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Revisiting the Lissajous figure as a tool to study bistable perception

V.A. Weilnhammer[a], K. Ludwig[a,b], P. Sterzer[a], G. Hesselmann[a,*]

[a] *Visual Perception Laboratory, Department of Psychiatry and Psychotherapy, Campus Charité Mitte, Charité Universitätsmedizin, 10117 Berlin, Germany*
[b] *Department of Psychology, Humboldt-Universität zu Berlin, 10099 Berlin, Germany*

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ABSTRACT

During bistable vision perception spontaneously "switches" between two mutually exclusive percepts despite constant sensory input. The endogenous nature of these perceptual transitions has motivated extensive research aimed at the underlying mechanisms, since spontaneous perceptual transitions of bistable stimuli should in principle allow for a dissociation of processes related to sensory stimulation from those related to conscious perception. However, transitions from one conscious percept to another are often not instantaneous, and participants usually report a considerable amount of mixed or unclear percepts. This feature of bistable vision makes it difficult to isolate transition-related visual processes. Here, we revisited an ambiguous depth-from-motion stimulus which was first introduced to experimental psychology more than 80 years ago. This rotating Lissajous figure might prove useful in complementing other bistable stimuli, since its perceptual transitions only occur at critical stimulus configurations and are virtually instantaneous, thus facilitating the construction of a perceptually equivalent replay condition. We found that three parameters of the Lissajous figure – complexity, line width, and rotational speed – differentially modulated its perceptual dominance durations and transition probabilities, thus providing experimenters with a versatile tool to study the perceptual dynamics of bistable vision.

1. Introduction

The study of conscious perception crucially relies on reproducible, robust and yet flexible experimental paradigms. To directly manipulate participants' conscious perception of sensory stimuli, various approaches have been conceived, particularly within the visual domain (Bachmann, Breitmeyer, & Ogmen, 2007; Kim & Blake, 2005). A widely studied phenomenon is bistable vision, during which perception spontaneously "switches" between two mutually exclusive percepts despite constant sensory input. The endogenous nature of these perceptual transitions has motivated extensive research targeting the underlying mechanisms, since spontaneous perceptual transitions of bistable stimuli should in principle allow for a dissociation of processes related to sensory stimulation from those related to conscious perception (Blake & Logothetis, 2002; Sterzer, Kleinschmidt, & Rees, 2009). Bistable perception may arise from presenting dissimilar images to the two eyes, resulting in binocular rivalry, or from ambiguous visual stimuli, such as the Necker cube, Rubin's face-vase illusion or apparent motion. Independently of whether both eyes receive the same or different sensory stimulation, transitions from one conscious percept to another are often not instantaneous, and participants usually report a considerable amount of mixed or unclear percepts (Anstis, Giaschi, & Cogan, 1985; Mueller & Blake, 1989; Yantis & Nakama, 1998). Recently, it has been suggested that this feature of bistability makes it particularly difficult to isolate transition-related visual processes (Knapen et al., 2011). Transition-related processes have usually been investigated by comparing spontaneous transitions with a "replay" sequence of perceptual alternations designed to closely match participants' perception during bistable vision in both perceptual quality and timing.

In this paper, we revisited an ambiguous depth-from-motion stimulus, first introduced to experimental psychology more than 80 years ago (Weber, 1930), as a tool that might prove useful in complementing other bistable stimuli: the Lissajous figure, named after the 19th century French physicist Jules Antoine Lissajous. The 2D Lissajous figure is formed by the intersection of two sinusoids with perpendicular axes (Fig. 1). Its planarly moving version, based on increasing phase-shifts of the sinusoids, yields the perception of a 3D object rotating in depth with ambiguous rotation direction (Supplemental Video). Lissajous figures were originally studied by means of twin-oscillators and analog cathode ray oscillographs in the 1940s and 1950s (Fisichelli, 1947, 1951; Fisichelli & Misiak, 1947; Philip, 1953; Philip & Fisichelli, 1945).

