TR－A－0106

# 運動視と両眼立体視の相互関係

## －運動視、立体視の成立と両眼入力画像の時間関係－

# *Motion and Depth Perception for Interocular-Sequential Presentation of Random-Dot Patterns*

**Takao SATO**
佐藤 隆夫

1990.10.31

ATR視聴覚機構研究所

〒619-02 京都府相楽郡精華町乾谷 ☎07749-5-1411

ATR Auditory and Visual Perception Research Laboratories

Inuidani, Seika-cho, Soraku-gun, Kyoto 619-02 Japan
Telephone: +81-7749-5-1411
Facsimile: +81-7749-5-1408
Telex: 5452-516 ATR J

## （１）はじめに

空間的にずれのあるパターンが継時的に入力されれば運動知覚が生じ，また両眼に同時に入力されれば奥行知覚が生じる．第１パターンが片方の眼にまず提示され，次いで第２パターンが他方の眼に提示された時（両眼分離・継時提示）どの様な知覚が生じるのだろうか．このテクニカル・レポートでは、この疑問に答えるために行なったいくつかの実験の結果を紹介する．また，こうした素朴な疑問に答えると共に，両眼分離・継時刺激法が近距離・遠距離の２つの運動検出メカニズムを切り分ける手段になり得るかどうかに関する理論的な検討も行なった．

ここでは，本文に入る前にこの研究の意義などに関して簡単な解説を述べる．

## （２）両眼分離・継時提示と運動知覚，奥行知覚

人間の視覚系は，三次元空間内で運動する物体の三次元的位置，運動方向の両者を正しく認識する．このとき，基本的な情報源は，両眼間の位置ずれ（両眼視差）と，各眼における継時的位置ずれと考えられる．つまり，奥行差の結果，両眼の網膜像の間には両眼視差が生じ，また運動の結果，各網膜上に継時的な位置変化が生じる．視覚系はこうした網膜からの入力から奥行や運動を回復するものと考えられる．この状況を図式化したものが図１（本文参照）である．図に示したように，両眼への同時的な差分（Ｒ１－Ｌ１，Ｒ２－Ｌ２）はは奥行知覚メカニズムによって，各眼における継時的変化（Ｒ２－Ｒ１，Ｌ２－Ｌ１）は運動知覚メカニズムによって評価される．では，パターンが両眼分離・継時提示されたとき，つまり図のＲ１とＬ２，またはＬ１とＲ２のみが提示されたときに，それらの情報は運動視メカニズムによって処理され，運動印象を生ずるのだろうか，それとも奥行視メカニズムによって処理され奥行印象を生ずるのだろうか．この疑問に答えることが今回の実験の第一の目的である．

現在までに知られている事実は，両方の可能性を示している．

両眼分離提示による運動視　線，点，円，四角形などの単純な図形の位置をずらし，継時提示すると仮現運動による運動印象が生じる．この，古典的な仮現運動においては，二つの刺激を両眼に分離提示しても同一眼に提示した場合とほぼ同等の運動印象が生じることが知られている．一方，Braddickは，ランダムドット・パターンに空間的な位置ずれを与え継時提示することによって生じる仮現運動(random-dot kinematograms,RDK)においては，両眼分離提示を行うと運動知覚が成立しないことを報告した．

ランダムドット刺激による仮現運動は，両眼分離提示に対する差異の他に，時空間的性質が古典的仮現運動とは異なっている．

①運動が認められる空間的隔たりの上限（Dmax，ここでは移動限界と呼ぶ）が短い．通常数十分程度．古典的仮現運動では数度から条件によっては数十度．

②運動が認められる時間的隔たりの上限が短い．古典的仮現運動では，各刺激の提示時間を一定にした場合，２刺激間の空間的隔たりが大きくなると，時間的隔たり(ISI)も大きくしたほうが，運動が観察しやすくなる(Korteの第三法則)．しかし，ランダムドットでは，Korteの第三法則は成立せず，提示時間が極端に短くない限りISIが短いほど運動が観察しやすい．

これらの事実をもとにBraddickは，仮現運動には以下の２つの異なったメカニズムが存在するという仮説を提出した．

①近距離運動メカニズム(short-range motion mechanism)　視覚系の低いレベルにあり，輪郭は必要としない．ランダムドット刺激の運動を処理できるが，運動が認められる２刺激間の移動限界は短い．

②遠距離運動メカニズム(long-range motion mechanism)　古典的仮現運動のメカニズムである．比較的高いレベルの処理であり，輪郭等のハッキリした手がかりを必要とする．運動が認められる２刺激間の移動限界は長い．

Braddickの仮説にしたがえば，近距離メカニズムは両眼分離運動刺激を処理できないが，遠距離メカニズムは処理できるという結論になる．Braddickの仮現運動に関する２メカニズム説は現在広く受け入れられているが，両メカニズムの境界は明確にさ

