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#### **Title**

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#### **Journal**

Proceedings of the Annual Meeting of the Cognitive Science Society, 38(0)

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#### **Publication Date**

2016

Peer reviewed

# Hysteresis in Processing of Perceptual Ambiguity on Three Different Timescales

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## Abstract

Sensory information is a priori incomplete and ambiguous. Our perceptual system has to make predictions about the sources of the sensory information, based on concepts from perceptual memory in order to create stable and reliable percepts. We presented ambiguous and disambiguated lattice stimuli (variants of the Necker cube) in order to measure a hysteresis effects in visual perception. Fifteen healthy participants observed two periods of ordered sequences of lattices with increasing and decreasing ambiguity and indicated their percepts, in two experimental conditions with different starting stimuli of the ordered sequence. We compared the stimulus parameters at the perceptual reversal between conditions and periods and found significant differences between conditions and periods, indicating memory contributions to perceptual outcomes on three different time scales from milliseconds over seconds up to lifetime memory. Our results demonstrate the fruitful application of physical concepts like hysteresis and complementarity to visual perception.

**Keywords:** perception, ambiguous figures; hysteresis, memory-effects

## Introduction

The environmental information available to our senses is incomplete and to varying degrees ambiguous. As a result, our perceptual system needs to disambiguate and interpret this information in order to construct fast and reliable solutions to all types of sensory input of whatever quality (the ‘visual inference problem’, von Helmholtz, 1911). Accordingly, perception has been widely discussed as a weighting of sensory (bottom-up) information with memorized (top-down) concepts in terms of Bayesian probability estimation (e.g., Kersten, Mamassian, & Yuille, 2004). The contribution of sensory and memory information to the perceptual outcome may thus change as a function of the

quality of the sensory information and probably also of the availability of fitting memory contents (e.g., Kornmeier & Mayer, 2014). However, the term “memory” encompasses information from the immediate perceptual history up to long-term memory and it is unclear exactly how memory contents from different time scales contribute to the perceptual outcome.

In the present study, we investigated perception of the ambiguous “Necker lattice” (Kornmeier, Heinrich, Atmanspacher, & Bach, 2001; Kornmeier & Bach, 2004), a variant of the classical Necker cube (Necker, 1832), and lattices variants with different degrees of disambiguation in order to quantify the contributions of sensory information and memory from three different time scales.

## Hysteresis and Ambiguous Figures

During prolonged observation of an ambiguous figure, such as the Necker lattice, our perception becomes unstable and suddenly alternates between different interpretations (e.g. the two different 3D perspectives of the lattice), although the stimulus information stays unchanged. Luminance changes of the apparent lattice back layer can disambiguate the stimulus and stabilize the observers’ percepts. Ambiguous figures are popular stimuli to study the respective bottom-up and top-down contributions to the resolution of sensory ambiguity (e.g., Long & Toppino, 2004) and their physiological correlates (e.g., Kornmeier & Bach 2012).

In the present study we focus on *hysteresis* effects in the context of ambiguous figure perception. Hysteresis is an elementary form of history-dependent behaviour that is frequently observed in physical systems (first demonstrated by Ewing, 1881). It describes *multistable* system-behaviour where, depending on the direction of parameter change, the system can be in one of several states. Specifically, transitions back to a

previous state lag behind the change in parameters. Hysteresis behaviour can be found in visual perception, e.g., in the perception of ambiguous figures and disambiguated variants thereof (e.g., Fender & Julesz, 1967; Fisher & Ciuffreda, 1989; Hock, Kelso, & Schöner, 1993).

Observation of hysteresis depends on preservation of history in parameter change and the presence of perceptual reversals in two directions. Figure 1 displays a series of stimuli that is designed to elicit two perceptual reversals. It starts with an unambiguous “front-side right bottom” view lattice “ $S_{FRB}$ ” with maximally reduced luminance  $m$  of the apparent lattice back layer (Figure 1, left). Linearly increasing  $m$  with each stimulus results in the most ambiguous lattice with iso-luminant front and back layers (Figure 1, third to left). Again linearly decreasing  $m$  to a maximally reduced back-layer luminance, results in the alternative unambiguous “front-side left top” view lattice “ $S_{FLT}$ ” (Figure 1, middle). This procedure is then reversed via the ambiguous lattice (Figure 1, third to right) back to the unambiguous front-right-bottom view  $S_{FRB}$  (Figure 1, right).