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[*] Corresponding author.
E-mail address: guido.hesselmann@charite.de (G. Hesselmann).

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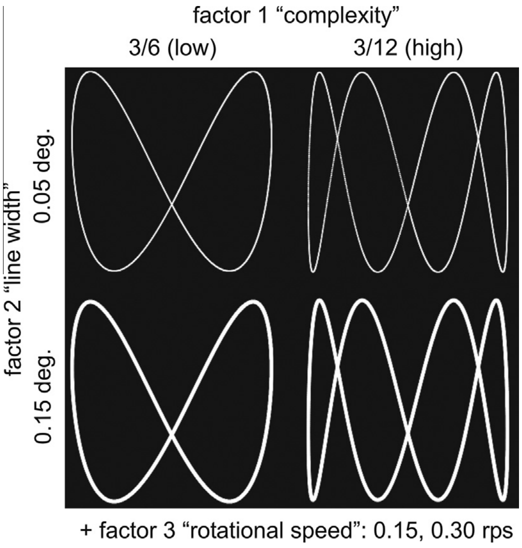

Fig. 1. Lissajous stimulus and experimental design. Three parameters of the Lissajous figure were varied in a 2 × 2 × 2 factorial design: "complexity", "line width", and "rotational speed". The complexity of the Lissajous figure was manipulated by changing the frequencies of the two perpendicular sinusoids A and B. The ratio A/B of these frequencies was either 3/6 (low complexity) or 3/12 (high complexity). Line width was either 0.05° or 0.15° visual angle, and rotational speed was either 0.15 or 0.30 revolutions per second (rps).

In contrast to binocular rivalry, perceptual reversals of the Lissajous figure are virtually instantaneous, thus facilitating the construction of a perceptually equivalent "replay" condition (Weilnhammer et al., 2013). Similar to other bistable depth-from-motion stimuli (Pastukhov, Vonau, & Braun, 2012; Stonkute, Braun, & Pastukhov, 2012), the rotating Lissajous figure elicits perceptual transitions only at critical stimulus configurations which are characterized by depth symmetry: during self-occlusions of the figure, the illusory 3D object is symmetrical with respect to the frontal plane. Here, we aimed to investigate how three parameters of the Lissajous figure – complexity, line width, and rotational speed – influence its perceptual dynamics. We hypothesized that perceptual transitions should be more frequent if the depth-symmetrical self-occlusions of the Lissajous figure last longer due to thicker line width or slower rotational speed, or if they occur more often due to higher stimulus complexity.

2. Materials and methods

2.1. Participants

11 right-handed observers participated in this study, which was conducted with local ethics approval at the Department of Psychiatry and Psychotherapy, Charité Universitätsmedizin Berlin, Germany. One participant was excluded because she reported no perceptual transitions in 4 out of 8 experimental conditions. All remaining 10 participants (8 female, mean age: 23.60) had normal or corrected-to-normal vision and provided informed written consent to take part in the study. The sample size was determined in advance, based on our previous psychophysical and functional magnetic resonance imaging (fMRI) experiments using the Lissajous figure (Weilnhammer et al., 2013).

2.2. Stimulus and procedure

All stimuli were generated with the Psychophysics Toolbox 3 (Brainard, 1997; Pelli, 1997) running under Matlab R2007b (MathWorks Inc., USA) and displayed by a CRT monitor (SAMTRON 98PDF) with a refresh rate of 60 Hz. Two identical moving Lissajous figures (size 2.05°), formed by the intersection of two sinusoids with perpendicular axes ($x(t) = \sin(At)$; $y(t) = \sin(Bt + \partial)$; with ∂ increasing from 0 to 2π), were presented separately to both eyes using a mirror stereoscope. Dichoptic stimulation was used because the stimulation protocol involved a final block of "replay" trials based on disparity cues disambiguating the stimulus (Weilnhammer et al., 2013). These "replay" data are not reported here. Fixation marks were displayed at the center, and fusion frames surrounded the stimuli.