れていない．ランダムドットのドット密度を低くして行けば最後は１つの光点になってしまうのであるから，ドット密度に依存して両メカニズム間に処理のシフトが生じることが当然予想される．実際，Ramachandranらは，ドット密度１％以下のランダム・ドット・パターンでは移動限界が１°以上になること，またその時Korteの第三法則が成立することを見いだしている4)．つまり，彼らの結果はドット密度が下がると運動刺激の処理が遠距離メカニズムに移行することを示唆している．これらの事実は，両眼分離刺激での仮現運動の成立がドット密度に依存することを示唆する．つまり，ドット密度が高い間は両眼分離刺激では運動が認められないが，ドット密度を低くして行くと運動が認めらる様になるという予測が成り立つ．また，こうした実験で近距離，遠距離両メカニズムの切り分けができる可能性がある．

継時刺激と立体視　両眼分離・継時刺激によって両眼立体視が成立することは，すでに実用化されているフィールド・シーケンシャル方式による立体テレビを見れば議論の必要は無い．市販の製品ではゴーグルに組み込んだ液晶シャッタをテレビ画面と同期させ，左右交互に開閉し，偶数フィールドが片方の眼に，奇数フィールドが他方の眼に入力される．交互提示の周波数が低くなると，まずフリッカが強く感じられるようになり，次いで立体視が成立しなくなる．ランダムドット・ステレオグラムを交互提示した場合，10-15Hz以下の周波数，つまり各刺激の提示時間(=ISI)が30-50 ms以上になると立体視が困難になると言われている．

継時刺激による立体視の研究は，かなりふるくから行われている．これらの研究によれば，継時両眼立体視においては，両刺激の立ち上がり間の時間(Stimulus Onset Asynchorony，SOA)が最も重要な要因であるとされており，SOAの限界値として，100-200ms程度の値が報告されている．これは，前述の値とはくいちがっているが，前述の30-50 msという値は実用的な限界，この100-200 msという値は絶対的な限界と考えるべきであろう．

### （３）今回の実験について

両眼交互提示に関するこれまでの研究は，すべて運動視または立体視のみに注目した研究であり，両者の関係を明らかにしようというものではなかった．従って，例えば立体視の研究では，ある条件で立体視が成立しないと記述されているだけで，その時，運動視が成立していたのかどうかは記述されていないというようなことが起こる．つまり，両眼分離・継時提示を行ったときに，どのような条件で運動視が成立し，どのような条件で立体視が成立するのかは従来の研究では明らかにされていない．

そこで，そこで今回の実験では，ランダム・ドット・パターンを両眼分離・継時提示し，ドット密度，ＳＯＡ，移動量をパラメータとして，各条件で，運動視，立体視の関係を詳細に分析した．

★本テクニカル・レポートは下記の資料に発表した実験をもとにまとめたものである。
佐藤隆夫　(1989/2)　両眼分離・継時刺激による運動視の検討
テレビジョン学会，視覚情報研究会・九州芸術工科大学．
テレビジョン学会技術報告 VVI 89-13．
佐藤隆夫 (1989/3)　両眼交互刺激による立体視の検討
電子情報通信学会，ＭＥとバイオサイバネティクス研究会・玉川大学．
電子情報通信学会技術研究報告 MBE 88-188．
Sato, T. (1989/5/)
Motion and depth perception with dichoptic-sequential presentation of random-dot patterns.
ARVO Annual meeting, May, 1989, Sarasota, Florida.(Supplement to Investigative Ophthalmology and Visual Science, 30, 1989).
佐藤隆夫(1989/5)両眼分離・継時刺激に対する運動知覚と奥行知覚
日本基礎心理学会第８回大会・関西学院大学．

# Motion and depth perception for interocular-sequential presentation of random-dot patterns

Takao Sato

ATR Auditory and Visual Perception Research Laboratories
Advanced Telecommunications Research Institute International
Seika-cho, Kyoto, 619-02 Japan

Running head: Motion and depth for interocular-sequential stimulation.
Key words: motion, depth, short-range motion, long-range motion,
random-dot patterns, dichoptic stimulation

Phone +81-7749-5-1421
Fax +81-7749-5-1408
email sato%atr-la.atr.co.jp@uunet.uu.net

## ABSTRACT

To examine the relationship between short- and long-range motion processes, motion perception for interocular-sequential presentation of two random-dot patterns was systematically analyzed by varying dot-density, interocular asymmetry, and pattern displacement. It was found that normal motion perception occurs under conditions suitable for long-range motion (low dot-density, large displacement). For short-range stimuli, interocular motion was either absent or abnormal; perceived direction depended only on the order in which two eyes saw the patterns. Next, the hypothesis that this absence of interocular motion sensitivity is due to absorption of the input by stereo system was tested and rejected by an experiment using temporally disparate random-dot stereograms; depth was seen only within very short temporal disparities. These results not only support the long-range/short-range dichotomy and interocular motion as a distinguishing feature of this dichotomy, but also suggest that there is a complex interaction between motion and depth mechanisms based on both monocular and binocular spatio-temporal characteristics.

# INTRODUCTION

We see apparent motion from two temporally disparate images. But what happens when images are presented sequentially to different eyes as shown in Fig. 1 ? We know that motion perception occurs with classical, long-range stimuli under interocular-sequential (IS) presentation (Shipley, Kenney, and King, 1945; Ammons and Weitz, 1951), but that motion perception with random-dot kinematograms is severely impaired under IS presentation (Braddick, 1974). Based on these findings, Braddick (1974) proposed the distinction between short-range and long-range motion processes and identified sensitivity to interocular motion as one of the features distinguishing them.