### Different Time-Scales of Memory

**Classic Hysteresis Effect** Presenting a series of lattices as described above, perceptual reversals are expected to take place around the ambiguous lattice. Assuming the absence of any type of influence of perceptual history on perception, the order of stimulus presentation should have no effect on the critical stimulus parameter for perceptual reversals. However, the presence of hysteresis implies that perception will reverse from  $P_{FRB}$  (front-right-bottom view, cf. stimulus  $S_{FRB}$ ) to  $P_{FLT}$  (front-left-top view, cf. stimulus  $S_{FLT}$ ) at a certain back-layer luminance value  $m_{critical,1}$ , which will be different from value  $m_{critical,2}$ , when moving back from  $P_{FLT}$  to  $P_{FRB}$ . In other words, the second perceptual reversal depends on the first perceptual reversal. We plan to quantify this classical hysteresis effect with a measure called “hysteresis distance” =  $m_{critical,1} - m_{critical,2}$ , and hypothesise this distance to be significantly different from zero.

Additionally, if multiple series are presented to a single person, his/her aggregated stimulus perception can be expressed as a sigmoidal probability function of the stimulus morphing parameter  $m$ , and the function’s inflection point at the probability  $p = 0.5$  can be used as an estimate of the aggregated critical morphing parameter value  $\bar{m}_{critical}$  (Figure 3; see method section for more details about the fitting procedure). These critical values can subsequently be used to understand memory effects on three different timescales.

### Immediate and Intermediate Memory Effects

Hysteresis is a hallmark characteristic behaviour of nonlinear dynamical systems (with its own set of

implications for understanding the behaviour of such systems, e.g., see Kaplan & Glass, 2012). In the context of visual perception, measures of hysteresis can quantify the influence of perceptual memory on the current percept. However, contrasting two reversals in a series of stimuli containing two periods of increasing and decreasing ambiguity (e.g.,  $S_{FLT} \Rightarrow S_{Amb} \Rightarrow S_{FRB} \Rightarrow S_{Amb} \Rightarrow S_{FLT}$ ), may reflect a mixture of memory effects on two different time scales: (1) An *immediate memory effect*, reflecting the influence of immediately preceding stimuli within one period and (2) an *intermediate memory effect*, reflecting the influence of period 1 (e.g.,  $S_{FLT} \Rightarrow S_{Amb} \Rightarrow S_{FRB}$ ) on the perceptual dynamics in period 2 (e.g.,  $S_{FRB} \Rightarrow S_{Amb} \Rightarrow S_{FLT}$ ). In order to fully disentangle immediate from intermediate memory effects, we tested several other contrasts.

**Long-Term Memory Effects** Long-term perceptual memory can also have an influence on the perception of an ambiguous stimulus. In the case of the Necker cube perception is biased towards the front-side right bottom perceptual interpretation (e.g. Sundareswara & Schrater, 2008; see also data from page 485 in Washburn, Mallay, & Naylor, 1931), reflecting a general view-from-above preference, which is also demonstrated in other contexts (e.g., Troje & McAdam, 2010) and which may be based on long-term perceptual memory. We will quantify the influence of this long term memory in the following way: The hysteresis effect should be manifested as a linear shift of the two sigmoidal perceptual probability functions coming from the two stimulus presentation orders in opposite directions along the abscissa (representing the morphing parameter). Moreover, if the a priori probabilities of the two Necker lattice interpretations are equal, i.e. in the absence of any perceptual bias, we should expect equal distances of two sigmoids’ inflection points from  $m_{Amb}$  (representing the Necker lattice with iso-luminant layers). Any deviation from this symmetry should indicate inequality of the two Necker lattice interpretations, which would allow quantification of long-term memory effects.

## Method

**Participants** Fifteen participants (9 women, 5 men, 1 unknown,  $M = 27.4 \pm 7.9$  years old) participated in an ambiguous figures experiment designed to measure memory effects such as hysteresis on perceptual reversals. Previous to participating, all participants were asked for their consent and given instructions about the procedure. The study was performed in accordance with the ethical standards laid down in the Declaration of Helsinki (World Medical Association, 2000) and approved by the ethics committee of the University of Freiburg.

