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Component processes in contour integration: A direct comparison between snakes and ladders in a detection and a shape discrimination task

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ABSTRACT

In contour integration, a relevant question is whether snakes and ladders are processed similarly. Higher presentation time thresholds for ladders in detection tasks indicate this is not the case. However, in a detection task only processing differences at the level of element linking and possibly contour localization might be picked up, while differences at the shape encoding level cannot be noticed. In this study, we make a direct comparison of detection and shape discrimination tasks to investigate if processing differences in the visual system between snakes and ladders are limited to contour detection or extend to higher level contour processing, like shape encoding. Stimuli consisted of elements that were oriented collinearly (snakes) or orthogonally (ladders) to the contour path and were surrounded by randomly oriented background elements. In two tasks, six experienced subjects either detected the contour when presented with a contour and a completely random stimulus or performed a shape discrimination task when presented with two contours with different curvature. Presentation time was varied in 9 steps between 8 and 492 ms. By applying a generalized linear mixed model we found that differences in snake and ladder processing are not limited to a detection stage but are also apparent at a shape encoding stage.

1. Introduction

Organizing a visual scene in coherent perceptual units requires perceptual grouping, that is combining elements in meaningful configurations, a process known to follow the principles introduced by Gestalt psychologists such as Wertheimer (1938; for recent reviews, see Wagemans et al., 2012a, 2012b). For instance, neighboring elements can be grouped based on proximity. Also similarity in color, orientation or shape of the elements can facilitate grouping or good continuation of the elements. A substantial part of research on perceptual grouping has focused on contour integration (for a review, see Hess, May, & Dumoulin, 2013). In contour integration, a contour can be grouped according to the Gestalt principle of collinearity by aligning the orientation of elements along a smooth path while keeping the orientation of the background elements random. In the path paradigm introduced by Field, Hayes, and Hess (1993), subjects have to detect a contour in an array of spatially separate Gabor elements. Their paradigm has initiated an elaborate line of research on the underlying mechanisms of contour integration. In the past twenty years, several studies have shown that detection performance increases with, for instance, decreasing contour length (Field, Hayes, & Hess, 1993), decreasing curvature (Field, Hayes, & Hess, 1993), longer presentation duration (Roelfsema, Scholte, & Spekreijse, 1999), phase similarity (Hess & Dakin, 1999), decreasing inter-element distance (Field, Hayes, & Hess, 1993) and motion drifting elements (Bex, Simmers, & Dakin, 2001). These and other dependencies on stimulus parameters have provided accumulating evidence for a mechanism of contour integration that combines responses of a number of local independent inputs mediated by long-range interactions between cells with similar orientation preferences (for reviews, see Hess, Hayes, & Field, 2003; Hess, May, & Dumoulin, 2013).

An important stimulus characteristic in contour integration is the relative orientation of the elements: contours elements can be aligned with the path of the contour or have an orientation orthogonal to the contour path. These contours are called ‘snakes’ and ‘ladders’, respectively, since the labels were introduced by Bex, Simmers, and Dakin (2001). Despite the similar statistical properties of snakes and ladders, several authors have observed a higher sensitivity for snakes than for ladders in a contour detection paradigm with static (Field, Hayes, & Hess, 1993; Ledgeway, Hess, & Geisler, 2005) and with dynamic stimuli (Bex, Simmers, & Dakin, 2001; Ledgeway, Hess, & Geisler, 2005). In addition, differential

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effects of phase manipulation (Bellacosa Marotti, Pavan, & Casco, 2012; Hansen & Hess, 2006), element separation (May & Hess, 2008), spatial arrangement (Bellacosa Marotti, Pavan, & Casco, 2012) and perpendicular context (Dakin & Baruch, 2009; Robol, Casco, & Dakin, 2012) have been observed between snakes and ladders. The observed differences in psychophysical experiments have raised the question whether snakes and ladders are mediated by the same mechanism or whether different mechanisms are involved (e.g., May & Hess, 2007, 2008). A study by Casco et al. (2009) suggested different temporal dynamics for ladders and snakes because they observed a late shift of ERP towards positive values at 275 ms for similarity (which is associated with ladder perception), while collinearity (which is associated with snake perception, see Bellacosa Marotti, Pavan, & Casco, 2012) evoked an earlier positive response between 40 and 179 ms. On the contrary, May and Hess (2007) have not found evidence for different integration speeds of snakes and ladders in a psychophysical experiment. In sum, whether snakes and ladders are processed differently is still unclear.

Statistical properties of natural images have been correlated with snakes and ladder detection (e.g., Elder & Goldberg, 2002). For instance, prevalence of aligned image segments was higher than that of parallel image segments, indicating higher probability of collinear contours compared to parallel contours in natural images (Geisler et al., 2001). The aligned information, which is also present in snakes, can be related to the contours in the images, while the parallel information, which is also present in ladders can be associated with (texture) regions of the same object (Hess, Hayes, & Field, 2003; Ledgeway, Hess, & Geisler, 2005). For instance, an edge at one side of a branch is made up of collinear lines, while there is another parallel edge that marks the boundary of the wooden texture surface of the branch. It has been suggested that there is a relationship between the natural image statistics and the strength of long-range connections between neurons in the visual cortex (Hess, Hayes, & Field, 2003), namely that higher probability in natural images is associated with stronger connections. These connections strengths can in turn be linked to performance differences between snakes and ladders.

