# Usefulness influences visual appearance in motion transparency depth rivalry

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Two sets of dots moving in opposite directions are usually seen as two transparent surfaces. Deciding which surface is in front of the other is bistable and observers exhibit strong biases to see one particular motion direction in front. Surprisingly, biases are dependent on stimulus orientation in a persistent, idiosyncratic, and irrelevant manner. We investigated here whether this preferred direction is arbitrarily fixed or can instead be updated from the context. Observers performed two tasks alternately. One task was to report the surface seen in front in a transparent motion stimulus. The other task was a visual search for a slow dot. Unknown to the observers, we systematically paired the target dot with one surface direction in an attempt to make that surface seen in front. This manipulation was sufficient to change the observer's preferred direction for the surface seen in front. Attentional explanations did not account for the results. Observers modified their idiosyncratic preference in motion transparency depth rivalry only because it was useful to perform well in an auxiliary task.

Keywords: vision, learning, visual search, visual attention, binocular rivalry

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# Introduction

Dots moving coherently in the same direction are experienced as a moving rigid surface. When several motion directions coexist, motion transparency is usually perceived (Andersen, 1989). The conditions needed for the transparency to occur have been extensively investigated (Braddick, Wishart, & Curran, 2002; Greenwood & Edwards, 2006; Mestre, Masson, & Stone, 2001). Interestingly, motion transparency is very often associated with a depth ordering of the surfaces. Indeed, dots moving in opposite directions are usually interpreted as two surfaces sliding on top of each other in transparency. Because there is no depth signal, the surface seen in front is arbitrary and the percepts are bistable (Mamassian & Wallace, 2010), a phenomenon that can be called *motion* transparency depth rivalry. This bistability is similar to numerous other bistable phenomena characterized by temporal alternations in consciousness between two interpretations of an ambiguous visual scene (Leopold & Logothetis, 1999).

Surprisingly, in motion transparency depth rivalry, which surface is seen in front strongly depends on stimulus orientation (Mamassian & Wallace, 2010). In one particular orientation, observers perceive in front either one surface or other with equal probability and this

rotated clockwise by 90 degrees, one surface is consistently seen in front and the other in the back. Rotating the stimulus counterclockwise by 90 degrees leads to the opposite depth ordering. The orientation that leads to the most unpredictable percepts is idiosyncratic in the sense that it varies from participant to participant (Mamassian & Wallace, 2010). One can imagine that the visual system always exhibits an intrinsic bias for one interpretation. A specific property of the bias would be its persistence: it would change slowly, what is referred as the *hypothesis of* persistent bias (Gepshtein & Kubovy, 2005). The existence of an intrinsic and persistent bias has been proposed as a simple way to explain some results in perception (Gepshtein & Kubovy, 2005). Moreover, the idiosyncratic bias found by Mamassian and Wallace (2010) was extremely stable across several days. Carter and Cavanagh (2007) also found an idiosyncratic bias in binocular rivalry: one interpretation durably dominates over the other depending on the location in the visual field. They argue that the bias was specific to the onset of rivalry and disappeared on an extended presentation. All these results suggest that the visual system is relying on some internal variable used during the interpretation of ambiguous stimuli. The value of this internal variable determines which percept is going to dominate as a function of stimulus orientation. This variable could be set to a

depth percept rapidly alternates. When the stimulus is

random value at the beginning of each new stimulus presentation. The stability of the preferences we have just described argues against a random assignment. The variable could be arbitrarily set at the beginning to a default value: in that case, the bias would not change over time. Otherwise, the variable could be set to a goaldirected value that would be based, for example, on the history of the most recent interpretations. The purpose of the present work is to determine whether an idiosyncratic bias, such as the motion transparency preference in Mamassian and Wallace, can be changed implicitly. We reasoned that if the default value is not set arbitrarily, it could be modified by learning the usefulness that is associated with each possible percept in an ambiguous scene.