---

Fig. 1 about here.

---

A link between interocular sensitivity and the separation of short- from long-range motion processes has gained support from studies on bistable motion perception with a Ternus type dynamic display. Two mutually exclusive percepts, element and group motion, are evoked by this type of display, and results have generally agreed that element motion is mediated by the short-range process and that group motion is mediated by the long-range process (for a detailed discussion, see Petersik, 1989). Element motion is more frequently observed with stimuli favorable to short-range motion, while the frequency of seeing group motion increases for long-range stimuli. In addition, only group motion was observed with interocular stimulation (Pantle and Picciano, 1976). Thus, the current assumption in motion research is that sensitivity to interocular motion distinguishes the two processes.

Although distinguishing the short-range from the long-range motion involves many features, a simplified approach is that the latter process mediates motion of simple figures over a long spatial range and the former mediates motion of complicated patterns within a limited spatial range (for a detailed discussion of the distinction, see Braddick, 1980; Anstis, 1980; Petersik, 1989; Cavanagh and Mather, 1989). If this simplified distinction is valid, motion perception with random-dot kinematograms should begin showing long-range-like characteristics at some point when dot density is decreased, thus making interocular motion observable. Although Baker and Braddick (1982) reported that the maximum displacement limit (D max) for random-dot kinematograms is not affected by dot density, this is a natural assumption since the limiting case for the density decrease is a single dot. Thus the first objective of this study is to investigate whether sensitivity to interocular motion changes when dot density and IOA are systematically varied, and to examine the relationship between interocular motion sensitivity and the short- and long-range distinction. To accomplish this, in Expt I, accuracy of motion direction discrimination is analyzed while varying dot density, IOA, and displacement of IS random-dot stimuli.

Insensitivity to interocular random-dot motion may be explained by absorption of input by the stereoscopic depth system, since depth perception is possible under sequential presentation of stereograms. It should be noted that interocular kinematograms and sequential stereograms are the same stimuli (Fig. 1). Depth perception with sequentially presented stereograms has been acknowledged and studied for many years (e. g. Ewald, 1906; Efron, 1957), and a three dimensional television system with liquid crystal goggles, which has been developed recently, clearly demonstrates the phenomenon. However, experimental research has shown that there is an upper limit for interocular asynchrony (IOA), or the upper temporal disparity limit for stereopsis, which ranges between 100 and 200 ms (Dodwell and Engel, 1963; Ogle, 1963; Engel, 1970; Ross and Hogben, 1974). This temporal limit coincides well with the upper limit of SOA for short-range motion (Braddick, 1974; Baker and Braddick, 1985). Therefore, the IS short-range input may be absorbed by the stereo system instead of the motion system, which may explain the disappearance of motion perception. However, the relationship between motion and depth perception for IS stimulation has not been clarified, since all past studies examine either only motion or only depth. The second objective of this study is to clarify the relationship between motion and depth perception for random-dot patterns under IS presentation. In Expt II, the relative frequency of motion and depth perception for IS random-dot stimuli was studied. In Expt III, the performance of only depth perception under IS presentation was analyzed while forcing the subject to make depth judgements.

## Experiment I: interocular motion perception

The purpose of this experiment is to examine how dot density and IOA affect the perception of interocular motion, and whether the stimulus range within which interocular motion is observed coincides with the stimulus range for putative short-range motion. For this purpose, accuracy of motion direction judgement for random-dot kinematograms under IS presentation (Fig. 1) was measured while varying dot-density, IOA, and displacement.

### Method

Two 6.4 x 6.4 deg pattern fields were displayed side-by-side on a 66 Hz non-interlace CRT screen (P22 phosphor) controlled by a Masscomp MC5600 computer system. The patterns were viewed through a mirror stereoscope with an opaque septum between the two eyes. Each pattern field was divided into 128 x 128 pixels, each pixel subtending 3 x 3 arc min (3 x 3 graphics pixels). A light (white) pixel comprised one dot, and dot density, i. e. the probability of each pixel being light, was varied between 0.1% and 50%. Dot luminance was 80 cd/m$^2$ and the dark background was less than 1 cd/m$^2$. Luminance of the areas surrounding the two pattern fields was 40 cd/m$^2$. Thus, the pattern fields, kept dark while stimulus patterns were not presented, were clearly segregated from the surrounding background, and were easily fused through the stereoscope. The two pattern fields were presented dichoptically in succession, i.e. one pattern for one eye and then the other to the other eye (Fig. 1). The second stimulus was generated by horizontally displacing the whole first pattern to either the right or left by an integral number of dots with a wrap-around so that the outer borders of the pattern field did not shift. The patterns would constitute random-dot kinematograms if they were presented to the same eye, and would induce motion perception. Duration of the first pattern was the same as that of the second pattern, and there was no blank display frame between the two stimuli, thus stimulus onset asynchrony (SOA) was equal to the duration of each pattern.

The display was viewed in a dark room at a distance of 104 cm. The subject started a trial by pressing a key on the computer keyboard. A fixation marker, consisting of 4 small dots in a square configuration separated by 8 min from each other, appeared at the center of each field. It was displayed for 500 ms to enable the subject to attain fusion and proper accommodation. Then, following a 500 ms blank period, the two random dot patterns were successively presented to different eyes. Order of presentation for the two eyes was randomized. The subject's task was to determine direction of motion, right or left, by pressing a key specified for each direction.

