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RESEARCH REPORT

Cueing the interpretation of a Necker Cube: a way to inspect fundamental cognitive processes

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Abstract The term perceptual bistability refers to all those conditions in which an observer looks at an ambiguous stimulus that can have two or more distinct but equally reliable interpretations. In this work, we investigate perception of Necker Cube in which bistability consists of the possibility to interpret the cube depth in two different ways. We manipulated the cube ambiguity by darkening one of the cube faces (cue) to provide a clear cube interpretation due to the occlusion depth index. When the position of the cue is stationary the cube perceived perspective is steady and driven by the cue position. However, when we alternated in time the cue position (i.e. we changed the position of the darkened cube face) two different perceptual phenomena occurred: for low frequencies the cube perspective alternated in line with the position of the cue; however for high frequencies the cue was no longer able to bias the perception but it appears as a floating feature traveling across the solid with the cube whole perspective that returns to be bistable as in the conventional, bias-free, case.

Keywords Temporal perception · Perceptual interpretation of bistable figures

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Introduction

A well-known phenomenon in vision science is perceptual bistability. In order to observe perceptual bistability it is necessary that observers look at an ambiguous stimulus that can have at least two distinct interpretations equally sound, conditions in which his/her perception will alternate over time between different percepts. Many studies have been devoted to this phenomenon (Attneave 1971; Blake and Logothetis 2002; Borsellino et al. 1972; van Ee et al. 2005; Gregory 1997; Leopold and Logothetis 1999; Raz et al. 2007) as bistable figures can be used to distinguish elementary sensory features of the physical image from the top-down processes involved in construing either of its visuospatial interpretations (Long and Toppino 2004).

The first report of such an effect is the Necker cube whereby the perspective of the front face of the cube alternates between two options as either facing upward and to the right or downward and to the left (Necker 1832) (Fig 1).

During a continuous observation of a stationary Necker cube, the perception of its perspective alternates with an apparently random frequency, but the distribution of the durations resembles a skewed Gaussian (Rubin and Hupe 2004). A variation on this investigation line consists of ambiguous figures where one of the two alternatives is cued which make that interpretation more likely than the others (Hupe and Rubin 2003). Even in situations in which the cue is able to strongly bias a specific perceptual outcome, an alternation remains. To explain such a behavior, two models have been elaborated (Moreno-Bote et al. 2007). One is an oscillator model in which switches are caused by adaptation. The other model consists of two stable attractors plus noise that induces the alternation between the two attractors. This strategy permits to obtain

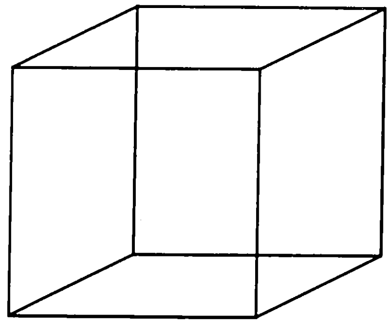

Fig. 1 The classic Necker cube. The perspective is ambiguous

a good fit between the experimental data and the model, but unfortunately the noise strength is decided only after the conclusion of the experiment and it appears as a "deus ex machina" that one invokes for lack of alternative explanations. A deterministic model whereby the switching time is related to the perceptual dynamics would be more appropriate.

In this work, we have investigated situations where the cue that causes the dominance of one face of the cube is so prominent that in a stationary presentation all observers perceive almost only the biased cube perspective with an absence of interpretation switching. We then alternated periodically in time the position of the cue. For low switching frequencies, the cube perspective alternated in line with the position of the cue; however for high frequencies the cue was no longer able to bias the perception but it appears as a floating feature traveling across the solid with the cube whole perspective that returns to be bistable as in the conventional, bias-free, case. The cube face motion perception experienced for fast alternation of the cube darkened face can be described as a kind of apparent motion. Intriguingly apparent motion have already been reported to be linked to bistable perception in the very well known Ternus display (Dawson 1991; Ternus 1926; Ternus and Ellis 1938).

In the next sections, we present the experimental procedure and the results while in the "Conclusions", we attribute the observed phenomena to the time-dependent interactions between the *what* and *where* perceptual pathways.

Experimental procedures

Subjects

Seven naive participants, 3 men and 4 women (mean age 25), all with normal or corrected-to-normal visual acuity served as subjects. The study was approved by the Ethical Committee of the National Institute of Applied Optics and informed consent for participation in the experiment was obtained at the outset.

