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Coarse-fine dichotomies in human stereopsis

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ABSTRACT

There is a long history of research into depth percepts from very large disparities, beyond the fusion limit. Such diplopic stimuli have repeatedly been shown to provide reliable depth percepts. A number of researchers have pointed to differences between the processing of small and large disparities, arguing that they are subserved by distinct neural mechanisms. Other studies have pointed to a dichotomy between the processing of 1st- and 2nd-order stimuli. Here we review literature on the full range of disparity processing to determine how well different proposed dichotomies map onto one another, and to identify unresolved issues.

1. Introduction

The exquisite precision of stereoscopic depth discrimination is well known. Humans are able to discriminate the relative depth between two objects based on relative disparity as small as 30″ for typical untrained observers and as small as 4–8″ in experienced observers. Less appreciated, but equally impressive, is its large disparity range. The images of objects with modest positional disparities are perceived as single, or fused, objects. Stereoscopic depth percepts are also obtained from binocular disparities that are well outside the fusable range, and so are seen as double or diplopic. It is important to keep in mind that the stimulus for stereoscopic depth is retinal disparity, and that this stimulus is continuous. That is, there is no obvious basis to divide the continuum of retinal disparities into two parts corresponding to small and large, and the diplopia point is a perceptual phenomenon. However, as is evident from the stereoscopic literature, there are repeated efforts to define such a division based on the *percept* of depth resulting from these disparities. For this review, we will use the terminology common to the field to refer to small and large disparities: fine and coarse respectively.

Early investigations of stereoscopic vision tended to focus on either stereoacuity thresholds, in the fine disparity range, or depth from diplopia, in the coarse range. Ogle (1952a, 1952b, 1953) was the first to describe stereoscopic vision in terms of two separable processes which he called ‘patent’ and ‘qualitative’. His distinction was based on the observation that small disparities provide precise information regarding relative depth (patent) and that there is very large range of diplopic disparities that provide only signed depth information (see Section 2 below). Although subsequent studies have been mixed in their support for such a distinction, there is growing evidence of a stereoscopic dichotomy that may be related to Ogle’s categorization, and may reconcile apparent discrepancies in the existing literature. By analogy to the related motion phenomena, these two categories of stereopsis have been called 1st- and 2nd-order.[1] Note that this distinction originally stemmed from stimulus properties, that is, stimuli that contain luminance-based vs. contrast-based disparity signals. Collectively, investigations of stereoscopic depth percepts from such stimuli (see Section 3) have shown that depth percepts from these stimuli also have different properties. The aim of this paper is to relate the recent research on 1st- and 2nd-order stereopsis to previous investigations of patent and qualitative stereopsis. To this end, we have divided the paper into four sections in which we review (i) patent and qualitative stereopsis, (ii) properties of 1st- and 2nd-order stereopsis, (iii) how the two dichotomies map onto one another and (iv) outstanding questions. Throughout this review we will make careful distinctions between discussions of stimuli, percepts and neural mechanisms.

2. Patent and qualitative stereopsis

It is a well known, but often overlooked, fact that stereoscopic depth percepts are reliably obtained over a range of disparities that

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[1] This dichotomy has also been referred to as Linear/Non-linear, and fine/course; while the 1st/2nd-order nomenclature has its shortcomings, we will use it here for consistency with the motion literature, and the majority of the research on this topic.

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include those that are perceptually fused (seen as single) and diplopic (seen as double). Both Helmholtz (1909) and Hering (1942) noted that consistent stereoscopic depth percepts resulted from stimuli that cannot be fused. From these observations it is clear that observers can identify depth sign at large disparities but this does not speak to the precision of stereopsis at large disparities. Using pairs of knitting needles as reference and target stimuli, Tschermak and Hoefer (1903 cited in Ogle, 1953) were among the first to measure the *precision* (discrimination thresholds) of stereopsis for stimuli with a large standing disparity. As Ogle (1953) recounts, they found that precise stereopsis was obtained not only for fusable stimuli but also for a range of disparities well outside the range where both target and reference could be simultaneously fused. In his review of the literature on depth from diplopic targets, Ogle (1953) pointed out that previous researchers did not adequately control for eye movements. Vergence eye movements made to change fixation between the target and reference could indicate the sign of the offset in depth if vergence direction were monitored, could reduce diplopia (motor fusion), and would make the retinal disparity of the target variable and ambiguous. In this review, we focus on the role of sensory fusion and retinal disparity and only mention the effects of vergence eye movements and motor fusion when they are possible artifacts.

2.1. Depth from diplopia

It is clear that Ogle (1952a, 1952b, 1953) knew that relative depth percepts were available from diplopic targets; his aim was to understand the nature of the depth percept, and how it varied with disparity. In Ogle's (1952a, 1952b, 1953) experiments he carefully controlled for a number of confounds including eye movements, blur and relative size. In his 1952 studies, observers fixated a point target and evaluated the quality of perceived depth generated by a thin polished needle. Ogle presented the stimuli in three different conditions which included continuous exposure to the needle as its disparity was changed (simulating smooth motion in depth), momentary exposure following adjustment, or momentary exposure of one half-image (the other was continuously viewed). The means of presentation influenced the range of disparities under which fusion and patent stereopsis were perceived (see

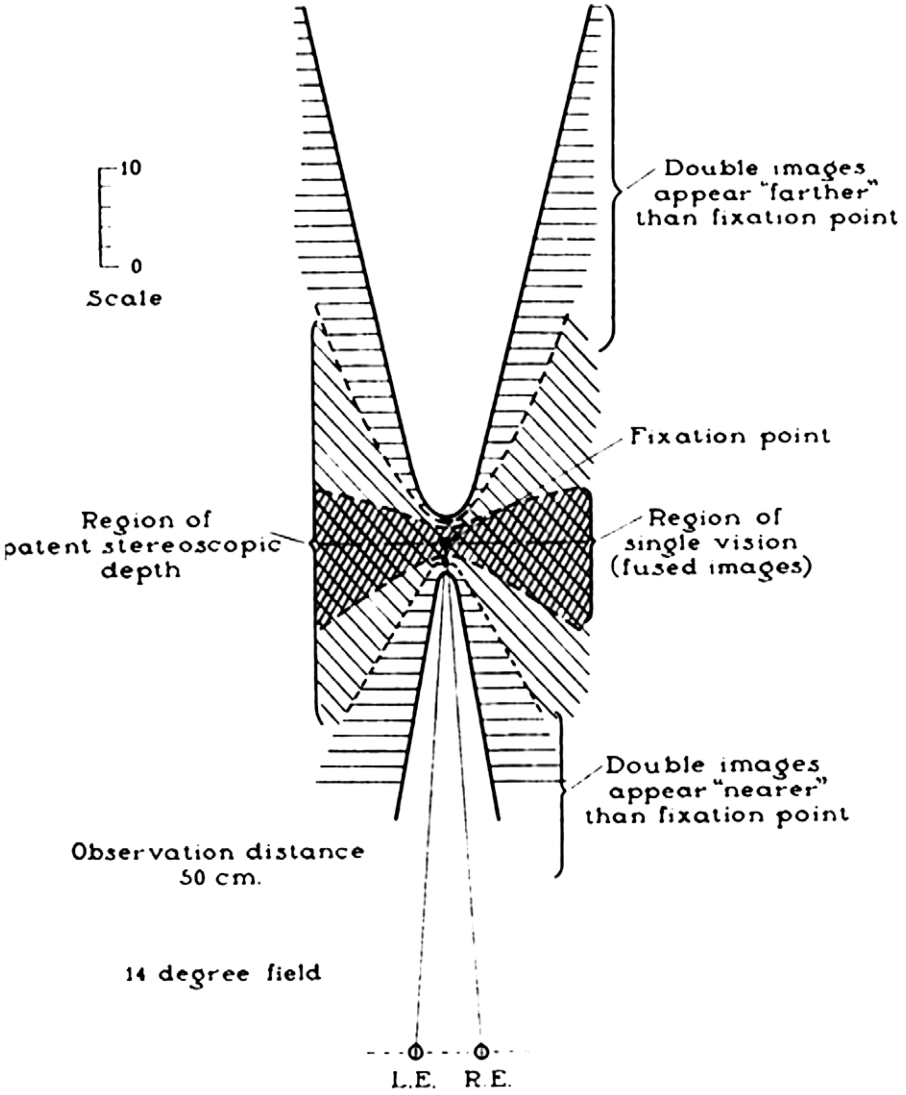

Fig. 1. Image adapted from Ogle (1952b) Fig. 5 depicting how the percept of depth changes with distance in front of and behind the fixation point. The double-hatched region about the fixation plane indicates the area of single vision and patent stereopsis. Patent stereopsis extends beyond this central region, as shown by the diagonal lines. Horizontal lines at the extreme disparities indicate disparities which result in qualitative depth and are perceived as diplopic. Note that all areas expand with increasing eccentricity, especially the qualitative range.