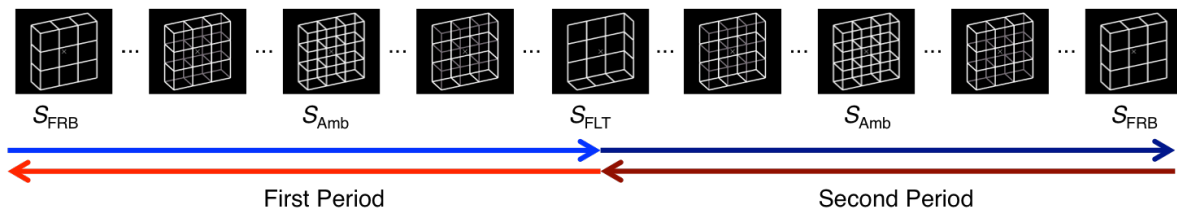


Figure 1: Necker lattices stimuli used in the experimental paradigm. From left to right, in the  $S_{FRB} \Rightarrow S_{FLT} \Rightarrow S_{FRB}$  series, we start with a fully disambiguated front-side right bottom view ( $S_{FRB}$ ), then ambiguity increases to full ambiguity ( $S_{Amb}$ ), then ambiguity decreases again to a front-side top left view ( $S_{FLT}$ ), and then the process is reverted back. Around the 9<sup>th</sup> and 26<sup>th</sup> trial ( $S_{Amb}$ ), we expect a perceptual reversal due to the changing orientation of the lattice. In the  $S_{FLT} \Rightarrow S_{FRB} \Rightarrow S_{FLT}$  series, the stimuli are presented in opposite order. S: Stimulus; Amb: Ambiguous; FRB: Lattice front-side to the right bottom; FLT: Lattice front-side to the left top.

**Stimuli** We presented an ambiguous “Necker lattice” consisting of 3x3 Necker cubes (Figure 1,  $S_{Amb}$ ) and 16 disambiguated lattice variants  $S_{FRB;1} - S_{FRB;8}$ , and  $S_{FLT;1} - S_{FLT;8}$ , with “FRB” = front-side right bottom and “FLT” = front-side left top, and S = stimulus (Figure 1). Stimulus disambiguation and thus percept stabilization was achieved by reducing the luminance of the virtual back layers of the lattices. Luminance was 0.8 cd/m<sup>2</sup> for the ambiguous Necker lattice and the front layers of all disambiguated lattices. Luminance values in cd/m<sup>2</sup> for the apparent back-layers were in descending order: 0.71, 0.59, 0.48, 0.37, 0.27, 0.18, 0.07, and 0.04. All lattices subtended an area of 5.5° x 6.5° visual angle. A cross in the centre of the lattices served as fixation target.

**Procedure** Each participant was presented with ten repetitions of a series of 33 Necker lattices with varying orientation<sup>1</sup>. The experiment consisted of two conditions, each consisting of two periods. In Condition 1 the lattice orientations were varied step-wise from  $S_{FRB}$ , over the fully ambiguous lattice  $S_{Amb}$  to  $S_{FLT}$  (first period) and back again over  $S_{Amb}$  to  $S_{FRB}$  (second period). In Condition 2 we presented the lattices in the reversed order:  $S_{FLT} \Rightarrow S_{Amb} \Rightarrow S_{FRB} \Rightarrow S_{Amb} \Rightarrow S_{FLT}$ .

Both conditions were presented five times to each participant in randomized order. After stimulus onset, participants indicated their perceived lattice orientation (either  $P_{FRB}$  for the front-side right bottom view or  $P_{FLT}$  for the front-side left top view) by pressing one of two buttons on a hand-held response box during the presentation of the stimulus. After participants’ responses the stimulus remained on the screen for another 1000 ms (but maximal 4000 ms in total) and was replaced by a blank screen with the fixation target for 400 ms.

## Results

Participants responded to more than 99% of the presented stimuli, indicating a sufficiently long response time window and ensuring an unequivocal stimulus-response relation.

