The computation of multiple matching doubly ambiguous stereograms with transparent planes

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Abstract—Psychophysical experiments have been previously described Weinshall, D. (1989) Nature 341, 737–739; (1991) Vision Research 31, 1731–1748 that involved the perception of many transparent layers, corresponding to multiple matching, in doubly ambiguous random-dot stereograms. Additional experiments are described in the first part of this paper. In one experiment, subjects were required to report the density of dots on each transparent layer. In another experiment, the minimal density of dots on each layer, which is required for the subjects to perceive it as a distinct transparent layer, was measured. The difficulties encountered by stereo matching algorithms, when applied to doubly ambiguous stereograms, are described in the second part of this paper. Algorithms that can be modified to perform consistently with human perception, and the constraints imposed on their parameters by human perception, are discussed.

1. INTRODUCTION

The depth of 3-D objects is lost in the optical projection process. Stereo vision, in which two simultaneous images of the same scene are recorded in the two eyes, can be used to recover the lost depth. In computational stereo algorithms, the extraction of depth from binocular stereo begins with the formation of a disparity map by matching the two images (the disparity of an object is defined as the difference between its positions in the two images). Thus, a disparity value is assigned to every location in the image. In order to solve the matching ambiguity at each feature in the image, neighboring features can be used. It is generally assumed that many neighboring features should have a match at about the same disparity for a matching to be plausible. Different stereo matching algorithms differ in how they implement this neighborhood interaction (or smoothness constraint), among other things.

I have previously described (Weinshall, 1989, 1991) psychophysical experiments whose results could not be readily explained by existing stereo matching algorithms. In these experiments, subjects were presented with doubly ambiguous stereograms (defined in Section 2.1). In some cases a few transparent surfaces were perceived corresponding to; multiple matches; in other cases transparent surfaces corresponding to unique matches were perceived. Some stereograms were constructed to have the same cross-correlation between the left and right images yet different numbers of transparent layers were perceived. The results of these experiments are briefly summarized in Section 2.

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In Section 3, additional experiments are described. First, subjects were required to report the density of dots on each transparent layer of a doubly ambiguous stereogram by adjusting the density of dots on three simple transparent layers. In another experiment, the minimal density of dots on each layer necessary for the subjects to perceive it as a distinct transparent layer was measured. These experiments were designed to clarify which algorithmic principle can be used to explain the results in the experiments with doubly ambiguous stereograms.

In Section 4, the difficulties encountered by stereo matching algorithms, when applied to doubly ambiguous stereograms, are discussed. Three simple matching algorithms, representing two different simple matching principles, are discussed in detail: a patch-wise correlation algorithm (e.g., Nishihara (1984) and Drumheller and Poggio (1986)), Prazdny’s matching algorithm (Prazdny, 1985) and PMF (Pollard et al., 1985). For comparison with human data, an additional stage was added to each algorithm, where the matching results were used to determine how many transparent layers exist in the image. The range of parameters for which the performance of these algorithms was consistent with that of humans, and the sensitivity of their tuning, is discussed.

2. MULTIPLE MATCHING IN AMBIGUOUS STEREOGRAMS

2.1. Doubly ambiguous stereograms

In a doubly ambiguous random-dot stereogram (RDS), a sparse random pattern (Fig. 1b) is copied twice in each image (Fig. 1a). The horizontal gap between the two copies is $G_\text{r}$ pixels in the right image and $G_\text{l}$ in the left image. Each dot of the original sparse random pattern (Fig. 1b) has two copies in each image. All these pairs, which are the micropattern of the doubly ambiguous RDS (Fig. 1c), are the same instance of the double nail illusion stimulus (Krol and van de Grind, 1980). There are four possible matchings of the elements of the micropattern that are equally plausible, two mutually exclusive pairs if matching is unique (namely, a point can only be matched to a single point in the other image, as shown by full and hollow circles in Fig. 1c).

2.2. Summary of previous results

In an unpublished study, O.J. Braddick presented subjects with ambiguous stereograms that were, in effect, a special case of the doubly ambiguous stereograms described in Section 2.1. In these stereograms, the generating pattern was copied twice only in one image, equivalent to choosing $G_\text{r} = 0$ or $G_\text{l} = 0$. The micropattern of such a stereogram, one dot in one image and two dots in the other image, is also known as Panum’s limiting case. When presented with Panum’s limiting case, subjects’ perception corresponds to matching the single dot in one image to both dots in the other image (if the disparity difference between the dots is within Panum’s limiting area, which is the range of disparities that can be fused simultaneously). When viewing a stereogram composed of such micropatterns, the perception was similar: subjects reported seeing two transparent surfaces, corresponding to a multiple matching of the generating pattern.

2.3. Multiple matching

In the first experiment, an ambiguous stereogram of the type described in Section 2.1,