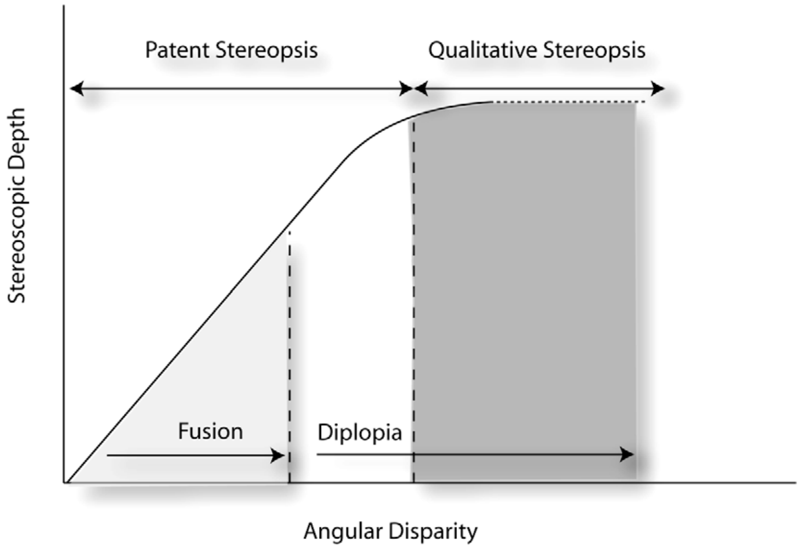

Fig. 2. A schematic of Ogle's categorization of patent and qualitative stereopsis showing perceived depth as a function of angular disparity (adapted from Ogle (1952b), Fig. 3). Fusion and diplopia are depicted, with diplopia spanning the patent and qualitative categories. Note that in the patent range, perceived depth varies with angular disparity, while in the qualitative range there is no such relationship.

Ogle, 1952b, Fig. 4 for details). However, they tended to follow the same pattern, and from these data Ogle generated the diagram shown in Fig. 1.

In his 1953 paper, observers fixated a point and adjusted the disparity of a thin vertical test line relative to a vertical reference line. The disparity of the reference line relative to fixation (the depth pedestal) and the relative disparity between the target and reference line were independently varied. Because his reference and target stimuli were positioned one to the left and one to the right side of fixation, as the stimuli were made more eccentric, the target-reference separation increased. Also, this arrangement made it difficult to assess performance at the fovea, because the stimuli would overlap. An often over-looked aspect of Ogle's research is that he assessed both the precision (response variance) and the validity or accuracy of disparity matching. As described below, he found evidence of a perceptual dichotomy only when he assessed the *accuracy* of disparity matching.

2.1.1. Accuracy of depth percepts from diplopic stimuli

In his 1952 papers, Ogle studied the 'experience' of stereoscopic depth and identified how it changed as a function of disparity, and retinal eccentricity. In doing so, he identified the transition between different categories of stereoscopic percept. As observers increased the amount of disparity between thin reference and test lines they indicated when:

i. The target became diplopic (delimiting Panum's fusional area).
ii. The perceived depth of the target ceased to increase proportionately with that of the reference line (defining the upper limit of Patent stereopsis).
iii. The percept of depth was lost entirely (the upper disparity limit)

According to Ogle (1952a, 1952b, 1953) stereoscopic depth percepts can be divided into two categories based on the test disparity and the quality of the percept. In the 'patent' range the observer had a "subjectively certain experience of depth" (Ogle, 1953) and perceived depth differences were proportional to binocular disparity. In the 'qualitative' range observers had only a vague sense of depth; they were able to report the direction of the depth offset, but could not reliably estimate its magnitude. Importantly, patent stereopsis resulted from both fused and diplopic stimuli, while qualitative stereopsis only occurred for very large test disparities, well beyond the fusional limit (Fig. 2). Note that the relationship between disparity and patent and qualitative depth percepts shown in Fig. 2 depends critically on the criteria observers adopt for judgements of diplopia and proportionality. These criteria are necessarily subjective and hence variable across observers and even sessions with a single observer. Nonetheless, reports of patent stereopsis were consistently obtained with subjectively diplopic targets.

Ogle (1952a, 1952b) commented on the fact that the transitions from patent to qualitative percepts were not abrupt, and that his estimates were influenced by many factors including fatigue, luminance, training and the size of the test object. He also observed that depth for diplopic stimuli decayed with increasing exposure duration and he emphasized the need for brief exposure durations for diplopic targets. In a subsequent publication, Ogle (1953) examined both the precision and accuracy of disparity matching for diplopic targets as a function of eccentricity. In these experiments, he asked observers to:

i. Match the depth of the target to a reference stimulus.
ii. Set the target to half the depth of the reference.
iii. Set the depth of the target to the same depth as the reference but in the opposite direction in depth.

The standard deviation of the settings in the matching condition (i) was used as a measure of stereoscopic precision while the linearity of the matched disparity was used to evaluate accuracy. While the distinction between accuracy and precision made by Ogle is an important one, the matching tasks described here are based on disparity probes, not necessarily perceived depth. Thus the validity measures reflect the proportionality of depth (or disparity) judgments; observers' judgements could have been off by a constant amount or a scale factor, but still vary in the same way with disparity; such distortions would not be apparent from Ogle's disparity probe measures.

Because Ogle was focussed on the effects of peripheral stimulation, he assessed accuracy at a range of retinal eccentricities. Ogle's data at 1° eccentricity consistently show that there is a disparity pedestal (e.g. 60′ at 1° eccentricity) at which depth percepts lose their monotonic relationship with disparity. At this point the functions flatten, and as later demonstrated by Westheimer and Tanzman (1956) if testing had continued to larger disparities, perceived depth would fall to zero. According to Ogle, the transition from patent to qualitative depth processing occurs when the functions flatten. This transition point has been the focus of subsequent disparity pedestal studies, but as discussed in Section 2.1.4, it is not clear that a precision measure would be expected to show the same plateau.

Shortly following Ogle's investigation of depth from diplopic images, Westheimer and Tanzman (1956) conducted depth pedestal experiments with small spots of light, and an exposure duration of 100 ms, less than the time it takes to initiate a vergence eye movement (Rashbass & Westheimer, 1961). Their results largely replicated those of Ogle. However, they also tested larger disparities and found that subjects could reliably indicate sign of a depth interval for disparity pedestals of up to 6–7°, on average, with one observer achieving near 100% correct at 10° disparity. Because Westheimer and Tanzman (1956) also used a side-by-side reference and target configuration, the reference and target dots must have been widely separated to permit disparities as large as 10°. Ogle's depth matching results with large pedestal disparities (though not as large as those used by Westheimer and Tanzman) show that at such large disparities the linear relationship between the physical disparity and the amount of depth perceived is lost. However, the exceptional performance of Westheimer and Tanzman's observers in this range is consistent with the operation of a stereoscopic mechanism that accurately signals the sign of the depth offset.

Blakemore (1970) also assessed depth discrimination (precision) and depth matching (accuracy) for briefly exposed (100 ms) line stimuli. He arranged the reference and target patterns vertically, rather than side-by-side, and so was able to probe central as well as peripheral vision. Like Ogle (1953) Blakemore's matching data show that precision is best near the fovea. The flattening of the data at large reference disparities, which Ogle equated with the subjective transition to qualitative stereopsis, is also evident in Blakemore's data (Blakemore, 1970, Fig. 8).