Percent correct scores for each combination of dot density and SOA were measured as a function of displacement using the method of constant stimuli. For each session, dot density and SOA were fixed while displacement was varied. Three sessions, each consisting of 16 repetitions, were run to obtain a psychometric function with 48 repetitions for each displacement. Four dot densities (0.1, 1, 10, and 50%, or 0.4, 4, 40, and 200 dots/deg$^2$) and five IOA values (15, 30, 60, 120 and 240 ms) were used. Displacement was varied in 6 steps (3, 6, 12, 24, 48, 72 arc min, or 1, 2, 4, 8, 16, 24 dots). For one of the subjects (TS), , for the 240 ms IOA condition only, zero displacement and no correlation conditions were added in addition to the regular 6 steps. In the zero displacement condition, the two stimuli were exactly overlapped between the two frames, and in the no correlation condition, two completely different patterns were presented.

Three subjects, one male and two female, participated in this experiment. They all had normal or corrected to normal vision. One subject, TS, was the author. The other two had some prior experience of psychophysical experiments but no knowledge as to the purpose of the experiment.

Results and discussion

Accurate motion discrimination was obtained only in conditions with low dot-densities and larger spatial displacements (Fig. 2), or conditions suitable for long range motion. At short displacements (< 20 min) and high dot-densities (> 10%), or conditions suitable for short-range motion discrimination, performance was at chance level. These results support the distinction between short- and long-range processes in motion perception, and indicate that they can be isolated from each other through IS presentation.

Two different kinds of subjective impressions occurred in the conditions in which motion judgement was inaccurate. When dot density was very high (50%) or IOA was short (30 and 60 ms), subjects often did not see motion; they perceived flicker instead. Judgement was inaccurate in these conditions simply because motion was not perceived. Although these conditions seem suitable for invoking stereoscopic depth perception (e. g. Dodwell & Engel, 1963), depth was never perceived. This is probably because there was no disparity gradient within a pattern pair (Ross, 1974; Elklens and Colleijn, 1985). Depth perception with IS presentation will be investigated and discussed in detail in Expts II and III.

---

Fig. 2 about here.

---

In other cases where motion judgement was inaccurate, i.e. at medium to low densities especially with short displacements and longer IOAs, subjects mostly had strong and definitely directional motion impressions, but could not give correct judgements. Further analysis of the data revealed that motion judgement in these conditions depended solely on which eye saw the first stimulus, regardless of the spatial shift in the pattern. Subjects perceived motion in the direction towards the eye which received the first stimulus. For instance, the subject perceived a rightward motion when the first stimulus was presented to the right eye. As a result, judgements were almost always correct when physical motion was toward the first eye, and almost always incorrect when motion was toward the second eye; thus, overall performance became chance level. The relationship between the presentation order and the perceived direction is schematically depicted in Fig. 3.

---

Fig.3 about here.

---

To illustrate this eye order effect, the data from Fig. 2 has been replotted in Fig. 4 according to eye-order categories. In this figure, percent correct scores were plotted separately for conditions in which the directions of physical displacement and the direction of the eye order effect were the same, and conditions in which the directions differed. Direction judgements are mostly determined by the eye order effect when displacement is small, i.e. in conditions presumably favorable for short-range motion. The effect is also evident in conditions of zero displacement and no correlation with subject TS. On the contrary, when displacement is large and dot density is low, i.e. in conditions favorable for long-range motion, physical displacement can overcome the eye order effect and the number of correct judgements increases.

The eye-order effect is weak at high dot densities (50%) or short IOAs (< 100 ms) even when displacement is small; motion is often invisible in these conditions. In conditions where eye-order dependent motion is perceived, two qualitative types of eye-order dependent motion are evident. Movement of individual dots was clearly observed at lower densities, but at higher densities, motion of the dot cluster as a whole and "shadow-like" motion in the opposite direction were often observed. The latter phenomenon seems similar to those reported by Shipley & Rawlings (1971) and Cogan (1990), and probably is due to a dynamic interocular luminance imbalance. The former type, however, seems pattern specific, since motion of individual dots was clearly discernible.

---

Fig. 4 about here.

---

The eye order effect might be explained by a vergent eye movement which is caused by unbalanced stimulation to the two eyes. However, Cogan (1990) examined eye movement by superimposing random-dot stereograms over an interocularly modulated luminance field, and found no effects of eye movement on stereopsis. In our study, subjects neither experienced any difficulty in maintaining fusion, nor detected any misalignment of the outer edges. To further evaluate influences of eye movement, several control sessions were run with a vertical nonius line at the center of the stimulus field. The upper half of this line was presented to one eye and the lower half was to the other eye; the line stayed on during the whole stimulus presentation. In these sessions, the subject was asked to fixate carefully and to try to maintain the alinement of the upper and lower halves of the nonius line. As a result, subjects could maintain a stable fixation at each stimulus presentation; they did not detect any shifts of the line comparable to the motion of the dots. However, a reliable eye order effect, although slightly diminished compared to that in the main experiment, was found in the results. These results indicates that vergent eye movements are not the main cause for the eye order effect.

