Perceiving numbers causes spatial shifts of attention

Martin H Fischer[1], Alan D Castel[2], Michael D Dodd[2] & Jay Pratt[2]

Number symbols are part of our everyday visual world. Here we show that merely looking at numbers causes a shift in covert attention to the left or right side, depending upon the number's magnitude. This observation implies obligatory activation of number meaning and signals a tight coupling of internal and external representations of space.

Most visual environments contain more information than the human brain can process in real time. To overcome this limitation, the attention system acts as a filter. Selective orienting of attention to specific regions of the visual field determines which information will be processed and which will be ignored. Thus, allocating spatial attention in the visual field is a major determinant of what we perceive. Attention is involuntarily oriented toward objects that abruptly appear in the visual periphery[1], as well as toward peripheral events that share a critical feature with a current goal[2]. Familiar symbols with a strong meaning, such as direction arrows, also generate involuntary (or obligatory) shifts of attention, even when observers know the arrows are irrelevant to their task and should be ignored[3].

There is mounting evidence that the perception of numbers also involves a spatial component: low numbers are associated with left-side space and higher numbers with right-side space. For example, odd or even judgments for low digits (namely, 1 or 2) are faster when responses are made with a left button-press rather than a right button-press; higher digits (namely, 8 or 9) are categorized faster with a right button-press[4]. Similar spatial performance biases occur for phoneme detection in digits' names, in digit magnitude classification and in midpoint localization of long digit strings[5–7]. These results suggest that a spatially oriented 'mental number line' is automatically activated as part of a number's meaning whenever we look at numbers[8].

If the perception of digits is so closely associated with space, this raises the question of whether number perception can induce a shift of attention to the left or right visual field. To address this question, 15 right-handed observers completed 480 trials in a simple detection experiment (**Fig. 1a**). They were positioned 44 cm from a black computer screen with their head positioned in a chin rest. They fixated a white point that was 0.2° in diameter and centered between two boxes (each had 5° eccentricity and 1° width). After 500 ms, one of four white digits appeared (1, 2, 8 or 9; size 0.75°) for 300 ms. Participants knew that digits did not predict the target locations and were irrelevant to the detection task. They were to fixate the center point during each trial. After the digit was removed, a random delay (50, 100, 200, 300, 400 or 500 ms) elapsed, followed by the presentation of a target (white circle, 0.7° diameter) in one of the boxes. The variable delays allowed for an examination of the time course of any potential shifts of attention. Observers responded with their preferred hand on the space bar as soon as they detected the target, which appeared randomly on either the left or right side on 80% of all trials. Catch trials (where no target appeared) occurred on 20% of trials to prevent anticipatory responses. Catch trial errors were rare (<1.5%).

After delays exceeding 300 ms, circles in the left visual field were detected faster when preceded by a low digit (1 or 2) relative to a high digit (8 or 9), and circles in the right visual field were detected faster when preceded by a high digit relative to a low digit