Psychophysical stimuli and procedures

All visual stimuli were generated by a Cambridge VSG 2/3 framestore and presented on a 21 in. color CRT monitor (Sony GDM-F500 800 × 600 pixels, refresh rate 100 Hz). The main stimulus consisted of a Necker cube (Necker 1832), an ambiguous bistable pattern involving changes in perceived depth. The cube was defined by black lines (0.12° thickness) and covered an area of about 5° × 5° from subjects view distance of 57 cm. The image of the solid was displayed at the center of the screen on a mid gray background with luminance of 25 cd/m^2. Subjects observed the cube monocularly (with their dominant eye) through a pinhole with their chin rested on a padded bar. Subjects were instructed to inspect the stimulus on the screen passively without special regard to eye movements. During each session the cube was continuously displayed for 10 min while two of the cube faces were alternatively colored in black to the aim of suggesting, by mean of the monocular depth index of occlusion, a specific cube perspective. An example of a time sequence of our stimuli is shown in Fig 2.

The cueing alternation rate varied from 0.25 up to 5 Hz with different alternation rates investigated in different sessions. The task of the subjects was to indicate by using a CB3 response box when the cube perceived depth was defined by the position of the cue (i.e. by which cube face was darkened) and when this did not occur. In the first case, whenever the cube dark face changes its position the cube perceived depth switch from one configuration to the other. In the second case, the usual phenomenological interpretation of the visual stimulus is to perceive just one out of two cube depth as "frozen" and to implicitly interpret the jumping dark face as moving *across* the solid. Subjects were instructed to indicate when a pattern among these three states (perception driven by the cue, cube depth 1 or cube depth 2) appeared and when it disappeared by moving

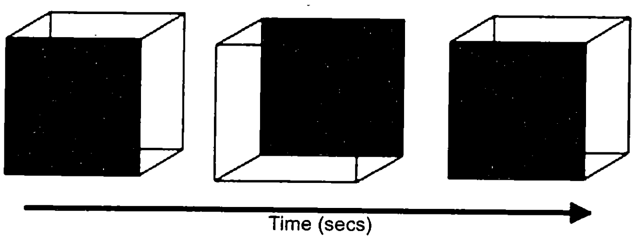

Fig. 2 Example of the stimuli utilized in our experiment. A face of the cube was alternatively darkened (cue alternation rate from 0.25 to 5 Hz) to occlude some lines constituting the cube suggesting a particular perceived depth on the other

the CB3 switch on one of three states: rest position, up or down. The position of the CB3 switch was sampled at 100 Hz ensuring an online accurate control of subjects' perceptual response. We define as "power of the cue", the proportion of time relative to the whole 10 min presentation that the cube darkened face determined the perceived dominant configuration.

Results

Data of seven subjects showing the relationship between the power of the cue and the cue alternation rate are shown in Fig. 3.

For all subjects the power of the cue varied relative to the cue alternation rate. For slow alternation rate (from 0.25 up to 1 Hz) the perception of the cube depth was found to be completely defined by the position of the cube darkened face (power of the cue 100%). However, by increasing the rate of cue position alternation, the perceptual interpretation of a specific cube perspective with a black face moving across the solid become more likely. With alternation rates comprised between 1 and 2 Hz, the power of the cue decreased linearly from 100% down to 20%, a value of minimum that remained constant even for higher alternation frequency (at least up to 5 Hz). Thus, for alternation rates faster than 2 Hz the cue was able to lead the interpretation of the cube depth for no more than 20% of the whole presentation time while in the remaining 80% of time subjects perceived an alternation in the interpretation of the cube depth similar to that observed when the darkened face is not even displayed: a stochastic oscillations between the two cube perspectives with any bias for none of them (Fig. 3). Figure 3b show mean data averaged across subjects along with the best fitting cumulative Gaussian curve (R^2 value close to 0.98) to them. The "population" data confirm the peculiarity of temporal range comprised between 1 and 2 Hz when perceptual system switch from a condition in which it utilizes the monocular depth index of occlusion to interpret the cube perspective to a different state in which an interpretation in the motion domain with the darkened cube face flickering from one position to another become the dominant one.

Conclusions

The Necker cube is an ambiguous figure in that its perspective can be interpreted in two different ways with subject perception flipping back and forth between the two valid interpretations to get a consistent percept at any single moment. This is what usually is referred to as multistable perception. However by darkening one of the cube faces, it is possible to disentangle the cube ambiguity by means of the monocular depth index of occlusion. The ambiguity loss is likely to rely upon the activation of both the main streams involved in visual perception: dorsal stream dedicated to the analysis of objects position and their spatial relationship (*where* pathway) and ventral stream that is instead mainly involved in the perception of what objects look like (*what* pathway) (Mishkin et al. 1983; Goodale and Milner 1992). The "*what*" pathway could provide information about the more appropriate perspective by analyzing which cube lines are occluded by the darkened face. As the ventral and dorsal pathways are widely reciprocally linked (Ungerleider et al. 1998) this information could be made available as input to the neural populations of the dorsal stream that would be triggered to clearly interpret the cube perspective.