### Classic Hysteresis Within Each Series

A total of 150 series (across participants and repetitions) containing 33 perceptual responses each were collected. Each series contained two potential perceptual reversals, i.e., there were 300 potential reversals in total. Of these, 102 were clearly identifiable with each response being preceded by a continuous sequence of  $P_{FLT}$ ’s (or  $P_{FRB}$ ’s, depending on the condition) and followed by a continuous sequence of  $P_{FRB}$ ’s (or  $P_{FLT}$ ’s). For these reversals, the particular stimulus for which the reversal took place was determined by averaging the respective stimulus values around the clear division between the two continuous sequences (see Figure 2, “clear reversal”). For the remaining 198 reversals, where participants recorded reversals more than once per period, we estimated this value, by first reordering the responses between the last of the preceding continuous sequence and the first of the following continuous sequence, in order to mimic a “clear reversal”. Then, we again took the average of stimulus order values before and after the resulting “clear reversal” (see Figure 2, “estimated reversal”). For 18 reversals this procedure did not work, the corresponding series were too messy and were excluded from the analysis, resulting in 274 reversals in 137 series (i.e. one reversal per period).

<sup>1</sup> Due to a coding error, the first eight participants were not presented with the 33<sup>th</sup> stimulus. In order to allow comparison across the entire group of participants, the resulting missing response in each

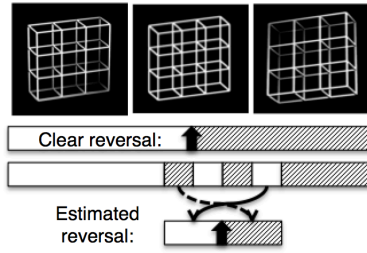


Figure 2: Two response pattern examples for a  $P_{FRB}$  (in white)  $\Rightarrow$   $P_{FLT}$  (in grey) reversal. The first pattern represents a “clear reversal”. The second pattern requires reordering the responses between the continuous sequences of  $P_{FRB}$ ’s and  $P_{FLT}$ ’s.

The hysteresis distance was computed by numbering the stimuli by presentation order and subtracting the stimulus order values  $N_i$  for which the two reversals in that series took place:  $N_{diff} = N_{rev1} - N_{rev2}$ . On average, the resulting difference values  $N_{diff}$  were significantly smaller than zero ( $Mean N_{diff} = -1.35$ ,  $SD = 2.33$ ,  $t(136) = -6.76$ ,  $p < .001$ ), indicating a *negative hysteresis* effect; rather than the second reversals lagging behind and occurring during more strongly disambiguated stimuli, they occur at less strongly disambiguated stimuli. In particular, the second reversals result 1.35 “disambiguation steps” sooner than the first. Comparing conditions showed no significant difference between the  $S_{FLT} \Rightarrow S_{FRB} \Rightarrow S_{FLT}$  and  $S_{FRB} \Rightarrow S_{FLT} \Rightarrow S_{FRB}$  conditions ( $t(135) = -1.84$ ,  $p = .07$ ).

### Aggregated Response curves

After collecting all responses, each  $P_{FLT}$  (i.e., the perception of a lattice in the front-side left top view) was coded as “0”, and each  $P_{FRB}$  as ‘1’.<sup>2</sup> Then, for each of the two conditions, i.e., taking 5 repetitions together, individual responses for each half of the series were fitted with a sigmoid curve as described by equation 1, where  $m$  is the point of inflection and  $s$  is the slope.

$$f(x) = \frac{1}{1 + \exp\left(\frac{m-x}{s}\right)} \quad (1)$$

Of the resulting fits, we excluded 11 response curves with R2 goodness-of-fit values below a predefined criterion of 0.5. Figure 3 displays the remaining aggregated response curves containing the first perceptual reversal of a series for each participant. About half of these response curves are  $P_{FLT} \Rightarrow P_{FRB}$  reversals, i.e., the first reversal in  $S_{FLT} \Rightarrow S_{FRB} \Rightarrow S_{FLT}$  series (displayed in red), and the other half  $P_{FRB} \Rightarrow P_{FLT}$  reversals, i.e., the first

<sup>2</sup> Of the fifteen participants, three had misunderstood the instructions and consistently responded exactly opposite to the remaining participants so their responses were recoded.

reversal from  $S_{FRB} \Rightarrow S_{FLT} \Rightarrow S_{FRB}$  series (displayed in blue). In addition, the means of all red and blue curves respectively are displayed in bold. For the remainder of the paper, we present the results using mean curves only.