Both Blakemore (1970) and Ogle (1953) found that depth discrimination thresholds increased more rapidly with disparity pedestal size near the fovea than in the periphery. In fact, for some observers, discrimination performance at 5° or 8° eccentricity was better than performance at the fovea, for reference disparities greater than 30′. Blakemore suggests that this result is related to the limits of bilateral representation of the central visual field in the visual cortex. In addition, a 30′ pedestal disparity at the fovea would be more likely to violate the disparity gradient limit (given its proximity to the fixation marker) than the same disparity presented at 1° eccentricity (see Burt & Julesz, 1980).

2.1.2. Precision of depth estimates for diplopic stimuli

Ogle's (1953) precision results show an increase in the standard deviation of depth estimates with increasing disparity, that he fit using an exponential function. He also reported that precision decreased with eccentricity for the tested range of 1–8° eccentricity from fixation. The limits of both patent and qualitative stereopsis were extended in the periphery. Ogle noted that there was no obvious change in the pattern of results with the transition from fused to diplopic images. However, he provided data for *diplopic* targets only. Overall, Blakemore's (1970) precision data are similar to those reported by Ogle. Because he positioned the reference and target stimuli one above the other he was able to show that the loss of precision of depth estimates with increasing reference disparity is also evident at the fovea.

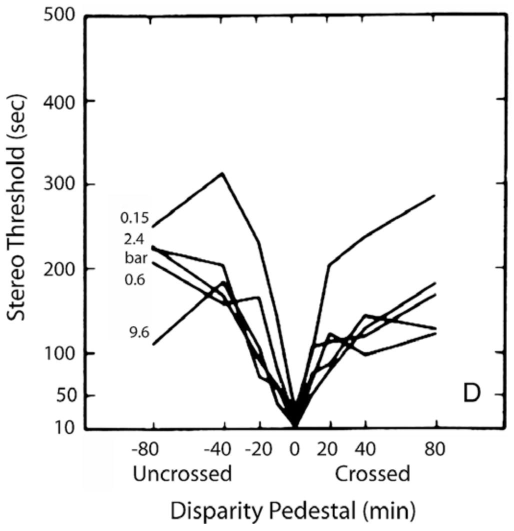

Fig. 3. Shown here is data from Fig. 3 of Badcock and Schor (1985) which depicts increment detection thresholds for one observer, using doG stimuli at a range of pedestal disparities, both crossed and uncrossed. Each function represents a different spatial frequency.

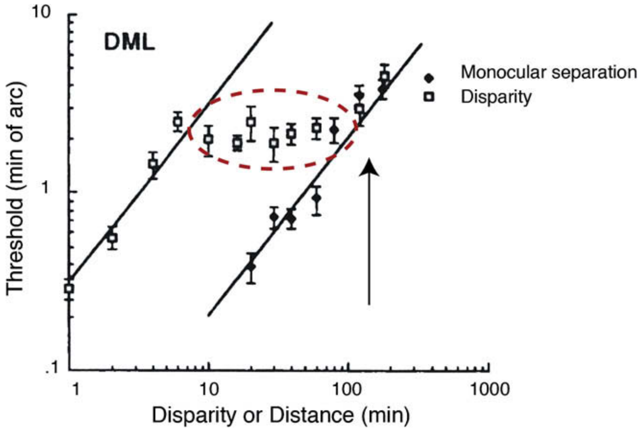

Fig. 4. Mckee et al.'s (1990) data adapted from their Fig. 3 with open symbols representing disparity judgements, and closed symbols, monocular width judgements. The dotted ellipse shows the range of disparity judgments that have higher thresholds than the corresponding monocular width judgements. The arrow indicates where the disparity judgements begin to follow the monocular data.

In the mid-1980s to early 1990s a number of studies measured depth discrimination as a function of pedestal disparity and stimulus spatial frequency/size. For example, Badcock and Schor (1985) used difference of Gaussian (doG) stimuli to assess depth increment thresholds at a range of pedestal disparities, which included diplopic conditions.[2] They found that thresholds scaled with stimulus width/frequency as spatial frequency increased from 0.15 to 0.5 to 2.4 cpd, but were similar for 2.4 cpd, 9.0 cpd and bar stimuli. As can be seen in Fig. 3 below, their thresholds increased rapidly with increases in disparity pedestal over a range of fine disparities (0–20′) but much less so over their range of coarser disparities (20–80′). Badcock and Schor (1985) reported that this knee point in the data was not related to spatial frequency although the flattening of the disparity threshold functions appears more pronounced at the higher spatial frequencies.

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[2] The advantage of doG stimuli is that they contain a restricted range of spatial frequency information, but are still well localized in space. Note that this is in contrast to bars or lines, which contain a broad mixture of low and high spatial frequencies.

This knee point also corresponded to the occurrence of diplopia and loss of depth percepts for spatial frequencies of 2.4 cpd or more while fusion and depth perception were maintained at all disparity pedestals with the lower spatial frequencies. Thus their discrimination functions have two components which have subsequently been interpreted as representing patent and qualitative processing. This is in sharp contrast to Ogle who found no reflection of the transition from patent to qualitative stereopsis in precision measures. However, the authors point out that when the stimuli became diplopic, observers based their judgments on the relative separation of the target and reference, *not on their relative depth*. This strategy was possible because Badcock and Schor (1985) did not interleave crossed and uncrossed test conditions. Siderov and Harwerth (1993) have argued that depth increment functions follow the form reported by Ogle (1953) and Blakemore (1970)[3], when the direction of the depth offset is randomized across trials.

In their depth pedestal studies McKee, Levi, and Bowne (1990) used a modified version of the method of constants which allowed them to assess depth increment thresholds as a function of disparity, without presenting a reference stimulus. Observers were asked to compare the depth of the test with that of the average of the set of test disparities. Importantly, they also measured monocular separation thresholds over the corresponding range of offsets. As can be seen in Fig. 4 below, the resulting depth increment functions have (at least) two components, an initial sharp increase with increasing pedestal disparity, followed by a flat portion where there is no change in threshold with increasing disparity. Interestingly, as disparity was further increased, a point was eventually reached where performance became aligned with monocular separation judgments, and began to increase again (see Fig. 4). These data are also at odds with Ogle's precision results. The sharp transition that occurs when the stimuli become diplopic is not evident in Ogle's (1953) data, but recall that he only includes results for diplopic targets in this publication.

The difference in precision estimates for diplopic stimuli in these two experiments may be due to the tasks employed. Ogle used a standard depth pedestal arrangement with simultaneous presentation of a fixation point, and reference and target stimuli. In the implicit reference condition used by McKee et al. (1990) observers viewed the fixation point and a target. On each trial McKee et al.'s observers made a depth interval judgment which necessitated comparison across a set of remembered depth intervals.

If the estimated depth of each of the test disparities was similar, the comparison of the target with the remembered average was also constant. However, it is possible that if those same stimuli had been presented simultaneously, observers may have been able to discriminate the target from the reference.

It has been argued that the flat portion of McKee et al.'s (1990) depth pedestal data reflects a shift to reliance on interocular separation (Siderov and Harwerth, 1993). However, this is unlikely because within this range of pedestal disparities (or monocular offsets) separation judgments (i) were more precise than binocular depth judgements and (ii) increased with the separation of the standard with a slope of 1. As indicated by the arrow in Fig. 4, there is a disparity at which thresholds begin to climb again. From this point onwards the binocular and monocular data overlap, thus McKee et al. conclude that this defines a transition from using disparity to using interocular separation to perform the task.

In sum, McKee et al.'s (1990) data show a clear transition in the precision of depth estimates as a function of retinal disparity, which is consistent with Ogle's patent and qualitative stereopsis. These authors did not report the width of their thin line targets or measure diplopia thresholds, so it is not possible to determine if the point at which their depth discrimination functions flatten corresponds to the upper fusion limit, or to disparities beyond this limit. However, McKee et al. (1990) did note that some stimuli appeared diplopic over the range of disparities corresponding to the flat portion of their increment detection functions.

2.1.3. The size–disparity correlation

In the late 1960s and 1970s there was a movement towards a linear systems approach to visual processing which was supported by both electrophysiological work (see Enroth-Cugell & Robson, 1966) and psychophysics (Campbell & Robson, 1968). There was convincing evidence that the fundamental processing units of human vision were tuned to specific spatial frequency information. Further, it appeared that there were spatial frequency-tuned channels that could be separately stimulated, and therefore adapted (Blakemore & Campbell, 1969). Early computational models of human vision relied on this knowledge of receptive field properties to generate multi-scale computational models of visual processing. For example, Marr and Poggio's (1979) model explicitly relied on a size–disparity correlation, as they proposed processing of disparity information proceeded from coarse scales to fine. There is a substantial psychophysical literature which examines the nature of disparity processing across scales. This research has focussed on a range of disparities within the high-resolution, patent region, not between the putative separate mechanisms discussed here, and so is beyond the scope of this paper.

