vertical dimension, results in poorer spatially-organised representation of numbers along the respective dimension. This could explain why the random number generation task is able to detect the horizontal spatial representation of numbers, whilst it is not sensitive enough to detect the vertical numeric representation.

Interestingly, SNARC studies were able to detect spatial-numerical associations within the vertical dimension (e.g., Schwarz & Keus, 2004). It must be noted, however, SNARC and random number generation tasks are based on very different mechanisms which could account for the discrepancies in findings. While SNARC tasks are more focused on the associations between stimuli and reactions to stimuli, random number generation tasks tap into the attentional deployment necessary for performance (see introduction part). Therefore, previous findings that the vertical spatial representation may not be as robust as the horizontal one, and that because of this, it cannot be detected by the random number generation task would explain results for British participants.

Contrarily, due to their vertically-oriented writing system, Japanese participants would be expected to possess a more robust vertical presentation of numbers, which should be more readily detected by the random generation task. One possible explanation for our results that did not indicate the vertical numeric representation in Japanese participants is their *age*. While older generations of Japanese have mainly been exposed to the vertically-oriented writing system, younger generations underwent a major *Western* influence, including the Western writing system. While Japanese written scripts in media such as newspaper and books are still vertically oriented, the horizontal writing system is applied to

scripts in other media such as the Internet and mobile phones. In fact, the use of computers and mobile phones has become extremely prevalent in the Japanese society (Ishii, 2004), Japanese population may now be equally exposed to horizontally and vertically oriented scripts.

Here, the Japanese sample consisted mainly of postgraduate students, whose generation is substantially exposed to the Western influence (Pike & Borovoy, 2004), and whose occupation requires an extensive use of English language (Butler & Iino, 2005; Kay, 1995), which has a row-based writing system. These factors might have rendered their number representation along the vertical dimension equivalent to that of their British peers (i.e., weak and hard to be detected by the random number generation task). To assess this hypothesis, follow-up studies might repeat this experiment testing Japanese elderly individuals, amongst whom the usage of the Internet, computers and mobile phones is less prevalent, and who are less exposed to the Western row-based writing system than younger individuals.

Nevertheless, this study, for the first time, investigated the spatial-numeric links within the vertical dimension across different cultures using the random number generation task. We conclude that the random number generation paradigm that was employed was not able to detect the less robust spatial representation of numbers along the vertical dimension, although its sensitivity has been shown to be sufficient to detect the mental number representation within the horizontal dimension.

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Vertikalne prostorne predstave brojeva u dve culture

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Postoje snažni dokazi da su mentalne predstave brojeva prostorne. Međutim, u velikom delu sprovedenih istraživanja mentalne predstave brojeva ispitivane su u horizontalnoj, a ne u vertikalnoj ravni. Prepostavlja se da to što je sistem pisanja organizovan u vidu redova i kolona ima ključnu ulogu u oblikovanju mentalne predstave brojeva. Ispitivali smo vertikalnu mentalnu predstavu brojeva kod Britanaca i Japanaca koji su zamoljeni da nasumično generišu brojeve nakon pomeranja glave gore-dole. Prethodna istraživanja su pokazala da ova metoda olakšava pristup odgovarajućim delovima horizontalne mentalne predstave brojeva. Utvrđili smo da pokretanje glave gore-dole nije imalo efekta ni na jednu ni na drugu grupu. Rezultati su diskutovani u terminima razlika između dve kulture, razlika u horizontalnim i vertikalnim prostornim i brojevним predstavama i u terminima osetljivosti zadatka nasumičnog generisanja brojeva.

Ključne reči: mentalna brojevna linija, predstave brojeva, prostorna predstava, kultura

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