Three parameters of the Lissajous figure were varied systematically in a three-factorial repeated measures design: "complexity", "line width", and "rotational speed" (Fig. 1). The complexity of the Lissajous figure was manipulated by changing the frequencies of the two sinusoids (A and B in the equations above). The ratio A/B of these frequencies was either 3/6 or 3/12, yielding two different Lissajous figures of low and high complexity, respectively. Line width was either 0.05° or 0.15° visual angle, and rotational speed was either 0.15 or 0.30 revolutions per second (rps).

The number of self-occlusions (i.e., critical depth-symmetrical stimulus configurations) of the Lissajous figure per full rotation (360° or 2π) was two for low complexity (3/6 Lissajous) and four for high complexity (3/12 Lissajous). Increasing the line-width of the stimulus from 0.05° to 0.15° yielded a sixfold increase in the duration of each self-occlusion. The time interval between two self-occlusions of the 3/6 Lissajous figure was either 3.33 s (at 0.15 rps rotational speed) or 1.67 s (0.30 rps); for the 3/12 Lissajous figure, these intervals were 1.67 s (0.15 rps) and 0.83 s (0.30 rps).

The three-factorial design yielded a total of $2 \times 2 \times 2 = 8$ conditions. During one block of the experiment (~11 min), each condition was presented once for a trial of 80.2 s. The order of conditions within a block was randomized, and trials were separated by 5 s fixation. All participants performed a total of three blocks.

Participants indicated the perceived rotation direction of the Lissajous figure by pressing a left (clock-wise, CW; within a top-view reference frame) or right (counter-clock-wise, CCW) button with their right hand. They were instructed to respond to the first perceived direction after trial onset and to all perceptual transitions, and to report unclear or mixed percepts by pressing a middle button.

2.3. Data analysis

Separately for the low-complexity (3/6) and the high-complexity (3/12) Lissajous figures, we calculated transition frequencies depending on the rotation phase of the figure. To this end, response times of button presses indicating perceptual transitions were expressed in degrees of rotation of the Lissajous figure (Fig. 2A). Next, we calculated the average distribution of dominance durations across participants, after dominance durations were normalized to their respective means for each participant, irrespective of condition (Fig. 2B). The same analysis was performed separately for each condition (Fig. S1). Additionally, dominance durations from all participants and conditions were analyzed following a "fixed effects" approach, i.e., without normalization and averaging, after removing response time variability by assuming that perceptual transitions occurred approximately in the middle of the transition window just prior to the key press (Fig. 2B, inset).

Separately for all experimental conditions, we calculated mean and median perceptual dominance durations. First, mean and median dominance durations were calculated for every participant, condition and block. Next, the resulting values for every condition were averaged across blocks for each participant and then across participants (Fig. 3A).