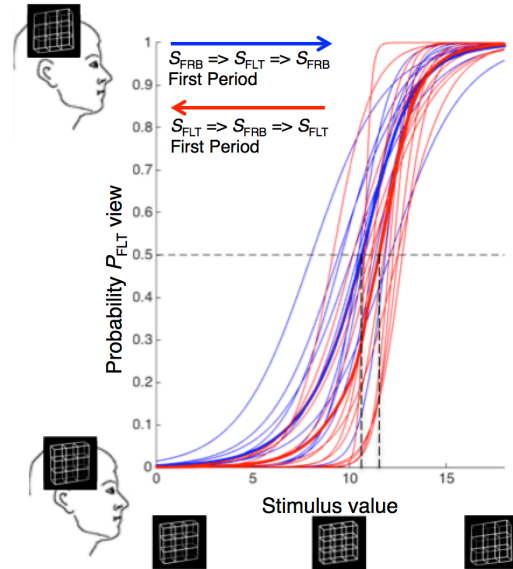


Figure 3: Response curves for each participant for the perceptual reversals in the first period of a series, from  $P_{FRB} \Rightarrow P_{FLT}$  (in blue), and  $P_{FLT} \Rightarrow P_{FRB}$  (in red). The aggregated response curves are displayed in bold.

### Immediate and Intermediate Effects

The sigmoids’ inflection points indicate where, on average, the perceptual reversals took place. Looking only at the perceptual reversals that occurred in the first period (see Figure 3), gives insight into the effect of immediate memory. On average, these first reversals occurred for the second stimulus to the right of the fully ambiguous lattice, ( $Mean N_{rev} = 10.97$ ,  $SD N_{rev} = 1.16$ ) meaning for the stimulus that has been disambiguated towards  $S_{FLT}$  with two steps. Furthermore, the two bold lines (aggregated data) indicate a difference between the  $P_{FLT} \Rightarrow P_{FRB}$  and  $P_{FRB} \Rightarrow P_{FLT}$  reversals. When the immediate predecessors of the more ambiguous stimuli are  $S_{FRB}$ , the corresponding percepts lose stability later (i.e., at  $Mean N_{rev} = 10.44$ ,  $SD N_{rev} = 1.16$ ) than when the immediate predecessors are  $S_{FLT}$  (i.e., at  $Mean N_{rev} = 11.39$ ,  $SD N_{rev} = 1.01$ ).

Figure 4 displays the response curves for both the first and second period of the  $S_{FRB} \Rightarrow S_{FLT} \Rightarrow S_{FRB}$  condition. Again we see that the perceptual reversals do not occur for the same values of back-layer luminance. The results we found when comparing the periods within conditions: Both perceptual reversals occurred at stimuli with luminance values favouring percepts  $P_{FLT}$ , whereas the reversals in the first period occurs closer to the

fully ambiguous stimulus ( $N = 9$ ) than in the second.

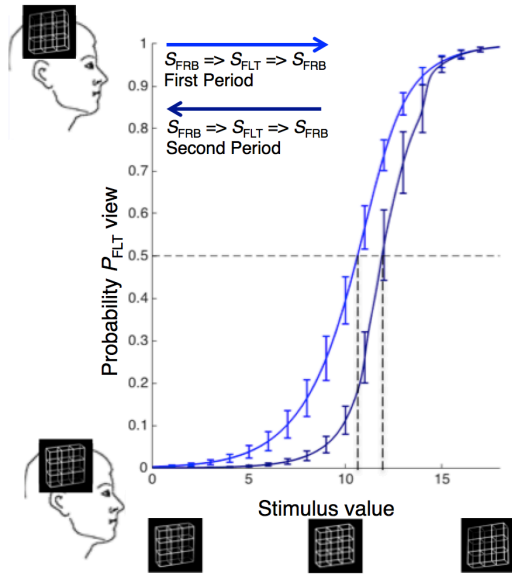


Figure 4: Aggregated response curves for the two periods within the same  $S_{FRB} \Rightarrow S_{FLT} \Rightarrow S_{FRB}$  condition. Perceptual  $P_{FRB} \Rightarrow P_{FLT}$  reversals occurring in the first (blue) and  $P_{FLT} \Rightarrow P_{FRB}$  reversals in the second (dark-blue) period.