Recently, we have shown that an interpretation is seen more often when that interpretation helps the observer to be successful in an auxiliary task (Chopin & Mamassian, 2010). Importantly, this usefulness effect was demonstrated with rivalrous stimuli. Binocular rivalry occurs when the left and right eye images cannot be fused because of their discrepancies. One rivalrous image (presented to one eve) was designed to help the observer be successful in an auxiliary task. We were interested in discovering whether the useful image would dominate the other. This issue was tested in using sets of left and right orientated Gabors in binocular rivalry. The auxiliary task consisted in finding a monocular target that was one of the rivalrous Gabors. Unbeknownst to the observers, the target was always displayed with the same orientation. As a main result, that particular orientation was found to become dominant over the other. This effect occurred only on the first perceptual decision of each bistable episode. In other words, the first percept of a bistable episode depended on its usefulness for the current task. In addition, the usefulness effect exhibited persistence: it was still found after the relationship between the target and the orientation was removed. We thus demonstrated using implicit learning that the task can have a long-lasting effect on the stimulus appearance of binocular rivalry.

Bistability encompasses a more general phenomenon than binocular rivalry: bistability is triggered by numerous stimuli, in particular ambiguous figures (sometimes called reversible figures). The Necker cube is a classical example of an ambiguous figure (Necker, 1832). The similarity between binocular rivalry and ambiguous figures is still debated (Leopold & Logothetis, 1999; Meng & Tong, 2004). For example, binocular rivalry involves displaying two different images at the same time, whereas only one image is displayed in ambiguous figures. Since binocular rivalry and ambiguous figures can be two different phenomena, what is true for binocular rivalry can be false for ambiguous figures. Therefore, the task usefulness effect that we found on binocular rivalry has still to be confirmed with ambiguous figures. Motion transparency depth rivalry is such a figure.

In the present experiment, we display two random-dot transparent surfaces moving in opposite directions. Observers are asked to complete two tasks: in one task, they have to localize one of the dots whose speed is lower, and in the other task, they have to report which surface is perceived in front (bistability measure). After a block of trials and unbeknownst to participants, the target is always presented within the same moving surface. In that case, observers have an interest in having that surface seen in front. Indeed, searching the target within the surface in front increases the efficiency of the search by decreasing the time needed to find the target (O'Toole & Walker, 1997). Therefore, we predict that the surface associated with the target in the search task will be perceived more often in front when measured in the bistability report task.

## Methods

#### Stimuli

The stimulus was made of 120 white dots, half of them moving in one direction and the other half moving in the opposite direction. This random-dot kinematogram consisted of two transparent squared surfaces (Movie 1). Each side of the square extended over 14.8° of visual angle. The luminance of the dots was fixed to 40 cd  $m^{-2}$  and their size to 0.26° of visual angle. The dot speed was maintained constant at 4.2 deg s<sup>-1</sup>. The background luminance was 10 cd m<sup>-2</sup>. The coherency was 100% with an infinite dot life span (the dots crossing a side of the square reappeared on the other side). In order to offer the observers the option to maintain fixation, a small opaque disk (size:  $2^{\circ}$  of visual angle; luminance: 5 cd m<sup>-2</sup>)

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Movie 1. Video of the stimulus in the experiment (that was displayed either for 600 ms or for a maximum of 14 s).



was centered in the surfaces with a red fixation dot in its center. Depending on the task (described below), the surfaces were presented in trials lasting at most 14 s (with a target) or exactly 600 ms (without target).

#### Apparatus

Observers viewed the stimuli from a distance of 58 cm in a darkened room. The stimuli were generated on an Apple Mac G5 with the PsychToolBox library (Brainard, 1997; Pelli, 1997) and displayed on a 21-inch CRT monitor at a frame rate of 60 Hz. The screen resolution was  $1024 \times 768$  pixels. A chin rest helped participants maintain their head position.

#### Observers

Eight naive observers with normal or corrected vision participated in the experiment. Three other observers were excluded from the beginning because they failed to perceive any transparency in the stimulus.

#### Procedure

Observers performed two different tasks (Figure 1). The first task was a visual search. The target was a dot whose speed was lower than the others. The target speed began at 3.6 deg s<sup>-1</sup>. To maintain constant the percentage of correct responses, a staircase varied the target speed from the beginning to the end of the experiment. A trial ended as soon as observers found the target or after 14 s. In both cases, they were asked to indicate the approximate location of the target. For this purpose, the surfaces were

split in five parallel stripes and participants were asked to choose one, after what feedback was provided. They were free to stare or not at the fixation dot.