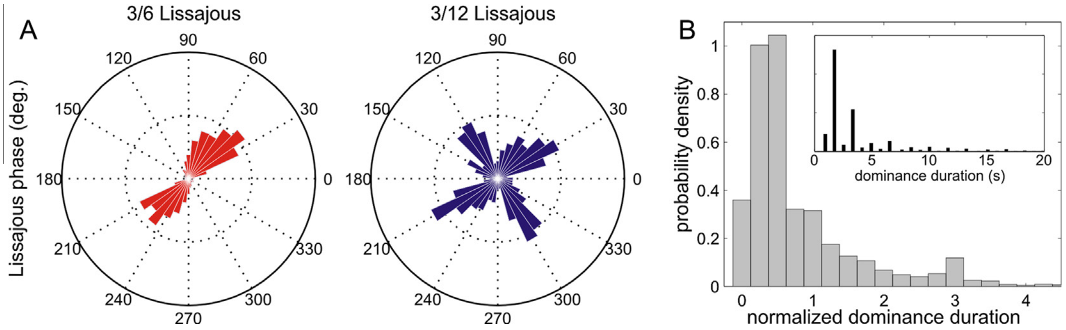

Fig. 2. Distribution of perceptual transitions and dominance durations. (A) Transitions relative to phase (degree of rotation) of the 3/6 Lissajous (low complexity, left panel, red color) and 3/12 Lissajous figure (high complexity, right panel, blue color). The panels show absolute transition frequencies across all participants. The inner dashed circles of the polar plots denote 100, the outer circles denote 200. Self-occlusions of the 3/6 Lissajous figure occur at 0° and 180°; self-occlusions of the 3/12 Lissajous figure occur at 0°, 90°, 180° and 270°. (B) Distribution of dominance durations. Plotted is the average probability density across participants (grey bars). Dominance durations were normalized to their respective means for each participant (19.54 s ± 5.65; mean ± standard error of the mean). The inset (black bars) shows dominance durations without normalization and averaging after removing response time variability. Plotted on the y-axis are absolute frequencies (range 0–1500). For visualization purposes, only dominance durations <20 s are shown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