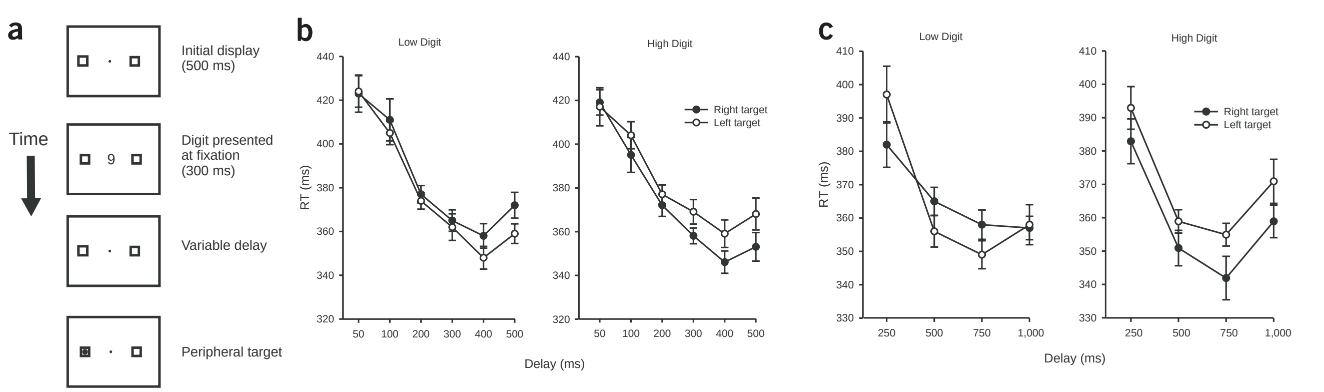

Figure 1 Task sequence and reaction time data. (**a**) Typical trial sequence. (**b**) Average reaction times (RT) to low or high targets at each delay (mean ± s.e.m). (**c**) Results of control study. Experiments were approved by the Ethical Review Board at the University of Toronto, and subjects gave their written consent to participate.

[1]Psychology Department, University of Dundee, DD1 4HN Scotland. [2]Psychology Department, University of Toronto, Department of Psychology, University of Toronto, 100 St. George Street, Toronto, ON M5S 3G3, Canada. M5S 3G3 Canada. Correspondence should be addressed to M.H.F. (m.h.fischer@dundee.ac.uk).

(**Fig. 1b**). A $2 \times 2 \times 6$ analysis of variance (digit low or high × target left or right × delay 50, 100, 200, 300, 400 or 500 ms) confirmed a digit × target interaction ($F_{1,14}$ = 9.98; m.s.e., 454; $P < 0.007$). Specifically, right targets were detected faster when preceded by high digits and left targets were detected faster when preceded by low digits. All remaining interactions were not reliable ($F < 1$). To determine at which delays the effect was present, post-hoc *t*-tests were conducted. Significant effects were found at 400 ms ($P < 0.016$) and 500 ms ($P < 0.019$), but not at the shorter delays ($P > 0.14$). Thus, the mere act of perceiving a digit induced attention shifts to a peripheral region of space that is congruent with this digit's relative position on a mental number line.

Although simple detection tasks typically do not involve saccadic eye movements[9], a control study was conducted to ensure that our finding reflects covert shifts of visual attention. Central eye fixation throughout trials was verified with closed-circuit video for ten new participants while they detected targets appearing at random intervals (250, 500, 750 or 1,000 ms) after one of the four central digits. As before, a digit × target interaction ($F_{1,9}$ = 6.63; m.s.e., 272; $P < 0.03$) indicated the presence of the number-related attentional asymmetry (**Fig. 1c**). No other interactions reached significance ($P > 0.17$). *Post-hoc t*-tests showed no effect at the 250 ms delay ($P > 0.3$), but did show a robust effect at 500 ms ($P < 0.02$). This replicates the initial finding in the absence of eye movements. Moreover, the effect lasted through to the 750 ms delay ($P < 0.03$) but began to decay by 1,000 ms ($P < 0.09$). Spatial biases in number tasks[4–7] are therefore not limited to motor responses but extend to perceptual encoding processes.

Our results suggest that mere observation of numbers obligatorily activates the spatial representations associated with number meaning. Shifting the focus of attention within a mental representation produces a corresponding shift of attention in the visual field. This, in turn, implies that similar structures underlie attention shifts across internal spatial representations and external space[10]. Future studies could explore whether this mapping is linear or logarithmic[11] and whether it generalizes to other sequentially ordered continua[12]. We conclude that perceiving symbols with familiar spatial associations influences the allocation of attention in the visual field, which in turn influences what we see.

ACKNOWLEDGMENTS

M.H.F. is supported by the British Academy (LRG 31696). A.D.C. and M.D.D. are supported by Natural Sciences and Engineering Research Council graduate fellowships. J.P. is supported by NSERC operating and equipment grants.

COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

Received 3 January; accepted 17 April 2003
Published online 18 May 2003; doi:10.1038/nn1066

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