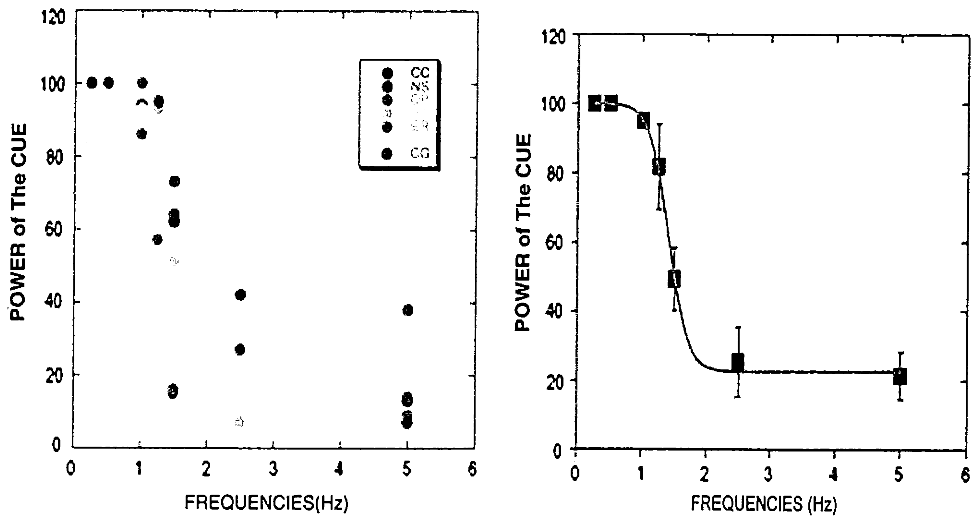

Fig. 3 On the left hand side data for all 7 subjects. The *power* of the cue (the proportion of time the cue lead the cube perceived configuration) is represented on the abscissa as a function of the alternation rate of the dark face position (on the ordinate). On the right hand, side data averaged across all subjects. *Error bars* indicate the standard errors while the continuous line the best-fit cumulative Gaussian curve to the data

By switching the position of the darkened face among two different positions it is possible to induce the subject to perceive the cube alternately either facing upward and to the right or downward and to the left. In this study, we have shown that this process is dramatically affected by the rate of alternations. In fact, when the alternation rate is between 1 and 2 Hz, a brand new phenomenological interpretation comes to be possible, i.e. perceiving the darkened cube face as moving across the solid. This perceptual interpretation, that becomes dominant for alternation rates faster than 1.5 Hz, is likely to indicate that the temporal window between 1 and 2 Hz is a break point where the dominant role in defining the perceptual interpretation of the cube shifts from the neurons of the ventral streams to those of the dorsal stream. Indeed, if the cue switching time is too short, the perceptual system is no longer able to achieve meaningful information from the occlusion index, but it has to rely on the motion perceptual interpretation suggested by neurons of the ventral stream that are highly dedicated to motion pattern detection.

The visual motion illusion described in this work of a cube face floating across the solid is likely to resemble the apparent motion illusions described by Wertheimer (1912) in his seminal work. In these studies, it was pointed out that the physical display of two static lights (in two different spatial positions) alternating at a proper rate yields a robust illusion of perceived motion. The perceptual phenomenon critically depends on the alternation rate. In fact, when the alternation rate is as high as 40 Hz what is perceived is a simultaneous flickering without any motion from one light position to the other. By slightly slowing down the alternation rate it is possible to yield a motion perception between the two lights without any intermediate position, an effect known as phi motion. Intriguingly for alternation rates close to 10 Hz a different perceptual feature called "beta motion" arise. In beta motion, a single light appears to move continuously back and forth and the movement is perceived as smooth being the intermediate positions between the two lights phenomenally present (Palmer 1999).

This latest kind of apparent motion is indeed very similar (perceptually) to what we described as "a floating feature traveling across the cube" suggesting at a first glance that the two illusions could be two aspects of the same phenomenon. However, the illusion we describe in this work is characterized within a temporal window comprised between 1 and 2 Hz that is on a temporal scale very different from that typical of beta motion (10 Hz). Probably this difference in time scales is due to the different framework in which the two illusions arise. The apparent motion of the moving cube's face concerns the perception of a three dimensional pattern (the cube) and the movement of the cube face is a movement in depth. As in vision the analyses of depth indexes are by far more complex relative to analyses of spatial cues for two dimensional translational motion, it is likely that a more complex computational mechanism underlie the perception of the face moving across the cube relative to that underlying the beta apparent motion. Although these issues seem to suggest that we are not talking about the same perceptual phenomenon further investigations are needed to achieve a final answer.

To conclude, in our opinion the temporal threshold we measured in this experiment could be useful to improve theoretical models devised to explain cognitive process underlying perception of bistable figures. In fact, it is now clear that in considering the role of a cue in disentangling the ambiguity of bistable figures, temporal dimension has to be take into account and has to be related to the other perceptual characteristics of the cue, an attempt that we did by introducing the new concept of "power of the cue".

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