Many investigators have reported that disparity thresholds increase with increasing stimulus width. Felton, Richards and Smith (1972) conducted psychophysical adaptation experiments explicitly aimed at testing the size–disparity correlation in human stereopsis. They asked if disparity selective neurons matched the edges of bar stimuli, or the full extent of the bar itself. Of course the latter was required to uphold the size–disparity correlation, for if the visual system could rely on a single edge, then the scale of the stimulus would have no effect on performance. Felton et al. (1972) measured contrast threshold elevation for a range of grating spatial frequencies, at a set of disparities relative to fixation. They found the greatest threshold elevation when the grating period was double the disparity. This suggests that the scale of the mechanism that is maximally adapted (and hence presumably maximally stimulated during the adaptation phase) increases proportionally with disparity. This relationship is compelling evidence for a size–disparity correlation in peak sensitivity, and the conclusions were subsequently supported by experiments using different techniques and stimuli (see Heckmann & Schor, 1989; Schor, Wood, & Ogawa, 1984; Tyler, 1973).

This relationship also exists in the cyclopean domain. That is, using the random dot stimuli (RDS) introduced by Julesz (1960), Tyler and Julesz (1980) showed that the upper disparity limit for cyclopean stimuli scales with stimulus area. Similarly Schumer and Julesz (1984) report a relationship between the depth modulation frequency of RDS and disparity thresholds, and Smallman and MacLeod (1994) demonstrated that a broader range of disparities were supported by low-frequency filtered RDS at contrast threshold.[4]

Richards and Kaye (1974) were also interested in the size–disparity correlation, more specifically whether it was a continuum or if it reflected the operation of distinct fine and coarse neural

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[3] Although Blakemore (1970) did not interleave crossed and uncrossed trials, he argued that observers based their judgements on perceived depth, not separation, a position supported by his comparatively low thresholds.

[4] Early work by Berry et al explicitly examined the effect of stimulus size on stereopsis and Vernier acuity (Berry, Riggs, & Richards, 1950). They found no change in performance with increasing stimulus width. However, they did not control for the presence of other depth cues such as size and blur, which could have aided stereopsis for the large stimuli.

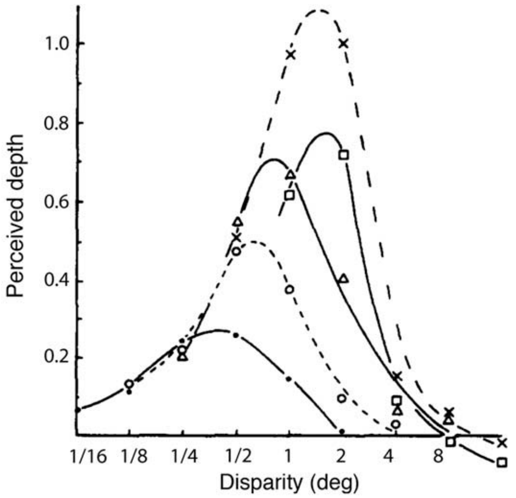

Fig. 5. Data from Richards and Kaye (1974), Fig. 1 showing perceived depth as a function of stimulus disparity for a range of bar widths. Each symbol represents a different bar width of 0.05 (dots), 0.1 (circles), 0.2 (triangles), 0.4 (crosses) and 0.5 (squares) deg.

mechanisms. Contemporary electrophysiological investigations of stereoscopic processing identified distinct populations of neurons tuned to either fine or course disparities. As shown by Poggio and Fischer (1977) tuned excitatory and inhibitory neurons showed a peak or trough in response at a small range of disparities, near fixation, and tended to give balanced responses to input from either eye. In contrast, near/far units showed a very different pattern of response, with a large region of suppression at fixation, with responses increasing for large disparities. Richards and Kaye (1974) looked for evidence of this categorization using a magnitude estimation task, and a range of stimulus sizes. They argued that if there are two distinct mechanisms subserving stereopsis then they should find an abrupt transition in perceived depth as the system passed from one mode of processing to the other. While they found no such abrupt change in perceived depth as a function of disparity, they did report that perceived depth varied with stimulus width. That is, as the size of the stimulus increased, so too did the peak of the depth estimation function (Fig. 5), a result which presumably reflects the size–disparity correlation. They concluded that there is a single mechanism underlying performance on their task.

Because Ogle (1953) found that the transition from patent to qualitative processing occurred at disparities well beyond the fusion limit Richards and Kaye tested only large disparities. That is, the smallest test disparity for each condition was equal to the width of the test bar. Thus, each function in Fig. 5 begins at or near the upper limit of fusion for that stimulus. If the transition from one mechanism to the other occurs at the point that the stimuli become diplopic, the abrupt change in perceived depth could not be seen in these functions. It is possible that the size-dependence of their depth magnitude estimates reflects the properties of only the coarse mechanism. Because these data were normalized it is not possible to assess the accuracy of observer's judgements.

Schor and Wood (1983) conducted a careful study of the relationship between spatial frequency/size and disparity processing. They used 1-D doG patterns, with a fixed height and variable width. Their results show that both the upper and lower disparity limits increase proportionally with increase in doG width. Further, the results of their depth matching manipulation show that at small reference disparities, matching performance is most precise with relatively high frequency test stimuli. As the reference disparity was increased, increasingly coarser scale stimuli provided the most precise matches. The matching data for the lowest spatial frequency/widest test stimulus suggested that all stimuli appeared at the same, presumably indeterminant depth corresponding to a large reference disparity. This aspect of the data is reminiscent of Ogle's qualitative stereopsis.

2.1.4. Outstanding issues

An issue not raised by these, or subsequent investigators, is if it is reasonable to expect similar patterns in the accuracy and precision data. We have seen only one instance in which this is true, and in that case McKee et al. (1990) avoided simultaneous comparison of the target and reference. The accuracy task determines if the matched disparity is close to that expected given the physical stimulus disparity. It appears that at larger disparities the percept of depth becomes merely signed, and is no longer quantitative in nature. Precision measures, on the other hand, assess the reliability of depth judgements. It is arguable that the transition to qualitative stereopsis may not be reflected in the same flattening in the variance of the responses. Instead it is possible that a transition from fine to coarse would be reflected in a sudden increase in depth discrimination thresholds, due to the use of broader receptive fields.

Both Ogle (1953) and Blakemore (1970) state that their precision data are well fit by a single exponential function. However, Ogle's functions were fit to only the diplopic range of stimuli, so it is not possible to say whether there was any evidence of a change in precision when the stimuli became diplopic. Blakemore's (1970) precision functions were also reportedly well fit with a single exponential. However, close examination of his foveal data reveals that data was collected at around 50 min, and the next larger test disparity was near 120 min. Over this range, thresholds increased by a factor of six, but most importantly, it is not clear whether this was the result of a smooth progression or a sharp transition, or if discrimination thresholds at even larger disparities would have been the same or higher.

3. 1st- and 2nd-order processing in stereopsis

Around the time that the increment detection experiments described above were published, there was increasing evidence that a linear systems approach to visual processing, while useful, was incomplete. In their seminal work in motion processing, Chubb and Sperling (1988) showed that human observers were able to discriminate motion direction in drift-balanced random-element stimuli. Critically, these stimuli were generated so that their Fourier power spectra contained no predictive information regarding the direction of motion. They argued that their results revealed the presence of non-linearities in visual processing that made contrast energy available to signal motion direction. Chubb and Sperling (1988) referred to this non-Fourier processing as a 2nd-order mechanism.