## Experiment II: motion and depth preference

The absence of correct interocular short-range motion found in Expt I might be explained by involvement from the stereo system. Since stereoscopic depth can be seen under IS presentation if IOA is short (Dodwell and Engel, 1963; Ogle, 1963; Engel, 1970), some input must be getting absorbed into the stereo system. In Expt I, however, depth was never observed, probably because there was no disparity gradient within the stimulus field. Previous studies have found a connection between depth perception and disparity gradient (Ross, 1974; Elklens and Colleijn, 1985). In a pilot study at our laboratory, we observed depth at short IOAs using successive presentations of random-dot stereograms that contained a disparity gradient, i. e. patterns with a central square target in depth, but motion of the target was also seen. Thus, to clarify the relationship between motion and depth perception under IS presentation, a second experiment was conducted using patterns with a disparity gradient, in which subjects reported whether they saw depth or motion.

### Method

The apparatus and stimulus are the same as in Expt I except for the differences described below. The patterns for this experiment had a central target, that is, the stimulus was the proto-typical random-dot stereograms (Julesz, 1971), but was presented successively to the two eyes. Only the dots within the target area were displaced between the two patterns while the dots in the surrounding remained stationary. The target subtended 3 x 3 deg (60 x 60 dots) and was placed at the center of 6.4 x 6.4 deg patterns.

Dot density was varied in four steps (0.2, 1, 10, and 50%, or 0.8, 4, 40, and 200 dots/deg$^2$). The lowest density was doubled from that in Experiment I so that there would be at least several dots within the target area. The IOA values were the same as in Experiment I (15, 30, 60, 120 and 240 ms). The displacement was kept constant at 12 arc min (4 dots). This value was chosen because it induced clear perception of both motion and depth under monocular-successive (motion) or dichoptic-simultanous (depth) presentation in a pilot experiment. The subjects had two tasks to perform. The first was to report whether they perceived depth or motion by pressing keys. When they saw both, they were asked to choose the one which gave a stronger impression. The second task was to judge the direction of whatever was selected in the first task, whether motion (right / left) or depth (far / near). The same three subjects as in the previous experiments participated in this one.

## Results and discussion

Unlike the previous experiment, subjects now saw depth, motion, or both depending on the stimulus condition. This difference between the two experiments is evidence that clear depth perception requires that patterns contain a disparity gradient.

The data on forced choice preference between motion and depth perception (Fig. 5A, B) indicate that depth perception was dominant at shorter IOAs, while motion perception became dominant at longer IOAs. That is, there is a clear upper "temporal" disparity limit for the stereo system, and the limit is shorter for lower dot density and longer for higher density. Relative frequency of depth decreases, while that of motion increases as IOA is increased. At intermediate IOAs, motion is seen more often with low density patterns, but depth is seen more frequently with high density patterns. Because of this effect of dot-density, the transition between depth and motion perception takes place at shorter IOAs for low dot-density, and at longer IOAs for high dot-density. For subject TS, for example, the transition for 50% density patterns occurs at 180 ms, while that for 1% density is at less than 50 ms. The effect of dot-density is reversed for motion and depth. Around these transition IOAs, subjects often had both motion and depth impressions simultaneously, but this simultaneous occurrence of the two percepts is not reflected in the result, since data were collected by using a two alternative forced-choice technique.

------------------------------

Fig. 5 about here.

------------------------------

As for accuracy (Fig. 5C, D), it was nearly 100% at shorter IOAs where depth is preferred, but due to the eye order effect, motion accuracy was at chance level even where motion is strongly preferred (see data at disp = 12 min in Fig. 4). These findings suggest that absorption by the stereo system can explain the absence of interocular short-range motion at shorter IOAs and shorter displacements, i.e. absolute absence of motion perception or inaccurate motion perception due to the eye order effect. However, involvement by the stereo system still does not account for the absence of correct motion perception, or predominance of the eye-order effect at longer IOAs, because depth perception was not evident at longer IOAs.

## Experiment III: depth perception with sequential stereograms

The primary objective of this experiment was to identify the upper IOA limit within which binocular depth perception is possible, while varying dot-density and binocular spatial disparity. The results of Expt II do not reflect the true upper IOA limit since they were obtained by a forced choice method between motion and depth, and subjects had to choose one percept which gave a stronger impression. Therefore, in this experiment, subjects were asked to make direction judgements of depth (near / far) in all trials so that the absolute upper IOA limit to detect depth could be measured.

### Method

A psychometric function for correct judgement of depth was measured for each combination of dot density and IOA while varying binocular disparity. The experimental method was exactly the same as in the first motion judgement experiment, while the stimuli were the same as in the second motion/depth preference experiment. The stimulus patterns for this experiment again had a central target. Dot density (0.2, 1, 10, and 50%, or 0.8, 4, 40, and 200 dots/deg$^2$), IOA (15, 30, 60, 120 and 240 ms), and displacement (3, 6, 12, 24, 36, 48 arc min, or 1, 2, 4, 8, 12, 16 dots) were varied. The subjects were asked to discriminate the direction of depth of the central target (near/far) relative to the background by pressing keys. The same three subjects participated in this experiment.