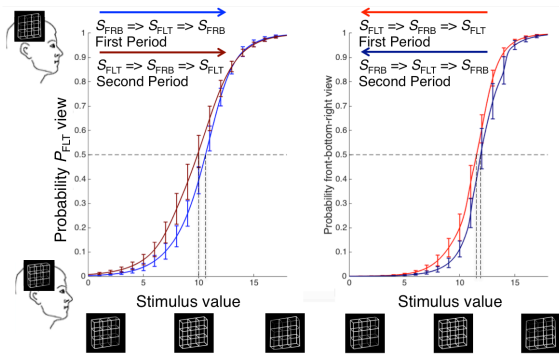


Figure 5: Aggregated response curves for the same type of reversal,  $P_{FRB} \Rightarrow P_{FLT}$  (left) occurring in the first period of Condition 1 (blue) and in the second period of Condition 2 (dark-red); and  $P_{FLT} \Rightarrow P_{FRB}$  (right) in the first period of Condition 2 (red) and in the second period of Condition 1 (dark-blue).

### Long-Term Memory Effects

Figure 5 displays the response curves together for the same *type* of reversal from different periods, and it is clear that regardless of the timing, the  $P_{FLT}$  percept loses stability “sooner” (Fig. 5 right, i.e. at lattices with more luminance contrast) than the  $P_{FRB}$  percept (Fig. 5 left), although both perceptual reversals occur past the ambiguous stimulus at luminance values in support of percepts  $P_{FLT}$ .

Altogether, using a Two-Way Analysis of Variance, we found a main effect for the factor *Condition* (i.e.,  $S_{FRB} \Rightarrow S_{FLT} \Rightarrow S_{FRB}$  versus  $S_{FLT} \Rightarrow S_{FRB} \Rightarrow S_{FLT}$ ) on the variable *inflection point position* ( $F(1,45) = 5.11, p = .029$ ) but no effect for

the factor *Period* (i.e., first versus second period,  $F(1,45) = .14, p = .74$ ). Furthermore, we found an interaction effect between condition and period ( $F(1,45) = 27.24, p < .001$ ).

### Discussion

Presenting a series of lattice stimuli with two different orders of increasing and decreasing ambiguity results in significant hysteresis effects around the resulting perceptual reversals. These hysteresis effects can be interpreted in relation to memory contributions to perceptual outcomes on three different time scales: (1) The critical stimulus parameter (back-layer luminance) for a reversal between the two different 3D percepts of the lattice stimuli differed between the two presentation orders, reflecting an *immediate memory effect*, i.e. the influence of the immediate perceptual history on a milliseconds time scale on the current percepts. (2) This immediate memory effect is stronger in the first time period of increasing and decreasing lattice ambiguity compared to the second time period, indicating the influence of the first period on the second and thus an *intermediate memory effect* on a time scale of seconds on perception. (3) The inflection points of all sigmoidal perceptual probability functions of any experimental condition are all located at luminance values favouring the lattice front side top left perspective  $S_{FLT}$ , reflecting a *long-term memory effect*.

At each moment in our everyday life our perception results from the disambiguation and interpretation of incomplete and to varying degrees ambiguous sensory information. Ambiguous figures are perfect stimuli to study the principles underlying these disambiguation processes, because we can compare perception at maximal stimulus ambiguity and during a stepwise parametrical ambiguity reduction. The literature offers plenty of evidence for top-down influences on the perception of an ambiguous figure (e.g., Long & Toppino, 2004) and studies about priming and adaptation effects in particular already indicate different memory effects on different time scales (e.g., Long, Toppino & Mondin, 1992).

The present experimental paradigm further allows a distinction of memory effects on three different time scales. Recent predictive coding approaches (e.g., Friston, 2012) postulate that the perceptual system makes predictions about the sources of the sensory information, based on the immediate perceptual history and stored concepts from perceptual long-term memory. The present results confirm this perfectly; any specific perceptual situation, like a specific experimental paradigm, can have a strong influence on the perceptual process and outcomes. This observation is highly relevant for any type of experiment on perception and interpretation of results.

The present experiment together with similar, earlier studies (e.g., Hock, Bukowski, Nichols, Huisman, & Rivera, 2005) demonstrate the fruitful application of the physical hysteresis concept to visual perception. Our results show patterns of another important concept from physics, namely complementarity or non-commutativity, which has already been successfully applied in the context of multistable perception and cognition (e.g., Atmanspacher, Bach, Filk, Kornmeier, & Römer, 2008).

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