The other task was a bistability report task. The same stimulus (without target) was displayed for trials lasting 600 ms. Participants had to report the direction of the first surface that was seen in front of the other. For this purpose, two symbols were positioned on either side of the stimulus and the task was to indicate the symbol toward which the surface in front was moving to. Stimulus orientation was varied, covering all orientations in steps of  $6^{\circ}$  (range: 3–177°,  $0^{\circ}$  is the horizontal rightward direction; all the dots being white, there is no difference between a stimulus orientation of x and  $x + 180^{\circ}$ ). Such a fine orientation resolution was needed to determine the most bistable orientation. Because longer trials would not have allowed us to complete the experiment in one session, short trials were preferred. We were comforted in this choice by the result that no effect was found after the first percept in the corresponding experiment in binocular rivalry (Chopin & Mamassian, 2010).

The experiment consisted of four consecutive blocks. Each block began with 32 visual search trials and was followed by 300 trials of the bistability report task (Figure 1), except for the first block in which the visual search trials were replaced by practice trials. In the following, we arbitrarily label one of the surfaces "#1" (the surface moving more upward than the other) and the other "#2." After the bistability report task of each block, the most bistable orientation was computed. In order to find the most bistable orientation, we plotted the percentage of trials where surface #1 was first seen in front as a function of stimulus orientation. From that plot, the Point of Subjective Equality (PSE) was extracted (Figure 2A). For the stimulus orientation corresponding to the PSE,



Figure 1. Illustration of the procedure. Each block was made of 32 runs of visual search followed by 300 trials of bistability report. Each run of visual search could have the target in surface #1 or #2 in blocks 1 and 4, but the target was always in the same surface in all runs of blocks 2 and 3 (association). Visual search runs in block 1 were a practice session.

surface #1 was first seen in front half of the time, by definition. In the other half of the trials, surface #2 was first seen in front. This most bistable orientation was taken as the stimulus orientation for the subsequent visual search task. The purpose was to always display a stimulus that would be as bistable as possible.

In the practice trials, the target could equally be present in surface #1 or #2 (randomized between trials). During the visual search trials of the two middle blocks, the target was always moving in the same direction, either within surface #1 or #2 (randomized between observers but neither between trials nor between blocks): we will refer to this manipulation as the *target-direction association*. In that case, the surface direction became predictive of the target presence: perceiving that surface in front became more useful than seeing the other in front. Observers were



Figure 2. Effect of stimulus orientation on the depth ordering. One of the two moving surfaces was arbitrarily called "surface #1" and the percentage of times that surface was perceived in front is plotted as a function of the stimulus orientation. The right part of the figure is shaded because the data are duplicated from the left part: rotating the stimulus by 180° gives back the original stimulus. (A) Cartoon of expected results for a target–direction association with surface #1. In block 1 (green), no target–direction association exists and observers prefer to see a surface in front at a particular stimulus orientation and the other one when the stimulus is rotated by 180°. Vertical lines indicate PSEs for each curve. In block 3 (red), if the target–direction association in the visual search task influences the surface seen in front, the percentage of surface #1 seen in front at the PSE orientation is expected to increase. It is equivalent to a leftward lateral shift, from the green to the red curve. (B) FD's raw data, an observer for whom the target always moved within surface #1 in blocks 2 and 3. The lateral shift is strongly observed.

not told about this target-direction association nor did they become aware of it. The last block presented no target-direction association.

## **Results**

From the data of the bistability report task, we first report the percentage of time surface #1 was seen in front as a function of stimulus orientation. For each observer, these data were split between blocks. Figure 2B illustrates such performance curves for one observer. In blocks 2 and 3 of the visual search task, the target was always moving within the same direction (either within surface #1 or within surface #2). The purpose was to test whether it could influence which surface is seen in front. In the first block, no target-direction association existed. For this reason, block 1 was used as a baseline for each observer. Let us assume that surface #1 was the *biased surface*, i.e., the surface within which the target is always moving. If visual search caused the biased surface to be seen more often in front in the bistability report task, the curve of block 3 would change as follows. The left part of the curve would shift upward (Figure 2A) at least around the PSE (the most bistable value, see Methods section) and the right part would shift downward.

These changes are equivalent to a lateral (left–right) shift of the curve. The PSE is then expected to shift with the blocks if visual search yields an effect of usefulness. The average amount of observed shift is plotted in Figure 3.



