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Temporal summation of global form signals in dynamic Glass patterns

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ABSTRACT

The ability to perceive complex objects in the environment requires that the visual system integrate local form information into global shapes. Glass patterns (GPs) are stimuli that are commonly used to study this integration process. GPs consist of randomly positioned dot-pairs oriented in a coherent way to create a global form. When multiple GPs are presented sequentially, observers report a percept of illusory coherent motion and have lower detection thresholds relative to a single presentation GPs. The percept of illusory motion has been attributed to the visual system interpreting the dot-pairs in GPs as motion streaks. However, it remains unclear why dynamic GPs are detected at lower thresholds than static GPs. Two main differences exist between static and dynamic GPs: (a) dynamic GPs contain multiple presentations of global form signals compared to a single presentation in static GPs and (b) dynamic GPs have a greater temporal frequency than static GPs. Here we investigated which of these two factors contributed to the heightened sensitivities for dynamic GPs. We systematically varied the number of unique GPs and the rate at which each unique frame is presented (i.e., temporal frequency). The results show that, within the range of temporal frequency used, the primary influence on detection thresholds was the number of unique frames. These results suggest that the improved detection sensitivities can be driven by a mechanism of temporal summation of global form.

1. Introduction

Researchers have long established that the mammalian visual system is organized in a modular fashion, whereby different areas are specialized for processing particular types of information (Calabretta & Parisi, 2005). Consistent with this idea, form and motion information are processed by distinct neural pathways at the lower levels of the visual system (Braddick et al., 2000; Livingstone & Hubel, 1988; Milner & Goodale, 1995; Ungerleider & Mishkin, 1982; Van Essen & Gallant, 1994). However, recent psychophysical and neurophysiological studies have demonstrated interactions between the form and motion pathways (see Kourtzi, Krekelberg, & van Wezel, 2008, for review). For instance, in the phenomenon known as structure-from-motion, two-dimensional motion information provides information about the three-dimensional structure of objects (Siegel & Andersen, 1988). In a similar way, form signals have been shown to influence motion perception (Geisler, 1999). For example, Ross, Badcock, and Hayes (2000) have shown that form information constrains incoherent motion to generate the appearance of coherent global motion when multiple independently-generated Glass patterns are presented in rapid succession.

A Glass pattern is a type of static stimulus that consists of an array of randomly-positioned dot-pairs (i.e., dipoles) that are oriented in a way to provide the percept of a global shape (Fig. 1A; Glass, 1969). Glass patterns are commonly used to study how the visual system pools local orientation information to allow us to perceive the global form of objects in the environment, in the same way that random-dot stimuli are used to investigate global pooling of local motion signals (Williams & Sekuler, 1984; Wilson & Wilkinson, 1998). Ross, Badcock, and Hayes (2000) have shown that if a series of independently-generated Glass patterns, with the same global form, are shown in rapid succession, termed dynamic Glass patterns (dynamic GPs), observers perceive a salient illusion of coherent motion. They considered this to be "implied motion" and noted that their participants could not differentiate implied motion from real motion. Furthermore, Krekelberg et al. (2003) and Krekelberg, Vatakis, and Kourtzi (2005) found that cells in the prototypical motion areas of monkeys and humans (medial temporal area [MT] and medial temporal complex [MT+], respectively) do not differentiate between real motion and implied motion. Thus, the results from Krekelberg and colleagues and those

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of Ross, Badcock, and Hayes (2000) provide evidence of an interaction between form and motion, whereby the motion system of the mammalian visual system translates global form information into coherent global motion information.

Various research groups have reported that the detection thresholds for dynamic Glass patterns are significantly lower than the detection thresholds for static Glass patterns (e.g., Burr & Ross, 2006; Or, Khuu, & Hayes, 2007). Because thresholds for real global motion are generally lower than those for global form, the lower thresholds for dynamic GPs relative to static GPs suggest that dynamic GPs are processed in a similar way to real motion. However, based on psychophysical evidence, Nankoo et al. (2012) have suggested that the decrease in thresholds with dynamic GPs is likely related to the form system (e.g., V4). Nankoo et al. (2012) measured the detection threshold for concentric, radial, spiral, horizontal and vertical static GPs, dynamic GPs, and real global motion. They showed that even though thresholds for both dynamic GPs and real motion were significantly lower than static GPs, the relative performance in each of the patterns suggests that the low thresholds of dynamic GPs and real motion are based on different mechanism. In particular, with real motion, detection thresholds were equivalent for all patterns except for higher thresholds for spiral motion (see also Morrone, Burr, & Vaina, 1995). In contrast, with dynamic GPs, participants were best at detecting concentric and radial patterns, and worst at vertical and horizontal patterns, with spiral at an intermediate detection threshold. The relative ranking of the thresholds for dynamic GPs were identical to the relative ranking of the thresholds for static GPs (see also Wilson & Wilkinson, 1998). Nankoo et al. (2012) argue that this suggests that the decrease in threshold found in dynamic GPs is driven by the same or similar form-related processes that drive the detection of GPs, as opposed to motion-related processes.