3.1. Spatial properties

3.1.1. Discrimination thresholds

The well-known geometrical similarities between stereopsis and motion-based depth cues led Hess and Wilcox (1994) and Sato and Nishida (1993) to look for a similar dichotomy in stereoscopic vision. Hess and Wilcox (1994) used Gabor patches which contained a luminance (1st-order) and a contrast (2nd-order) based disparity signal. Gabor stimuli are created by multiplying a sinusoidal 'carrier' by a Gaussian envelope. Like doGs they permit presentation of a narrow range of spatial frequencies, but because the sinusoid is multiplied by a Gaussian envelope, which limits the spatial extent, the width does not covary with the centre frequency. Their original logic was simple; stereoacuity thresholds

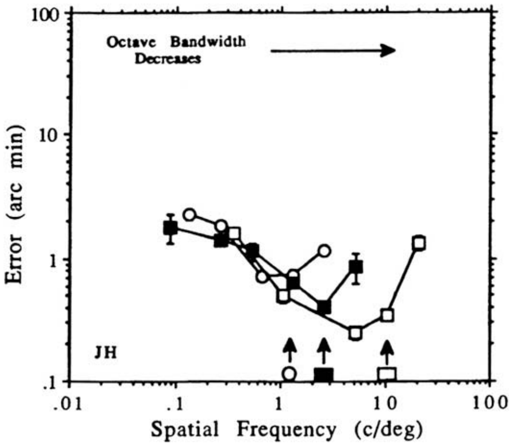

Fig. 6. Data from Hess and Wilcox (1994) are reproduced here showing stereoscopic thresholds as a function of the spatial frequency of Gabor stimuli. Each function represents a different envelope size and the symbols with arrows indicate an octave bandwidth of 0.5

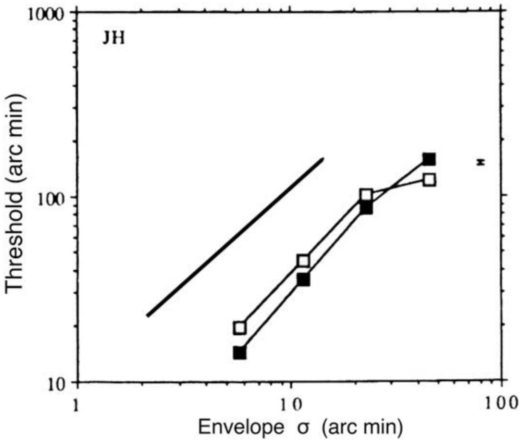

Fig. 7. The upper disparity limits for Gabor stimuli, as a function of envelope size, reproduced from Wilcox and Hess (1995). The open and closed symbols represent spatial frequencies of 0.66 and 1.31 c/deg, and the solid line without symbols indicates a slope of 1 on log-log axes. Over a large range of envelope sizes (σ = 5.73–45.8 min) upper disparity limit was not affected by carrier frequency.

were measured as a function of the centre frequency of Gabors for a range of Gaussian envelope sizes. If the stereoscopic system relied solely on the output of linear spatial filters tuned to the spatial frequency of the carrier, then depth percepts should not have been affected by the size of the Gaussian envelope. Hess and Wilcox's data showed that there was a range of frequencies at each envelope size for which performance improved with increasing frequency, as expected from Schor and Wood's (1983) data. For each envelope size, there was a point at which thresholds suddenly increased to much higher values. This transition occurred at approximately the same octave bandwidth for each condition (0.5), that is, when approximately four cycles of the carrier grating were visible.

The data in Fig. 6 show that, like motion, stereopsis cannot be fully understood by referring only to the energy in the Fourier power spectrum. Also, this work raised the possibility that this non-Fourier, or 2nd-order, mechanism might be a distinct system, providing coarse depth estimates based on the contrast envelope of the stimulus when the 1st-order information is unreliable. This conclusion is also supported by the work of McKee, Verghese, and Farell (2004, 2005), who showed that a sinusoidal grating viewed through an aperture is localized at the edges of the window, when many cycles of the sinusoid are visible. However, this 2nd-order signal adapts after steady viewing for 3–5 ms and then the grating segment is localized at the phase-specified depth of the sinusoid (McKee, Verghese, Ma-Wyatt, & Petrov, 2007). The separability of these two mechanisms was also demonstrated by Langley, Fleet, and Hibbard (1999) using an adaptation paradigm.

3.1.2. Upper disparity limits

In a follow-up study Wilcox and Hess (1995) evaluated the upper disparity limit for these same stimuli, and again separately varied the envelope size and centre frequency. Given existing data concerning the upper limits of stereopsis, it was expected that stimulus scale would be an important factor, but since the visual system is able to use either the 1st- or 2nd-order disparity signal, it was not clear which of these would determine the upper limits for Gabor stimuli. The data showed that the upper disparity limit was determined solely by the 2nd-order information, that is, the size of the Gaussian envelope (Fig. 7). At a given envelope size, varying the centre frequency from 0.33 to 5.25 c/deg had no significant effect on performance. Instead the upper disparity limit was tied directly to the size of the Gaussian envelope.

Prince and Eagle (2000a) also showed a strong dependence of the upper limits of stereopsis on the size of Gabor patches. In a companion paper Prince and Eagle (2000b) presented a weighted energy model of stereopsis which fit their results, and those of Hess and Wilcox (1994) and Wilcox and Hess (1995, 1997). They argued that their model was able to capture both 1st- and 2nd-order performance, along with a range of other disparity phenomena, without necessitating a distinct coarse disparity mechanism. Note though that their model does require a 'non-linear' operation to extract the position of the contrast envelope. While it may be possible to account for some aspects of 1st- and 2nd-order stereopsis using a single mechanism, the majority of the psychophysical results suggest that in fact depth percepts rely on two distinct types of processing. This conclusion is also supported by recent electrophysiological results (see Tanaka & Ohzawa, 2006) which we discuss in Section 5.4 below.

3.1.3. Interocular stimulus differences

The preceding experiments used Gabor stimuli which contain both 1st- and 2nd-order disparity signals. In subsequent papers Wilcox and Hess (1997) used uncorrelated noise patches to present 2nd-order disparity stimuli without reliable 1st-order signals. These noise stimuli consisted of vertical 1-D luminance noise, multiplied by a Gaussian envelope. The stimuli could be presented with or without a reliable 1st-order component by either presenting the same noise sample to each eye on a given trial, or by randomly choosing the noise sample for each of the stereopairs. Wilcox and Hess (1997) showed that reliable depth judgments could be made using the uncorrelated stimuli, but that thresholds were a factor of ten higher than those obtained for correlated patches.

The preceding results call to mind Mitchell's (1969) experiments that demonstrated that depth identification was unaffected by gross dissimilarities in the stereoscopic images. This resilience to image content occurred when the stereoscopic images were diplopic and briefly presented. Under these conditions performance remained near 90% correct when a circle was presented to one eye and an oblique cross to the other. It is possible that these data reflect coarse stereoscopic matches made by a low-frequency 1st-order filter. However given the temporal requirements it seems likely that Mitchell's results foreshadowed those of Wilcox and Hess, and reflected the operation of a 2nd-order stereoscopic mechanism. That is, mechanism that is able to average

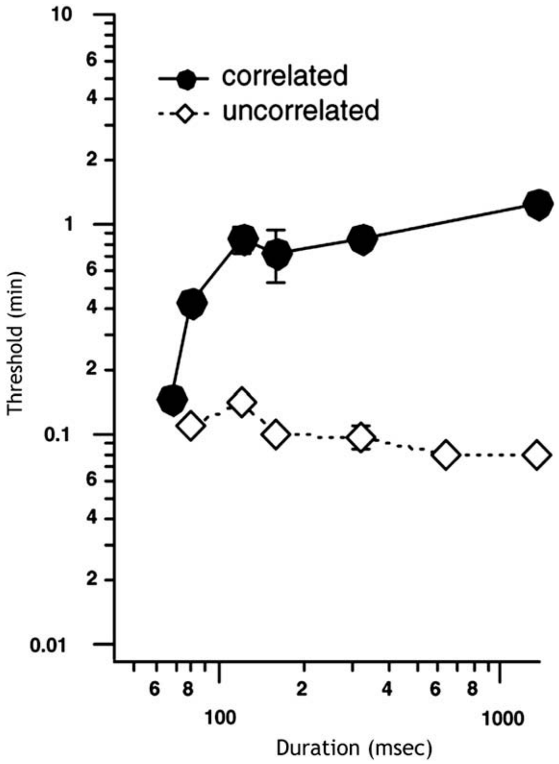

Fig. 8. Data adapted from Hess and Wilcox (2008) showing stereoscopic sensitivity (inverse of slope) for correlated (1st-order) and uncorrelated (2nd-order) Gaussian enveloped noise patterns. The arrows indicate exposure durations of approximately 80, 200 and 1000 ms.

over the interior, luminance-defined detail to provide a coarse, but reliable depth estimate for the object as a whole.