Figure 3. Average lateral shift of the PSE in each block relative to the PSE in block 1. PSEs are obtained from the percentages of biased surface seen in front as a function of stimulus orientation in each block (n = 8). Error bars are bootstrapped 95% confidence intervals. Asterisks code for significance (\*p < 0.05, \*\*\*p < 0.001).

The PSE were different between blocks (ANOVA with repeated measures, F(3,21) = 10.51; p < 0.0005). The difference between the PSEs in blocks 1 and 3 is significant (Tukey's post hoc HSD, p = 0.04). The same stands for the difference between blocks 1 and 4 (Tukey's post hoc HSD, p < 0.0005) but not between blocks 1 and 2 (Tukey's post hoc HSD, p > 0.10). The dominance of the biased surface in front for the stimulus orientation that was the most bistable (50%) at the beginning of the experiment increased to 82.4% on average at the end of the experiment (t(7) = 4.61; p < 0.005).

In the data obtained in the visual search task, no difference occurred between blocks in the percentage of correct responses (F(2,14) = 2.27; p > 0.10). Significant differences between blocks were neither found for target speed (F(2,14) = 0.79; p > 0.10) nor for search durations (F(2,14) = 0.86; p > 0.10; Figure 4).

## Discussion

In the work presented here, we investigated how idiosyncratic biases in bistable perception could be changed. In motion transparency depth rivalry, observers exhibited an idiosyncratic bias in perceiving one surface in front of the other that depended on stimulus orientation. We were interested in changing that bias by manipulating the usefulness of each interpretation. For this purpose, observers searched for a target in two random-dot surfaces sliding in opposite directions. After a practice session, the target was systematically presented in the same direction (targetdirection association). From the literature, we know that it is faster to find a target when it is presented within the front surface (O'Toole & Walker, 1997). Participants were unaware of this result from the literature and were not informed of the target-direction association. Nevertheless, observers could be more successful in the search task if they were able to learn the target-direction association and to use it to see the biased surface more often in front. We found that the biased surface was perceived in front more often (Figure 3) than the other one. The effect took at least one block to appear (32 trials, 8 min minimum) and was maintained at least one block after the target-direction association was removed. This result mirrors the one we obtained in binocular rivalry with a similar paradigm (Chopin & Mamassian, 2010). It suggests that the usefulness of a percept in a task can modify the interpretation of an ambiguous stimulus. Alternative explanations have to be evaluated. We will review evidence that attention alone cannot account for our results.

#### Implication of endogenous attention

Endogenous attention could play a role in two ways in that experiment. First, if observers noticed the target-direction



Figure 4. Results from the visual search task. No difference was found between blocks. Block 1 was replaced by a practice session. (A) Average search time in each block. (B) Percentage of correct responses in each block, maintained constant by varying the target speed. (C) Average target speed in each block, which is here a measure of task difficulty. In each plot, bars are standard errors.

association, they could decide to look for the target only in the biased surface. We call this strategy the voluntary selective search. Second, if they noticed the target–direction association and were aware of the benefit of seeing the biased surface in front of the other, they could try to voluntary control their bistability. We discuss these two strategies in turn.

To begin with the *voluntary selective search*, there is evidence that participants did not use this strategy. During the debriefing after the experiment, when asked to guess the direction of the target-direction association, only 5 out of 8 observers picked the correct direction, a proportion not different from chance. The search strategy was interesting because it could lead to an attentional sensitization of the elements moving within the biased surface. Tseng, Gobell, and Sperling (2004) showed that the visual search of a colored element among others is able to increase the saliency of this color as measured in a third-order motion paradigm. However, if such a sensitization could appear in our experiment, it does not explain why it should change the surface seen in front. Furthermore, if they had searched in the same surface direction during the whole experiment including the last block, the task would have been impossible on half of the trials in that last block. It would have explained why the effect is maintained in the last block but would have resulted in a strong impairment in the search task. Since the percentage of correct responses was maintained constant (by continuously adjusting the target speed), a decrease of the target speed or an increase in search durations would be expected. No difference between blocks 3 and 4 was found in the target speed or in the search durations (Figure 4).