### Results and discussion

The results indicate that the stereo system prefers lower IOA and high dot density when stimuli are presented sequentially (Fig. 6). For IOAs below 30 ms, depth discrimination was accurate for disparities up to 24 min. However, as IOA was increased, the upper disparity limit became narrower, and then depth perception completely collapsed. This upper temporal disparity limit depended on dot density, and was longer for higher dot densities and shorter for lower densities as in the previous experiment (Expt II). For subject TS, for example, depth discrimination for 1% density patterns collapsed at 60 ms of IOA, whereas it did not disappear until 240 ms for 50 % density patterns. The effect of dot density is shown in Fig. 7, where performance of depth discrimination at 12 min disparity for different dot densities is plotted against IOA.

---

Fig. 6, 7 about here.

---

The 60 to 240 ms range of upper IOA limit found in the present experiment generally agrees with those reported previously (Dodwell and Engel, 1963; Ogle, 1963; Engel, 1970; Ross and Hogben, 1974). However, the effect of dot density on the upper IOA limit has not been reported elsewhere.

## Discussion

The present study reveals a relationship between motion and depth perception with random-dot patterns under IS presentation. The results can be summarized as follows. (1) Depth perception occurs for IS stimulation with shorter IOAs, but a disparity gradient within the pattern is necessary for clear depth impression. When there is no disparity gradient, neither depth nor motion perception occurs. (2) Motion perception becomes dominant at longer IOAs, but correct interocular motion perception is obtained only for low dot density stimuli when they are presented with large displacements. That is, the conditions in which interocular motion is perceived coincide with those suitable for long-range motion. (3) For a wide range of stimulus conditions which do not give rise to either correct motion or binocular depth, motion sensation depends solely on the order of presentation to the two eyes: a new phenomenon which I call the eye order effect. The relationship between depth perception, correct motion perception, and the eye order effect is schematically summarized in Fig. 8.

---------------------------

Fig. 8 about here.

---------------------------

### IS motion perception

The fact that correct interocular motion detection occurred only for stimuli with very low dot densities indicates that a shift of dominant processing between the short-range and long-range processes takes place as dot density is decreased. However, the shift takes place at very low dot densities between 1 and 0.1%, or between 4 and 0.4 dots / deg$^2$. This result agrees well with Ramachandran and Anstis (1983) who found Dmax values exceeding 1 deg using a large field size (8 x 10 deg) and low dot-densities (9 and 4.5 dots / deg$^2$). They also found that Korte's third law, which has been acknowledged as one of the important characteristics of long-range motion, also holds for motion of low-density patterns.

The present results together with those of Ramachandran and Anstis (1983) apparently contradict the findings of Baker and Braddick (1982) that dot-density has little effect on Dmax. In their experiments (their Expt. 3), they fixed the field size (0.77 x 1.53 deg) and dot size (2.3 min) and varied dot density between 1 and 50%. In light of the present results, however, it is likely that a dot density of 1% was still too high to invoke involvement from the long-range process, or that the field-size they used was too small to detect the effect.

The effect of dot-density cannot simply be related to spatial frequency content of the stimuli, since the random-dot patterns used in the present study have the same low-pass shaped spatial frequency distribution regardless of dot-density. The shape of a spatial frequency distribution is only determined by dot-size (sampling interval), which was kept constant in the present experiments. The most significant difference between patterns with high and low dot densities can be found in the spatial distribution of high spatial frequency components; high spatial frequency components are more densely distributed over the space in high density patterns, which mean that more receptive fields tuned for high spatial frequencies are stimulated by patterns with a higher dot density.

Georgeson and Shackleton (1989) have reported intriguing results on dichoptic motion perception with missing fundamental patterns, i.e. square wave gratings without fundamental frequcny component. With these patterns, edges corresponding to the missing fundamental frequency are visible when the contrast is high. When the patterns are presented as a motion sequence, dichoptic motion of the missing fundamental component is dominant when stimulus contrast is high, but when contrast is low, the motion of the third harmonic (actual lowest frequency component) in the opposite direction is observed more frequently. Based on these results, Georgeson and Shackleton claimed that while monocular short-range motion is mediated by spatial frequency tuned filters, or Fourier motion sensors, dichoptic motion is mediated by feature matching mechanisms (see also Chubb and Sperling, 1990).

Although Georgeson and Shackleton's results with shorter sequences, especially with 2-frame motion stimuli, were not very conclusive and thus their conclusion may not be applicable to the present results, the distinction between Fourier and non-Fourier motion detectors is suggestive. The long- and short-range distinction is a descriptive distinction based on stimulus parameters, but the distinction of Fourier and non-Fourier motion is based on differences in the processing algorithm. With respect to the present results, it is quite plausible that non-Fourier motion detectors which are not too effective at higher dot densities become effective and dominant at low dot densities. We are now conducting a series of experiments on motion detection performance for random-dot patterns with various dot sizes and densities, and also for spatial frequency filtered dot patterns. Our tentative results suggest that the shift between Fourier and non-Fourier type processing takes place as dot density is reduced (Sato, 1990).