Recently, Day and Palomares (2014) reported a negative linear relationship between temporal frequency and coherence threshold in dynamic GPs; as temporal frequency was increased, threshold decreased (see also Edwards & Crane, 2007). Day and Palomares (2014) argued that their result is consistent with the idea that the dynamic GPs is processed by the ‘motion streak’ system (Ross, 2004; Ross, Badcock, & Hayes, 2000). The motion streak model is based on the finding that fast-moving objects leave a trailing blur due to temporal integration (Geisler, 1999). At high velocities, the visual system appears to utilize the form from the trailing blur (i.e., streak) to disambiguate direction information (Burr & Ross, 2002). Day and Palomares suggested that if dynamic GPs are interpreted as motion streaks by the visual system, it follows that increasing the temporal frequency would increase sensitivity. However, while Day and Palomares’ study showed the importance of temporal frequency, it does not rule out the possibility that lower detection thresholds for dynamic GPs are also due to the additional form signals present in dynamic GPs. The increase in temporal frequency also means that there is an increase in the number of unique frames presented. Thus, it is unclear whether the increased sensitivity of dynamic GPs relative to static GPs is due to the summation of multiple global form signals.

In the current study we tested the hypothesis that the lower thresholds observed for dynamic GPs are due to a summation of the form signals. Given that dynamic GPs consist of multiple independent static GPs, and thus contain multiple presentations of unique global form signals relative to static GPs, we measured the detection thresholds of our participants for static GPs (one GPs frame), dynamic GPs (12 GPs frames), and intermediate stimuli containing two, four, and six unique GPs frames, presented in different types of frame alternation sequences to also manipulate temporal frequency (see Table 1). If the lower thresholds observed for dynamic GPs are due to the summation of multiple form signals, we can expect a linear decrease in threshold as the number of unique frames increases. In addition, each GPs in dynamic GPs is presented for a short duration relative to one GPs in static GPs (i.e., temporal frequency). In order to account for this factor, we measured the thresholds for stimuli that contained blocks of unique GPs (Table 1).

2. Method

Nine adults with normal or corrected-to-normal vision participated in this study ($n = 9$). This sample included three of the authors, two graduate students, and four undergraduate students from the University of Alberta. All the participants were naïve to the purpose of the experiment, except for the three authors. The experiment was conducted in accord with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

2.1. Apparatus

The stimuli were displayed on a 22″ Viewsonic VX2268wm FuHzion LCD monitor (resolution: 1680×1050 pixels; refresh rate: 120 Hz). Participants were seated comfortably at a viewing distance of 45 cm to the monitor, with the center of the monitor positioned at eye-level. Participants’ head position was fixed with a chin rest. Stimuli were generated using in-house MATLAB code and presented using the Psychophysics toolbox (Brainard, 1997; Pelli, 1997).

2.2. Stimuli and design

Each stimulus was presented for a total duration of 200.00 ms (12 frames, 60 Hz image update rate). Each GPs subtended a visual angle of 10.7° (diameter of aperture), and each square dot within the stimulus subtended $0.04° \times 0.04°$. The density of dots within each pattern was set at 6% and the dot separation was 0.25°. The dipoles were oriented to generate a percept of vertical structure (Fig. 1). We chose vertical GPs because Nankoo et al. (2012) have previously shown that the improvement in the detection threshold between static GPs and dynamic GPs is largest for vertical patterns relative to other orientations such as concentric or horizontal, and thus would provide us with the greatest statistical sensitivity for the current study.

A temporal two-alternative forced-choice design was used, whereby the participants were presented with two consecutive patterns; one pattern that contained form signals (i.e., GPs) and one that contained a noise pattern (i.e., randomly-oriented dipoles). The participants’ task was to identify which pattern contained the signal. The order of the signal stimulus and the noise stimulus was pseudo randomly counterbalanced across trials.

Detection thresholds were determined using the QUEST adaptive staircase method (Watson & Pelli, 1983). In this method, coherence (the % of dipoles aligned in the pattern) was systematically increased or decreased depending on the participant’s performance. In each trial, a psychometric function is fit to all the data collected, and an estimate of the threshold is derived.

2.3. Presentation sequence

As shown in Table 1, the number of unique GPs (i.e., unique frames) used was 2, 4, and 6, in addition to the static and dynamic GPs condition (i.e., 1 and 12 unique frames, respectively). The unique frames were presented in two ways. In one presentation format, the unique frames were presented in an alternating sequence whereby a sequence of unique frames was repeated for a total of 12 frames per stimulus. For example, in patterns with two unique frames (“A” and “B”), the pattern would consist of a repeating