Another interesting possibility is the *voluntary control strategy*. In addition to the discovery of the target–direction association, it assumes that observers are able to control which surface they see in front. While to our

knowledge no effect of voluntary control has been specifically established on motion transparency depth rivalry, it seems reasonable to speculate that it is at least partially possible. However, a fully conscious strategy is very unconvincing. It implies, moreover, that observers were aware of the beneficial effect of seeing the biased surface in front (we already provided some evidence that it was not the case) and effectively used this information to control the stimulus. That strategy also predicts a loss of the effect as soon as participants stopped the voluntary control strategy. In contrast, the effect was still present in block 4. In addition, if the strategy is fully conscious, it should be stopped in the bistability report task because of its worthlessness in that task: there was no target to find. Finally, trials were probably too short for the control to be successful (600 ms).

In conclusion, both strategies (voluntary selective search and voluntary control strategy) have requirements that are not fulfilled to explain our results.

#### Implication of exogenous attention

Exogenous attention could play a role in the effect we observed. However, this class of effects misses some of the key characteristics that are revealed here. Learning should be long lasting because we introduced the target–direction association and registered the bistability in different sets of trials. Target–direction association needs to be learned and unlearned not too quickly, within around 30 trials, because the effect was not significant before block 3 and remained during block 4.

With a spatial cueing paradigm, Kristjánsson, Mackeben, and Nakayama (2001) found that allocation of exogenous attention could be enhanced by the learning of contingencies. The phenomenon only needed the repetition of an association between the cue and the target. That association could be based on position, color, or shape (Kristjánsson & Nakayama, 2003). In our experiment, a relationship was systematically imposed between the motion direction and the presence of the target in the middle blocks. This association could mediate the deployment of exogenous attention. However, cueing paradigm effects peak after only 150 ms and the association is learned very quickly: the maximum of the effect is reached between trials 4 and 8. In contrast, in our experiment, the effect was able to survive from the set of visual search trials to the set of bistability report trials and 32 trials were necessary for the PSE shift to appear.

In our experiment, one of the features that defines the target is known to observers (the lower speed), and the other is not (the motion direction in blocks 2 and 3). The repetition of the unknown feature could potentially trigger a priming of pop-out (Fecteau, 2007; Maljkovic & Nakayama, 1994, 1996, 2000). Priming of pop-out is usually described in visual search for an odd target (by its frequency or color) among distractors. The attention is then automatically drawn to the feature that defined oddity during the previous trial. This phenomenon creates a pop-out when the odd feature is repeated. This effect is cumulative and reaches a maximum after ten consecutive trials. The priming persists up to 90 s (Fecteau, 2007). In contrast in our experiment, there was no sign that the maximum was reached after more than 96 trials and the effect persisted around 8 min after the termination of the target-direction association. For these reasons, the effect we describe here is probably unrelated to the priming of pop-out.

As attentional explanations cannot account for our results, we conclude that the visual appearance of our stimuli is influenced by the computation of usefulness. In binocular rivalry, usefulness effects have been demonstrated to appear quickly and exhibit persistence (i.e., they survive in block 4, where the target association is removed). However, in motion transparency depth rivalry, we report a delay instead of a persistence: the usefulness effect needed a complete block to appear, and it survived block 4 and even increased compared to block 3, indicating that the peak of the effect was still not reached.

Optokinetic nystagmus may have a role in mediating the modification of appearance from the usefulness computations for the observers who decided to carefully stare at the fixation dot. However, several pieces of evidence suggest that this is not the case. Watanabe (1999) showed that motion transparency depth rivalry is not stopped by attending to the surface in front (or back) and is then pre-attentive, while optokinetic nystagmus follows the perceived direction of the attended surface. Thus, optokinetic nystagmus is more of a consequence than a cause for the modification of appearance. Furthermore, in following the attended surface in our experiment, optokinetic nystagmus would have mainly changed the speed characteristics of the surface on the retina: it has been showed recently that those speed characteristics do In summary, we found an influence of usefulness on motion transparency depth rivalry: the more a motion transparency percept is useful for a task, the more often it is perceived. Given that the usefulness effect is not solely confined to binocular rivalry and can be generalized to ambiguous figures, it is plausible to argue that usefulness computation is a general step in visual processing. While Pavlovian conditioning of appearance has been demonstrated (Haijiang, Saunders, Stone, & Backus, 2006), the usefulness effect is equivalent to an operant conditioning of appearance. Moreover, our results show that the idiosyncratic bias can be modified by usefulness computations. It advocates against the complete arbitrariness of the idiosyncratic bias: its value is not set definitively but instead is chosen, at least partially, on the basis of its usefulness.

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