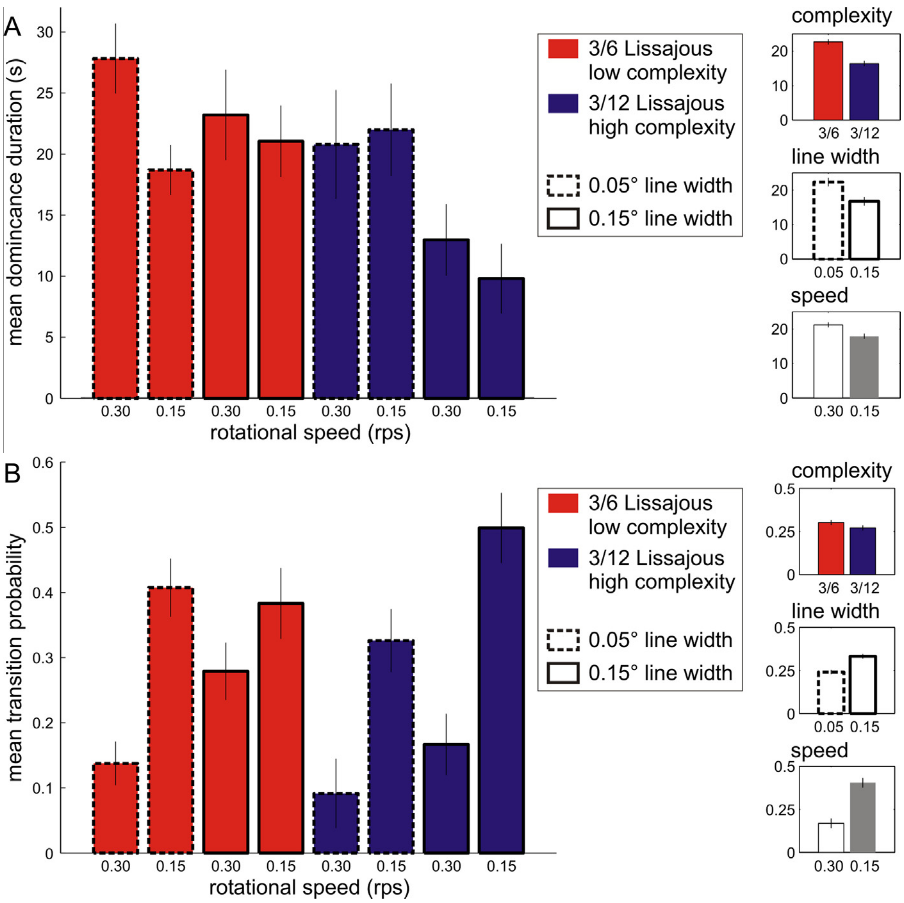

Fig. 3. Dominance durations and transition probabilities. (A) Mean dominance durations. Small panels on the right illustrate the main effects of Lissajous complexity, line width and rotational speed. (B) Mean transition probabilities (transitions/self-occlusions). Small panels on the right illustrate the main effects of Lissajous line width and rotational speed. No main effect of complexity was found. (AB) In the left panels, rotational speed is plotted on the *x*-axis (fast: 0.30 rps; slow: 0.15 rps). Red bars indicate low-complexity Lissajous figures, blue bars indicate high-complexity figures (low: 3/6; high: 3/12). Bar outlines indicate the line width of the Lissajous figures (dashed: 0.05°, solid: 0.15°). Error bars represent 95% confidence intervals following the corrected method by Cousineau for within-subject designs (Cousineau, 2005; Morey, 2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Transition probabilities were determined based on all self-occlusions of the Lissajous figure, where 0° and 180° rotational angle (phase shift ∂ in the equation above) represent self-occlusions of the low-complexity figure, and 0°, 90°, 180°, and 270° represent self-occlusions of the high-complexity figure. For each condition, transition probabilities were defined as the number of perceptual transitions divided by the total number of self-occlusions, and were averaged across participants (Fig. 3B).

Due to the relatively small number of dominance phases per trial, the effect of our stimulus manipulations on the serial correlation between successive dominance phases (van Ee, 2009) could not be examined.

We calculated 95% confidence intervals following the corrected method by Cousineau for within-subject designs (Cousineau, 2005; Morey, 2008). Mean and median dominance durations as well as transition probabilities were submitted to repeated measures ANOVAs (2 × 2 × 2). We report partial eta squared (η_p^2) as measure of effect size (SPSS 13.0 for Windows, SPSS Inc.).

3. Results

None of the participants reported mixed or otherwise unclear percepts by pressing the according button. Fig. 2A plots transition frequencies relative to phase (degrees of rotation) of the 3/6 (low-complexity) and 3/12 (high-complexity) Lissajous figure. As can be seen, transition frequencies followed a bimodal and quadrimodal distribution, respectively, since self-occlusions occurred at two rotational angles of the 3/6 Lissajous figure (0°, 180°), and at four rotational angles of the 3/12 Lissajous figure (0°, 90°, 180°, 270°). The offset of the distribution modes with respect to these critical phases most likely corresponds to response time. Fig. 2B shows that the average distribution of normalized dominance durations was unimodal and followed a sharp rise and a slow fall. This was also the case for all distributions plotted separately for each condition (Fig. S1). Without normalization and averaging, the distribution reveals that dominance durations were multiples of the inter-occlusion intervals (Fig. 2B, inset).

Fig. 3A plots the mean perceptual dominance durations for all eight experimental conditions. The high-complexity Lissajous figure was associated with shorter dominance durations than the low-complexity figure (16.39 s vs. 22.69 s); the repeated measures ANOVA yielded a significant main effect of "complexity" (Table 1A). Lissajous figures of thick line width produced significantly shorter dominance durations than Lissajous figures of thin line width (16.76 s vs. 22.32 s). Rotational speed also had a significant effect on dominance durations: fast rotations resulted in significantly longer dominance durations than slow rotations (21.20 s vs. 17.89 s). None of the two-way or the three-way interactions was significant. The ANOVA based on median dominance durations yielded highly comparable results.

Fig. 3B represents the same behavioral data in terms of transition probabilities. Transition probabilities were defined as the number of perceptual transitions divided by the total number of self-occlusions. Transition probabilities were higher for Lissajous figures of thick line width than for Lissajous figures of thin line width (0.33 vs. 0.24); the ANOVA showed a significant main effect of "line width" (Table 1B). The main effect of rotational speed was significant as well: interestingly, fast rotations resulted in significantly lower transition rates than slow rotations (0.17 vs. 0.40). By contrast, there was no effect of Lissajous "complexity" (low: 0.30; high: 0.27) and no two-way interaction. The three-way interaction was significant, because the effect of "line width" and "complexity" on transition probability was modulated by "rotational speed" (fast: $F_{1,9} = 3.25$, $p = .105$, $\eta_p^2 = .27$; slow: $F_{1,9} = 5.07$, $p = .051$, $\eta_p^2 = .36$). At slow rotational speed, post hoc tests revealed that transition probabilities differed significantly between thin and thick line widths of the high-complexity Lissajous figure (0.33 vs. 0.50; $t_9 = 2.98$, $p = .015$), but not between line widths of the low-complexity figure (0.41 vs. 0.38; $t_9 < 1$; paired two-sided t-tests, not corrected for multiple comparisons).