In a subsequent paper Mitchell and O'Hagan (1972) evaluated the combined effects of interocular orientation differences and line length differences on stereoscopic thresholds. In a series of experiments they showed that there is a resilience to these interocular image differences that echoes their previous work, described above. Importantly they found that thresholds are elevated substantially by the introduction of large interocular differences in line length or orientation, but depth sign is preserved. Mitchell and O'Hagan (1972), like Ogle before and Hess and Wilcox (2008) after them, point out that this depth sign signal depends critically on the use of brief exposure durations.

In 1995, Cogan, Kontsevich, Lomakin, Halpern and Blake reported a series of experiments in which they examined the resilience of disparity processing to opposite polarity patterns. They used very short exposure durations, and reported that depth discrimination performance for reverse polarity patterns was typically an order of magnitude poorer than for luminance-matched versions. This difference in thresholds corresponds well to that obtained with uncorrelated noise stimuli. The authors concluded that matching for these stimuli occurred following a stage of rectification, much as has been described for 2nd-order stereopsis. It seems likely that in fact their data reflect 2nd-order processing.

As detailed in Section 3.2 below the reliance on short exposure times argues against the use of coarse-scale 1st-order mechanisms in the tasks described by Mitchell and colleagues, Cogan et al. (1995) or by Wilcox and Hess (1995, 1996, 1997). The luminance-based system exhibits a very different temporal response function, with performance improving with increasing viewing time.

3.2. Temporal properties

The issue of exposure duration is raised repeatedly in the study of coarse disparity processing. An obvious concern when presenting diplopic stimuli is the possibility that the large disparities initiate a vergence response which in turn may signal the sign of the depth offset. A separate issue identified by Ogle (1953) and others after (Mitchell & O'Hagan, 1972) him is that depth percepts for diplopic stimuli fade with extended viewing, even with careful fixation. Thus it has been common practice to use very brief exposure durations when testing large disparity stimuli.

3.2.1. Sustained vs. transient stereopsis

The temporal properties of a coarse stereoscopic mechanism have been well documented in a series of experiments by Edwards Pope and Schor (Edwards, Pope & Schor, 1998, 1999, 2000; Pope, Edwards & Schor, 1999a, 1999b). They have argued that there are two stereoscopic mechanisms differentiated by their temporal properties. This distinction was based on evidence of distinct sustained and transient vergence mechanisms (see Mitchell, 1970; Westheimer & Mitchell, 1969). The properties of their sustained and transient stereoscopic mechanisms map well onto 1st- and 2nd-order stereopsis. As with 2nd-order mechanisms, the transient system requires very large disparities, which are often outside Panum's fusional range. Furthermore, like the 2nd-order mechanisms it does not require matching of the interior luminance signals of the half-images—the transient mechanism responds to opposite polarity stimuli in the two eyes (Pope et al., 1999a).

Hess and Wilcox (2008) examined the temporal properties of 1st- and 2nd-order stereopsis by measuring stereoscopic thresholds for these stimuli, as a function of exposure duration (Fig. 8). Thresholds for 1st-order stimuli decreased with increasing duration, while the 2nd-order thresholds remained unchanged, or increased over the same range. Importantly, it is clear from these data that it is not possible to target a particular mechanism using a given exposure duration; both operate at all durations. Instead it is only by using either diplopic targets (as Pope and colleagues have done), or carefully generated 2nd-order stimuli, that we can isolate a single type of processing.[5]

Hess and Wilcox's (2008) results concerning the temporal properties of 2nd-order stereopsis are consistent with the work of McKee et al. (2007). In a series of experiments these authors showed that the 2nd-order stereoscopic envelope signal adapted allowing observers to use the 1st-order component of their stimulus. This suggests that 2nd-order mechanism is transient in nature.

4. Does the new dichotomy map onto Ogle's classification?

It is very likely that 1st- and 2nd-order mechanisms partially reflect the patent/qualitative dichotomy observed by (Ogle 1952a, 1952b, 1953). Both the putative 2nd-order and qualitative disparity mechanisms are associated with large disparities, give less definitive percepts of depth than 1st-order or patent stimuli, are tolerant of interocular image differences, exhibit transient dynamics, and scale with but do not depend on diplopia.

However there are some significant differences, that suggest that this is not a straightforward mapping. It is clear that 2nd-order stereopsis can provide reliable stereoscopic thresholds, with performance depending on the size of the test stimuli. Thresholds for contrast amplitude modulated (AM) stimuli vary directly with modulation frequency (Wilcox & Hess, 1996). At the highest test

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[5] The potential exception to this is at short exposure durations (72 ms) where some of Hess and Wilcox's (2008) 1st-order results are very close to that obtained for 2nd-order stimuli. In these conditions the observers may be using the 2nd-order envelope of the stimuli.

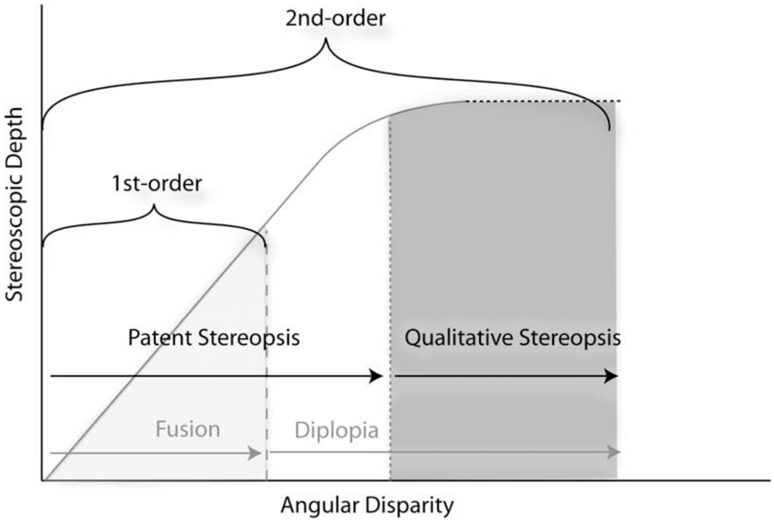

Fig. 9. Shown here is a modified version of Ogle's (1952a, 1952b) illustration of the range of patent and qualitative stereopsis, indicating the range of fusion and diplopia as well. On top of this we have indicated where 1st- and 2nd-order processing operate as a function of stimulus disparity and fusion state.

modulation of 3 c/deg thresholds were near 0.3 of a min for both observers. Note that at such values the test stimuli are well within the fusional area, as were thresholds for uncorrelated noise patches. Thus 2nd-order stereopsis operates over a substantial range of disparities, including, but not limited to those inducing diplopia, while 1st-order stereopsis appears to be restricted to fused stimuli. According to Ogle, qualitative stereopsis only occurs within the diplopic range, well outside the conventional fusional area. To clarify this distinction, the diagram in Fig. 9 maps the regions of fusion and diplopia, patent and qualitative depth percepts, and 1st- and 2nd-order stereopsis.

To summarize, 1st-order stereopsis provides high-resolution depth information for stimuli that are well matched in the two eyes, and the precision of depth estimates improves with increasing contrast and exposure duration. It is not clear from the 1st-/2nd-order stereopsis literature where the transition from 1st- to 2nd-order processing occurs or whether, instead of a transition, they coexist for a considerable range of disparities. However, given the reliance of 1st-order stereopsis on the presence of a reliable luminance match in the other eye, for instance in the case of the Gabor stimuli used by Hess and Wilcox (1994), it seems unlikely that this system would function outside Panum's fusional area. Thus it appears that the transition from 1st- to 2nd-order stereopsis occurs at or near the diplopia point, and within this range the luminance-based signal provides patent depth percepts. On the other hand, 2nd-order processing is available across a large range of fused and diplopic disparities and provides both patent and qualitative depth percepts. As shown by Hess and Wilcox (1994) and Wilcox and Hess (1995) and likely Mitchell and O'Hagan (1972), the 2nd-order disparity signal is tightly tied to the size of the test stimulus, so it is possible to use 2nd-order mechanisms to process relatively small disparities, but only if the stimulus is correspondingly narrow. The term 'coarse' can only be used in relative terms for 2nd-order stereopsis, that is, relative to the width of the stimulus.