At least at the conceptual level, two aspects of contour processing can be distinguished (Loffler, 2008). One aspect concerns the grouping of contour elements belonging to the contour and the segregation of these elements from the background (two processes that often go hand in hand; see Machilsen & Wagemans, 2011; Sassi, Machilsen, & Wagemans, 2012; Sassi et al., 2010; Vancleef et al., 2013). This process is necessary to be able to detect the contour in a field of randomly oriented elements. The type and strength of grouping will differ between snakes and ladders, and between different shapes. For instance, the linking will be faster in shallow curves, where the orientation differences between the elements are smaller, compared to highly curved contours (Hess, Beaudot, & Mullen, 2001). For precise shape judgments, however, this process is probably not sufficient (Loffler, 2008). In a second type of processing, which is focused more on the shape of the contour than its detection, it seems quite likely that an abstraction of the elements is made and the contour is represented as a whole, irrespective of its parts. At that level of representation, characteristics of the contour, like shape, curvature, symmetry or length can be assessed.

These two aspects of contour processing are at stake in detection and (shape) discrimination tasks, respectively: in a detection task subjects have to merely detect the contour, while in a shape discrimination task subjects have to process and identify the shape in addition to detection (Robol, Casco, & Dakin, 2012). In other words, for detection the first type of processing is sufficient, while for shape discrimination both types of processing are necessary. Loffler (2008) also suggested that an imprecise fast feed-forward collinearity mechanism is involved in detection, while shape discrimination (e.g., curvature discrimination) requires a refine slower mechanism that includes additional lateral and feedback connections. Moreover, Prins, Kingdom, and Hayes (2007) have pointed to the important distinction between a contour detection task and a shape discrimination task. They referred to the processing mechanisms in contour curvature analysis that have been identified by Watt and Andrews (1982): (1) an orthoaxial position system that is sufficient for contour detection, and (2) a slope and position analysis system that extracts curvature and can compare shapes in a shape discrimination task.

Although it has been suggested that both tasks are related to different aspects of contour processing, requiring different component processes and different levels of representation, a direct comparison between tasks has been made thus far in the context of contour integration. This is what our study sets out to do. To recapitulate, snake and ladder perception have mainly been studied in detection paradigms (Field, Hayes, & Hess, 1993) and these studies have shown a better detection for snakes than for ladders following various low-level stimulus manipulations (Bellacosa Marotti, Pavan, & Casco, 2012; Bex, Simmers, & Dakin, 2001; Field, Hayes, & Hess, 1993; Hansen & Hess, 2006; Hess, Ledgeway, & Dakin, 2000; Ledgeway, Hess, & Geisler, 2005; May & Hess, 2007, 2008). Whether encoding of the contour at the second level is still different for snakes and ladder is unclear. Comparing a detection task and a shape discrimination task would indicate if snakes and ladders are still processed differently at the level of shape encoding, or whether the differences are limited to the early processing stages that only play a role in a detection task. Our study aims to address this issue.

A first suggestion that shape encoding differs between snakes and ladders has been provided by Dakin and Baruch (2009), who investigated snake and ladder perception in a shape discrimination task and also found weaker performance for ladders than for snakes. However, because no direct comparison with a detection task was made in that study, it is not clear whether this difference can be completely attributed to an early processing stage like contour detection, or whether the difference is specifically due to different mechanisms at a shape encoding level. In addition, the effect of local orientation (parallel or orthogonal to the contour path) on shape discrimination of – mostly closed - contours and in the absence of background noise has been studied and contrasting results have been observed with different methods. On the one hand Gheorghiu and Kingdom (2008) found evidence for orientation selectivity of shape encoding since shape after-effects where reduced when the adaptor and test stimulus differed in orientation. Also, Levi and Klein (2000) observed an advantage for aligned elements in shape discrimination of closed circles. Another example is the study by Saarinen and Levi (2001) who found an effect of local element orientation on contrast detection thresholds in judging the orientation of a C-shaped figure. On the other hand, Vernier acuity does not seem to be influenced by a collinear or orthogonal orientation of the flankers (Keeble & Hess, 1998; Kooi, De Valois, & Switkes, 1991). In addition, the detection thresholds of radial frequency patterns (RFPs) are influenced in a similar way by parallel and orthogonal masks (Habak et al., 2004). Last, Keeble and Hess (1999) showed that the detection of positional jitter on the contour is not affected by the element orientations in both circles and open contours. Taken together, these findings illustrate that it is unclear whether collinearity has an influence only on detection and not on shape discrimination of contours, as concluded by Keeble and Hess (1999).

The aim of our study, therefore, was to investigate whether shape encoding of contours in a contour curvature discrimination task also differs depending on the nature of the regularity in the element orientation (which differs between snakes and ladders).