IS depth perception

When IOA is very short, stereoscopic depth perception is observed, but a disparity gradient within the pattern is required, as shown by Expts II and III. When there is no disparity gradient, neither depth nor motion is observed, as in Expt I. Such dependence of stereoscopic depth perception on disparity gradients has been reported frequently (e. g. Ross, 1974; Elklens and Colleijn, 1985).

The conditions where depth was seen best, that is, combinations of very short IOAs and high dot densities, approximately corresponds to the range where no interocular motion, neither correct motion nor eye-order motion, was seen in Expt I. In this regard, there is a partially competitive interaction between the motion and binocular depth systems. Input with short IOAs brings about depth perception, whereas input with longer IOAs is fed into the motion mechanism and either correct or wrong motion perception results. However, the assumption that absence of interocular short-range motion is due to absorption of input by the stereo mechanism seems only partially valid, since the stimulus range for IS stereopsis is much smaller than that within which abnormal IS motion perception, either no motion or the eye-order motion, comes about. It should also be noted that the stimulus range within which IS stereopsis occurs does not coincide exactly with that for normal, monocular, or binocular short-range motion (Braddick, 1974). The stimulus range for IS stereopsis is wider in the spatial extent, but narrower in the temporal extent than that for short-range motion.

The upper IOA limit for binocular depth perception, however, depends on dot density; the limit is longer for stimuli with higher dot densities. The value of this limit observed in this study ranged between 60 and 240 ms, and agrees well with past results (e.g. Dodwell and Engel, 1963; Ogle, 1963; Engel, 1970; Westheimer, 1979). However, no preceding studies reported the effect of spatial parameters on this limit.

The upper IOA limit found in the present study might be related to visual persistence, since most past research on IS stereopsis assumes simultaneity of dichoptic input at the site of disparity processing, and that the simultaneity is caused by persistence, or the iconic memory in the monocular input (see Coltheart, 1980). Studies on persistence have shown that persistence is longer for brief presentations (e. g. Bowling & Lovegrove, 1980; Coltheart, 1980), and this explains depth dominance at shorter IOAs. The effect of dot density is more difficult to relate to persistence since no persistence data random-dot patterns are available for comparison. Although it has been shown for sinusoidal gratings that visual persistence is inversely related to spatial frequency (Bowling & Lovegrove, 1980; Breitmeyer, Levi, and Herwerth, 1981) and contrast (Bowling, Lovegrove & Mapperson, 1979), these data cannot be related to the present findings. Patterns with higher dot densities have higher power levels, but the relative power distribution between high and low spatial frequency regions is constant regardless of dot density. Persistence for wide band stimuli such as random-dot patterns certainly merits further experimental analysis.

### The eye-order effect

Although the eye order effect found in this study may reflect functions of the motion system alone, it is more plausible to assume interaction between the motion and stereo systems, or to assume a separate mechanism processing interocular spatio-temporal disparities. Such a view has been suggested by several researchers. Ross (1974) reported that when interocular delay is introduced to continuously plotted random-dot stereograms, depth perception prevails only at IOAs shorter than 60ms, but at longer IOAs an eye-order specific motion similar to that found in the present study is observed. This motion perception was accompanied by a depth perception; the dots appeared behind the stimulus plane. Based on these data, Ross argued for the existence of two separate stereoscopic depth systems, the regular stereoscopic system which is operative over shorter temporal disparities (< 50 ms), and a second system which positively processes longer temporal disparities. Tyler (1974) found a similar phenomenon in television snow-noise when an interocular delay was introduced. Tyler (1974, 1977), however, explained his findings as chance pairing of random-dot patterns by the conventional stereo mechanism. MacDonald (1977), and Mezrich and Rose (1977) also reported similar phenomena.

More recently, Shimojo, Silverman and Nakayama(1989) have reported a depth perception induced by IS presentation of "real" motion. Their display was designed to mimic a bar moving behind an occluding screen with a slit (Fig. 9 a). Subjects perceived a single bar behind the slit with a depth corresponding to the amount of IOA. The depth perception could not be explained by ordinary stereopsis, since depth was perceived even when there was a temporal gap between the two moving stimuli. Shimojo et al. (1989) argued that this phenomenon is evidence that the occlusion constraint is implemented at an earlier stage within the visual system. In a natural scene, monocular motion direction, eye order, and depth are integrated under the occlusion constraint, and when depth is missing, the visual system can retrieve it by using available cues based on the constraint. This occlusion constraint scheme might explain the eye order effect found in the present study.

-----------------------------

Fig. 9 about here.

-----------------------------

Both monocular motion and depth are missing in the stimuli of the present study as well as in past studies with interocular delays (Ross, 1974; Tyler, 1974; Mezrich & Rose, 1977; MacDonald, 1977). Therefore, even with the occlusion constraint, motion and depth should remain ambiguous for these stimuli. There are two possibilities. One is the combination of receding depth and motion towards the leading eye (Fig. 9 a). This occurs when motion of an object behind an occluder is seen through a slit or a hole. The other combination is one of protruding depth and motion towards the following eye (Fig. 9 b), and it occurs when there is a narrow occluder in front of the moving object (Fig. 9 b). Past random-dot studies actually indicate that these only two combinations are perceived when there is an interocular delay (Ross, 1974; Tyler, 1974; Mezrich & Rose, 1977).

