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Running head: Movement dynamics in line bisection

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Several lines of evidence have converged on the idea that numerical and spatial cognition is linked (Dehaene, Bossini, & Giraux, 1993; Hubbard, Piazza, Pinel, & Dehaene, 2005; Wood & Fischer, 2008). Bisecting a line, flanked by task irrelevant cues, to indicate the line midpoint is one way to assess number-space interaction. When using non-symbolic numerical cues as flankers, a systematic bias away from the midpoint has been reported. While this bisection bias initially has been attributed to a cognitive illusion of length caused by magnitude information encoded in the flankers (de Hevia, Girelli, & Vallar, 2006; de Hevia & Spelke, 2009; Stöttinger, Anderson, Danckert, Frühholz, & Wood, 2012), an alternative explanation has suggested a prominent influence of the visual properties of the flankers (Gebuis & Gevers, 2011; Gebuis & Reynvoet, 2012, 2013).

Cleland and Bull (Cleland & Bull, 2015; henceforth C&B) recently showed that subtended area and aggregate surface area of the non-symbolic flankers largely explain the bisection bias. In line with Gebuis & Gevers (2011), they observed a reversed bias when controlling for these visual properties, i.e. participants bisected the line closer towards the smaller number covering a larger area. This influence of area was also observed when flankers contained the same number of dots. C&B therefore suggested visual cues as primary driver of their bisection bias.

In addition to the supposed influence of visual properties on bisection, higher cognitive processes could also affect line bisection. C&B speculated that prioritising and weighting of different cues may take place, which would imply competing mental representations. However, paper-and-pencil designs usually employed in line bisection studies do not allow investigating the dynamics of the underlying processes across time, which is necessary to investigate the presence of competing mental representations. In the following, we will thus discuss a computerised bisection task as a tool for exploring the *temporal* dynamics of number-space interactions.

Using a computer mouse for line bisection ensured a highly standardised paradigm (see Supplemental Material) and added a novel measure of the bias reflected in movement trajectories. The rationale behind our approach was based on past mouse tracking studies on response behaviour: if there is a conflict between competing mental representations, one can see continuous movement deflections towards one (e.g. incorrect) alternative early on in time that may eventually switch to the other (e.g. correct) response alternative (Faulkenberry, 2014; Scherbaum, Dshemuchadse, Fischer, & Goschke, 2010; Spivey, Grosjean, & Knoblich, 2005). Applied to line bisection, this conflict could represent magnitude information derived from higher cognitive processing vs. visual properties of flankers. Because movements are projections of the internal processes onto behavioural output (Spivey et al., 2005) they can provide valuable insights into these processes. Furthermore, the strength of computerised line bisection is that it reduces the motor-load in favour of perceptual demands (Rolfe, Hamm, & Waldie, 2008). Our approach is therefore highly advantageous when assessing the role of visual cues.

As C&B showed that different ratios of the number of flanking dots as well as the total amount of dots in- or outside the subitising range did not affect the bias, we tested the original 2- and 9-dot stimuli from the study of Gebuis & Gevers (2011). This revealed a bias towards larger number when controlling for aggregate area (Figure 1, solid lines). However, the larger number also subtended a larger area. Yet, when area subtended and aggregate area was larger for the 2-dot array, we observed a reversed bias towards the smaller number (Figure 1, dotted lines). No endpoint bias was seen for conflicting visual properties, where overall contour length was matched but area subtended was larger for the 9-dot and aggregate area was larger for the 2-dot array (Figure 1, dashed lines). This conflict may also explain the initial trend of the trajectory when presenting the 9-dot array to the right that reverses towards a null bias throughout the remainder of the movement. Altogether, these findings support C&B’s conclusions of a major role for visual cues in spatial bias.

< Figure 1 appears here >

Beyond this replication of C&B, our computerised version of line bisection showed for the first time that movement dynamics were stable. Reaction time (*M* = 249 ms, *SD* =104 ms) and time from movement initiation to response via mouse click (*M* = 635 ms, *SD* = 187 ms) were not different between our three conditions or between the different arrangements of dot arrays (see Supplemental Material for statistics). This is evidence against a role for visual attention or stimulus salience mentioned in C&B. Moreover, trajectories evolved similarly for the biases we found: after an initial deflection to the right, presumably attributable to initiation of a right-handed movement, trajectories did significantly differ for the remaining movement path (Figure 1). Despite the reversed bias, i.e. to smaller number, for our condition three, these similarities strongly suggest common underlying processes.

What are these processes driving line bisection behaviour? The robust bias that persisted without periods of perturbations or reversals in the mean movement path is evidence against a continuous competition between different mental representations of magnitude. The missing late effects also speak against the concept of a cognitive illusion or C&B's alternative idea that magnitude could have emerged out of the visual cues as an illusion. Instead, our findings support C&B and others (Fink, Marshall, Weiss, Toni, & Zilles, 2002; Gebuis & Reynvoet, 2012) suggesting an early influence of visual cues on bisection performance. Still, we do not claim that numerosity cannot play a role in bisection. In our third condition, we introduced a conflict between different sources of magnitude and the resulting bias towards the 2-dot array was smaller than in our congruent first condition. This suggests that number nevertheless may have influenced the spatial bias. As C&B correctly pointed out, an automatic cognitive number system may be actually closely linked to visual features in natural settings: larger number often is equivalent to objects of higher density or larger area. Therefore numerical and non-numerical information may be balanced depending on context and type of task.

This close connection has also been described in recent findings of a topographic “numerosity map” (Harvey, Klein, Petridou, & Dumoulin, 2013). Neurons were tuned to preferred numerosity but their strength of tuning was not insensitive to stimulus properties like circumference of the dots. Hence, the same neurons most likely can encode number or visual features or a mixture of both. In this light, the temporal dynamics of movement trajectories during line bisection will contribute to a better dissociation of visual and numerical processing in future studies.

Supplemental Material

The Supplemental Material can be found at the address

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Figure legends

Figure 1. Grand average x-coordinates of the movement trajectories across trials and participants for each of the 101 normalised time steps. The bold, dashed, and dotted lines represent the conditions in which aggregate area, contour length and subtended area, respectively, were controlled across dot arrays. The left figure depicts the bias over time for trials in which the 9-dot array was presented on the left side of the line, the right figure depicts the bias over time for trials in which the 9-dot array was presented on the right side of the line. Note that the last time point corresponds to the bisection bias reported in paper-and-pencil tests of previous studies.