Table 1
Repeated measures ANOVAs (2 × 2 × 2). Partial eta squared (η_p^2) is reported as measure of effect size.

Effect	$F_{1,9}$	p	η_p^2
A: Perceptual dominance duration			
Complexity	20.29	.001	.69
Line width	6.43	.032	.42
Rotational speed	6.18	.035	.41
Complexity × line width	2.23	.169	.20
Complexity × speed	0.95	.356	.10
Line width × speed	0.04	.838	.01
Complexity × width × speed	3.78	.084	.30
B: Transition probability			
Complexity	1.43	.263	.14
Line width	16.05	.003	.64
Rotational speed	20.81	.001	.70
Complexity × line width	2.30	.163	.20
Complexity × speed	2.28	.165	.20
Line width × speed	0.20	.666	.02
Complexity × width × speed	6.55	.031	.42

To further explore the effects of rotational speed on the perceptual dynamics of the Lissajous figure, we analyzed transition rates based on the total duration of self-occlusions instead of the total number of self-occlusions. Durations for the different stimulus manipulations were calculated in units of the shortest self-occluding configuration (low-complexity Lissajous of thin line width). The total durations for the two speed levels were identical since faster rotations resulted in self-occlusions which were twice as frequent but also half as long. Even though the total time available for transitions was independent of speed, fast rotations were still associated with significantly lower transition rates than slow rotations (3.52 vs. 4.95; $F_{1,9} = 6.95$, $p = .027$, $\eta_p^2 = .44$).

4. Discussion

We investigated how three stimulus parameters – complexity, line width, and rotational speed – modulate the perceptual dynamics of a bistable rotating Lissajous figure. These parameters are related to the timing and duration of depth–symmetrical self-occlusions of the figure, which have been shown to be critical stimulus configurations for the perceptual transitions of similar bistable depth-from-motion stimuli (Pastukhov, Vonau, & Braun, 2012; Stonkute, Braun, & Pastukhov, 2012).

In accordance with the original findings by Philip and Fisichelli (1945), who studied the effects of Lissajous complexity and rotational speed on perceptual reversals, we found that high-complexity Lissajous figures were associated with significantly shorter perceptual dominance durations than low-complexity Lissajous figures. In their study with 16 normal observers, Philip and Fisichelli (1945) used three levels of complexity (corresponding to A/B frequency ratios of 3/12, 3/18, and 3/24). Our psychophysical data do not only offer a replication of these earlier results but also show that the effect of complexity on perceptual transitions extends to Lissajous figures of lower complexity (3/6). However, our finding of a significant increase in dominance duration for higher rotational speed appears to be in conflict with the results from Philip and Fisichelli (1945) who report a progressive increase in the number of reversals (i.e., shorter dominance durations) from slow to fast rotational speeds (corresponding to 0.5, 0.2, 0.14, 0.07, and 0.05 rps). It is interesting to note that the authors concluded that speed of rotation affects the perceptual dynamics of the Lissajous figure "probably to a lesser degree" (p. 539) than complexity, which is in line with our estimated effect sizes for speed ($\eta_p^2 = .41$) and complexity ($\eta_p^2 = .69$).

But how can we explain the opposite effects of rotational speed on dominance duration observed by us and by Philip and Fisichelli (1945)? Unfortunately, since the differences in experimental setups between the two studies are quite substantial with respect to display (1940s single-color cathode ray oscillograph; 2000s multi-color CRT) and response recording devices (kymograph; PC keyboard), and since we cannot easily reproduce Philipp and Fischelli's analog setup in our psychophysics laboratory, we can only speculate at this point. It is conceivable that the planar movement of the Lissajous figures was perceptually different for the two setups (analog: slight mistuning of the twin-oscilloscope frequencies; digital: software-based continuous phase shifts of the sinusoids), possibly further aggravated by the different phosphors used in the two cathode ray displays which may have resulted in different levels of motion streaking. It seems worth mentioning that the increase in dominance duration for higher rotational speeds observed by us has been consistent across studies from our lab. Previously, we have used the same directional effect for the individual adjustment of dominance durations in an fMRI study (Weilnhammer et al., 2013).