5. Outstanding questions

5.1. Individual variability

In their studies Wilcox and Hess have found that, as might be expected, observers tend to default to the more precise 1st-order signal when it is reliable. Observers switch to the 2nd-order stimulus envelope when the fine-scale information becomes unreliable or ambiguous, e.g. when there are more than four cycles of a sine wave visible in a Gabor. Thus, within the same experiment, observers may rely on different sources of disparity information. This observation may explain some of the variability in the increment detection experiments described above. That is, some observers may be more sensitive to 2nd-order information and be able to use it to interpret depth sign over a large range of stimulus offsets.

5.2. The disparity range of 2nd-order processing

The diagram in Fig. 9 shows one way in which 1st- and 2nd-order stereoscopic mechanisms could map onto Ogle's patent/qualitative dichotomy. But there are some open questions. For instance, 2nd-order stereopsis defines the upper disparity limit and is available at a wide range of disparities (depending on stimulus size). But to our knowledge no one has yet shown that *only* 2nd-order processing occurs across the full range of diplopic conditions. It will be necessary to show that there is no 1st-order contribution within the range of disparities that are diplopic but still provide patent depth information. There is evidence from the work of Schor et al. (1984) that the diplopia threshold increases as the centre frequency of doG stimuli is reduced from 9.6 to 0.079 cpd. This frequency dependence suggests that fusion depends on 1st-order processing, however, it should be noted that such stimuli also contain 2nd-order information, which will also scale with frequency; further research is needed to address this issue.

Also, all of the existing investigations of 2nd-order stereopsis have used some form of precision measure. To date there has been no systematic attempt to determine how valid depth percepts from 2nd-order stereopsis are. If the proposed mapping in Fig. 9 is correct, 2nd-order stereopsis should provide both patent and qualitative percepts, and the transition between the two should depend on (i) the reliability of the 1st-order disparity signal and (ii) the amount of disparity relative to stimulus width.

5.3. Stereopsis or vergence?

Another unresolved issue is the link between large disparities and vergence eye movements. Westheimer and Mitchell (1969) found transient vergence responses to the same dissimilar, diplopic, stimuli used by Mitchell (1969) for his studies of transient stereopsis. However, Rashbass and Westheimer (1961) demonstrated that the strength of the vergence response is proportional to the magnitude of retinal disparity. It is reasonable to ask then if the qualitative depth percepts for stimuli presented well outside Panum's fusional area result from interpretation of transient vergence signals (see Howard & Rogers, 2002 for a review of this issue). The percept of depth from 2nd-order stimuli is reliably observed at exposure durations far below the 160 ms it takes to initiate a voluntary vergence movement; Blakemore (1970) and Westheimer and Tanzman (1956) showed their stimuli for only 100 ms. Thus, for these stimuli, such a mechanism would have to rely on monitoring of eye movements initiated after the stimulus disappeared. Ziegler and Hess (1997) addressed this issue by asking observers to make simultaneous judgements of the displacement of two diplopic targets in depth. The fact that observers were able to do this at well above chance levels, shows that they were not relying on vergence information. Thus, while is possible that vergence signals *could* be exploited to signal briefly exposed diplopic stimuli, the results of Ziegler and Hess (1997) suggest this is not the case.

5.4. Distinct neural mechanism?

Psychophysical studies suggesting coarse vs. fine or 1st-order vs. 2nd-order dichotomies naturally lead one to wonder whether these dichotomies have neural correlates. Poggio and Fischer (1977) identified distinct classes of disparity-selective units in the monkey visual cortex including tuned excitatory/inhibitory and near/far cells. The tuned excitatory/inhibitory neurons were the most prevalent; they showed a peak or trough in response over a small range of disparities near fixation. The near and far units showed a very different pattern of response, with a large region of suppressed response at fixation, with responses increasing for large disparities. As shown in Ferster's (1981) data (see Fig. 10), the response of these units tended to plateau with increasing disparity. Unlike tuned neurons, which showed balanced input from the two eyes these cells were dominated by one eye, and were often classified as 'monocular'. Poggio and Talbot (1981) argued that the tuned neurons were responsible for depth percepts in Ogle's (1953) patent range while the near/far units subserved qualitative depth percepts.

More recent work by Prince, Cumming, and Parker (2002) has suggested that such distinct classes of neurons are not found in monkey V1 but rather there is a continuum of disparity tuning that includes both the tuned and near/far neurons. However, it is important to note that while they included a large number of neurons in their analysis, Prince et al. (2002) tested a relatively narrow range of disparities, from 0° to 1°, used dynamic random-dot stereogram stimuli, and recorded from area V1 only. Further, because they were primarily interested in the results of fitting the neural response with a Gabor function they did not include cells whose output could not be adequately fit by a Gabor function. These differences may be why they did not observe a distinct category of neurons responsive to large disparities.

Tanaka and Ohzawa (2006) focussed more specifically on the 1st-order vs. 2nd-order distinction in neural processing. They used windowed 1st-order sinewaves, and 2nd-order amplitude modulated sinusoids to determine if neurons in the cat extra-striate cortex respond to the disparity of a contrast modulated (2nd-order) stimulus. Further, they examined whether the same neurons responded to 1st- and 2nd-order modulation at the same, or different frequency, and if the two types of processing exhibit the same phase preference. Some of their results are shown in Fig. 11 below.

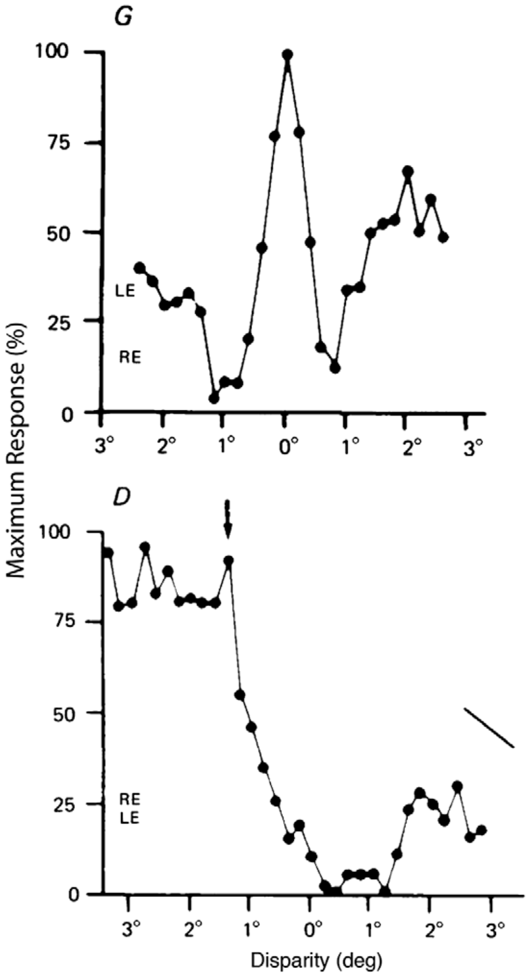

Fig. 10. Response profiles of tuned excitatory (upper) and far (lower), cells from Ferster (1981), Figs. 1 and 2. Arrows in near/far data depict the maximum response of the cell occurring closest to the reference point.

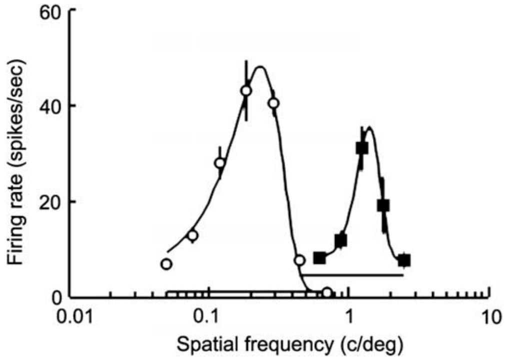

Fig. 11. Typical data from a single neuron is shown here from Tanaka and Ohzawa (2006), Fig. 2. Responses to 1st- and 2nd-order stimuli are shown as open and closed symbols respectively. Note that the peak sensitivity is different depending on the nature of the stimulus, and that the response profiles show little overlap.