Our results show that the absolute number of critical positions per given time interval (e.g., a trial of 80 s), which is directly related to the complexity of the Lissajous figure, impacts on dominance durations: as self-occlusions occurred twice as often for the high-complexity figure as for the low-complexity figure, dominance durations were shorter for the high-complexity Lissajous stimulus. Interestingly, transition probabilities at critical positions of the stimulus turned out to be comparable across the two degrees of Lissajous complexity.

This potential for an increased number of transitions due to the amount of self-occlusions was overridden by the factor "rotational speed": dominance durations were longer and transition probabilities lower for stimuli rotating at 0.30 rps as compared with stimuli rotating at 0.15 rps, even though the faster rotation produced twice as many critical positions per trial. Our data thus suggest different mechanisms underlying the "complexity" and the "rotational speed" effects.

Based on the study by Pastukhov, Vonau, and Braun (2012), we hypothesized that stimulus parameters related to the timing of self-occlusions modulates the perceptual dynamics of the Lissajous figure. Specifically, we predicted that perceptual transitions are more frequent if critical depth–symmetrical positions last longer. In our paradigm, we therefore varied the duration of self-occlusions by means of two independent factors: first, by increasing the line-width of the stimulus from 0.05° to 0.15°, yielding a sixfold increase in the duration of each self-occlusion; second, by decreasing rotational speed from 0.30 to 0.15 rps, resulting in a twofold increase of self-occlusion duration. In line with our prediction, both factors significantly influenced perceptual transitions, and longer self-occlusions resulted in shorter dominance durations. Under the assumption that self-occlusion duration is the main factor influencing the probability of perceived transitions, one would expect a larger effect on perceptual dynamics from our manipulation of line-width as compared with the manipulation of rotational speed. However, despite their differential influence on self-occlusion duration (sixfold and twofold, respectively), our results show comparable effects on perceptual dynamics for the experimental factors "line width" and "rotational speed". We conclude that the effect of rotational speed on perceptual dominance durations cannot be explained only on the grounds of prolonged self-occlusions for slowly rotating Lissajous stimuli. We tentatively propose that higher rotational speed resulted in larger 'momentum' (Hubbard, 2005; Kelly & Freyd, 1987), thereby rendering a perceptual transition (i.e., an inversion of rotation direction of the 3D Lissajous object) during critical time points less likely, just as it needs more effort to inverse the rotation direction of a rotating physical sphere when it is rotating faster. Further supporting the momentum account was the fact that fast rotations were still associated with significantly lower transition rates than slow rotations when transition rates based on total durations of self-occlusions were analyzed. Inconsistent with the momentum account, however, a recent study using an ambiguously rotating sphere stimulus showed that perceptual durations *decreased* as a function of increased rotational speed (Brouwer & van Ee, 2006). To further investigate potential 'momentum' effects on dominance durations of the Lissajous figure, future studies with parametric variations of both rotational speed and line width are necessary. These studies will also need to aim at further disentangling the perceptual effects of the two physical changes associated with rotational speed, namely its influence on the rate of occurrence and the duration of self-occlusion events.

To conclude, we have shown that three basic parameters of the bistable rotating Lissajous figure can be manipulated to modulate its perceptual dynamics. Complexity, line width, and rotational speed can easily be varied to titrate dominance times and transition probabilities in behavioral as well as event-related EEG and fMRI studies, thus providing experimenters with a versatile tool to explore the cognitive and neuronal processes underlying bistable perception.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.visres.2014.03.013.

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