The results of Tanaka and Ohzawa (2006) were similar to those obtained by Zhou and Baker (1993) for 1st- and 2nd-order motion stimuli. That is, a single neuron might respond to both 1st- and 2nd-order stimuli, but with a different preferred frequency. However, regardless of the preferred frequency all units showed similar interocular phase tuning. Importantly the 2nd-order response was not affected by the phase of the carrier grating, it was influenced only by the phase of the (2nd-order) contrast modulation. Tanaka and Ohzawa (2006) concluded that the 1st- and 2nd-order responses form separate neural pathways.

The majority of physiological studies of stereopsis have focussed on V1 and/or V2. However, disparity-tuned neurons exist throughout visual cortical areas beyond V1. Recent studies of neurons in the macaque medial temporal area (MT) show that the majority of these neurons respond to binocular disparity (DeAngelis, Cumming, & Newsome, 1998; Uka & DeAngelis, 2003, 2006). The link between MT neurons and disparity processing seems to be tightly tied to the type of disparity signal. DeAngelis and colleagues have shown that microstimulation of MT neurons only influences behavioural responses for RDS when the task is 'coarse' rather than 'fine' (Uka & DeAngelis, 2006). It is important however, to note that this distinction reflects more than the range of test disparities used. The fine task was much like the increment detection tasks described above, where the animals fixated a point and judged the relative depth of two stimuli positioned off the horopter. In the coarse test condition, the depth of a set of random elements was judged relative to a fixation point. In the physiological literature these tasks are referred to as relative vs. absolute but in the latter there is relative disparity with respect to the fixation point. The amount of disparity between the test and reference is not affected by vergence shifts in the relative depth configuration, but is affected in the absolute condition. In Uka and DeAngelis' studies coarse, or absolute, thresholds were measured by assessing the amount of binocular correlation required to perform the task reliably. However, in the fine or relative depth test condition no depth noise was added, and the animals simply discriminated the relative depth offset. The resilience to electrical stimulation in the fine condition may therefore be due to the task, not the range of disparities assessed. However, Uka and DeAngelis (2003, 2006) argued that the selective effects of microstimulation on the coarse but not fine task reflected a specialization of MT for large disparities. Another possibility is that the large receptive fields in this area limit the disparity resolution. Uka and DeAngelis (2006) argue that these neurons are linked to vergence eye movements, and processing motion in depth. Neri (2005) outlines this proposal suggesting that the specialization of MT for coarse stereopsis maps onto specialization for support of motor action appropriate for its placement in the dorsal stream of the dorsal/ventral dichotomy. This description remains speculative however, and other physiological experiments with humans (fMRI) and monkeys show that high-level form or shape perception also occurs in area MT (among others see Chandrasekaran, Canon, Dahmen, Kourtzi, and Welchman, 2007; Nguyenkim and DeAngelis, 2003).

5.5. What is the functional advantage of having a distinct coarse stereoscopic system?

In this section we describe several possible functional roles for coarse disparity processing in human vision, and the evidence that 2nd-order or qualitative stereopsis is involved. These range from extending the range of stereoscopic function to off-horopter stimuli, to providing a back-up mechanism for normally functioning visual systems, and for those with slight ocular misalignment.

5.5.1. Extending the range of stereoscopic function

Although we are not aware of it, much of our visual environment at any point in time lies well off the horopter, and outside Panum's fusional area. Therefore, many objects in the field of view are diplopic. An obvious advantage of having a disparity mechanism that processes diplopic stimuli is to provide depth estimates for such objects. The coarse mechanism may work in concert with other depth cues, such as motion parallax, to provide relative depth information throughout the field of view as we navigate through the world.

5.5.2. A guide to vergence

As outlined in Section 5.3, it is not likely that depth judgements for diplopic targets reflect depth signals from the vergence response per se. However, it is possible that 2nd-order stereopsis is related to the transient vergence response. The rapid disparity response provided via 2nd-order stereopsis may guide vergence, directing eye movements towards the disparate object. When viewing a scene extended in depth, one must often change fixation between stimuli with large disparities. To initiate vergence to such large disparities the visual system would only need to determine the sign of the required movement. Hence a qualitative stereoscopic system that signaled the sign of the disparity would be sufficient to initiate these large disparity responses. As motor fusion is approached sustained vergence becomes sensitive to the retinal disparity of the target and requires binocularly matched targets (Westheimer & Mitchell, 1969). The similarities between the stimuli that drive transient stereopsis and transient vergence suggest that they may be related. However, stereopsis produces percepts of relative depth from relative disparity while vergence acts to eliminate the absolute retinal disparity of the target. There is no need for any perceptual correlate of the signal that drives disparity vergence. However, the vague sense of relative depth provided by coarse stereo mechanisms may also be used more directly to set the direction of proximal or voluntary vergence.

5.5.3. A back-up mechanism for typical and atypical visual systems

There is preliminary evidence that the coarse stereoscopic mechanism serves as a 'back-up' system to our high-resolution system. Investigations of 1st- and 2nd-order stereopsis have repeatedly shown that if there is a reliable luminance-based disparity signal, the 1st-order mechanism will be used. However when that information is unavailable (e.g. in uncorrelated noise stimuli) or unreliable (e.g. with diplopic stimuli), the 2nd-order disparity signal can be accessed. This proposal does not rule out some interaction between the two mechanisms; for instance, McKee et al. (2007) showed that the 2nd-order system could define a plane in depth and the 1st-order system signaled depth with respect to that plane.

The utility of a coarse back-up mechanism is even more apparent in the case of individuals with strabismus. The misalignment of one eye disrupts the precise registration of images in the two eyes necessary for fine stereopsis. However, in cases where the deviation is small, it is possible that the coarse stereoscopic system is available to provide residual binocular depth information.

McColl, Ziegler, and Hess (2000) provided support for this hypothesis with their finding that some individuals who are stereoanomalous are able to localize stimuli in depth via coarse disparity signals. In their experiments, they used stereograms consisting of uncorrelated noise and anti-phase Gabor patches to isolate 2nd-order stereopsis. They found that patients who were classified as mildly stereoanomalous could see stereoscopic depth using the uncorrelated patterns. Similarly, in a study comparing individuals with normal acuity, and small angle strabismus, Harris, Wilcox, Moroz-Harris, Day, and Smith (2000) found that strabismic observers could see depth from diplopic stereograms. Interestingly a subset of their strabismic observers were able to judge the relative depth of diplopic targets *better than visually normal subjects*, in spite of the fact that they performed very poorly on conventional tests of fine stereopsis.

The potential use of coarse (2nd-order) stereopsis as a backup system, which can function in the absence of a high-resolution system, is an exciting possibility. That is, existing clinical tests of stereopsis like the popular RandDot Stereotest™ are designed to assess stereoacuity, or the finest resolvable disparity. Understandably, they present a limited range of disparities, and often use random-dot stereograms, rather than isolated targets.[6] Such tests do not assess depth percepts from diplopic targets, thus it is likely that there are individuals with micro-strabismus who are classified as stereoblind on these tests, when they have residual coarse stereoscopic function.

6. Conclusions

There is strong evidence that there are two distinct stereoscopic mechanisms which can broadly be classified as ‘fine’ and ‘coarse’. The fine mechanism works over a modest disparity range and provides a quantitative or ‘patent’ stereopsis. The coarse mechanism works at larger disparities and provides qualitative stereopsis that is clearly signed but with a vague impression of depth magnitude. From the comparison provided here it appears that the 1st-order mechanism which relies on luminance information, is responsible for the patent stereoscopic percept identified by Ogle, but likely only for fused stimuli. This mechanism requires that the input to the two eyes be similar along a number of dimensions. Also, 1st-order stereopsis improves with increasing viewing time. Only 2nd-order processing is evident at the upper limit for stereopsis, where the disparities are well beyond the fusional range. Additional research is needed to determine the relative contribution of 1st- and 2nd-order processing for diplopic stimuli in the range that Ogle (1952b) argued produces both patent and qualitative percepts. It will also be necessary to evaluate the accuracy of disparity judgements using 2nd-order stereopsis, and the link between this mechanism and the vergence response. However, it is clear from existing research on coarse disparity processing that the stereoscopic mechanism is not unitary, but instead consists of at least two perceptual mechanisms, with different functional roles in human depth perception.

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[6] There are good reasons to use random-dot stereograms in these clinical tests as they can be used to make monocular cues uninformative.

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