The motion direction found in the present eye order effect is one which should be accompanied by receding depth, and there is some evidence that the receding depth, and hence direction, found in the present study is a default solution for the visual system. Ross (1974) reported that subjects mostly saw receding depth and motion compatible with that depth; protruding depth was found only in very limited conditions. Mezrich and Rose (1977) reported that in some conditions where coherent motion was marginally identifiable, although motion was not accompanied by any depth impression, motion was perceived only in the direction compatible with receding depth. When Shimojo et al. (1989) presented the two moving bars in reversed order as in Fig. 9b, subjects did not find motion of a single object in protruding depth. Instead, they perceived two bars moving in parallel behind the slit. The visual system somehow has difficulty in perceiving protruding depth, probably because fixation on a point behind a narrow occluder is not a very likely event in the real world.

Although the occlusion involved in the demonstration by Shimojo et al. (1989) appears global, it could be very local and physiologically more plausible than they suggest. All the cells at earlier stages of the visual system are looking at the world through a small hole, since they all have a relatively small receptive field (Fig. 9c). And only the objects moving on the holopter plane hit the corresponding retinal position simultaneously. While there are infinite combinations of spatial and temporal disparities are possible, two limiting cases for an object moving on or off-holopter are to hit simultaneously with spatial disparity (conventional binocular disparity), or to hit corresponding retinal positions with a temporal disparity. In the latter limiting case, the temporal disparity is always associated with a local motion direction in the same way as discussed in the occlusion of Shimojo et al. (1989). Therefore, a specific depth should be available when the local motion direction and temporal disparity (i. e. IOA), at the corresponding positions are available. It should be noted that local motion and IOA can be evaluated by different cells which reside at the same position. This is a plausible algorithm to solve off-holopter motion and depth, and it is physiologically feasible, since several past studies have reported temporal disparity tuning (Cynader, Gardner, & Douglas, 1978; Carney, Paradiso, and Freeman, 1989).

In summary, the present demonstration of the eye order effect, together with past results (Ross, 1974; McDonald, 1977, Shimojo et al., 1989), indicate that motion and depth perception are inter-dependent. The visual system resolves spatio-temporal binocular input as an object in motion and in depth, based on monocular and interocular spatial and temporal disparities.

## Conclusion

The present study clarified the following perceptual aspects of interocular-sequential stimulation. It was found that IS random-dot stimuli give rise to three types of motion and binocular depth perception depending on stimulus parameters. The three types of motion are correct apparent motion, eye-order dependent motion, and no motion. The stimulus conditions in which correct interocular motion occurs generally agree with those suitable for putative long-range motion. This result therefore supports the notion that only the long-range process is operative for interocular stimulation. The conditions where no motion at all was perceived correspond to the stimulus range where IS stereoscopic depth is possible. Therefore, the loss of short-range motion with IS stimulation for this stimulus range can be explained by absorption of input by the binocular stereo mechanism. However, the stimulus range in which eye-order dependent motion was observed does not correspond to the optimal conditions for stereopsis. The eye order dependent motion, most likely, is an active resolution by the visual system of spatio-temporal binocular input as an object in motion and in depth based on the geometric occlusion constraint.

# REFERENCES

Anstis, S. M. (1980) The perception of apparent movement. Philosophical Transaction of Royal Society London, B290, 153-168.

Baker C. L. and Braddick, O. J. (1982) The basis of area and dot number effects in random dot motion perception. Vision Research, 22, 1253-1259.

Baker and Braddick (1985) Temporal properties of the short-range process in apparent motion. Perception, 14, 181-192.

Bowling & Lovegrove (1980) The effect of stimulus duration on the persistence of gratings. Perception and Psychophysics, 27, 574-578.

Bowling, Lovegrove & Mapperson (1979) The effect of spatial frequency and contrast on visual persistence. Perception, 8, 529-539.

Braddick O. J. (1974) A short-range process in apparent motion. Vision Research. 14, 519-527.

Braddick, O.J. (1980) Low-level and high-level processes in apparent motion. Philosophical Transaction of Royal Society London, B290, 137-151.

Breitmeyer, B. G., Levi, D. M. & Herwerth, R. S. (1981) Flicker-masking in spatial vision. Vision Research, 21, 1377-1385.

Carney, T., Paradiso, M. A. and Freeman, R. D. (1989) A physiological correlate of the pulfrich effect in cortical neurons of the cat. Vision Research, 29, 155-165.

Cavanagh and Mather, 1989) Motion: The long and short of it. Spatial Vision, 4, 103-129.

Cogan, A. (1990) The interocular luminance yoke: a vestige of phototaxis. Vision Research, 30, 181-185.

Coltheart, M. (1980) Iconic memory and visible persistence. Perception and Psychophysics, 27, 183-228.

Cynader, M., Gardner, J. and Douglas, R. (1978) Neural mechanisms underlying stereoscopic depth perception in cat visual cortex. In Frontiers in Visual

Science (Edited by Cool S. J. and Smith E. L. III), pp.373-386. Springer, Berlin.

Dodwell, P.C. & Engel, G.R. (1963) A theory of binocular fusion. Nature, 198, 39-40, 73-74 (1963).

Efron, R. (1957) Stereoscopic vision -- I. Effect of binocular temporal summation British Journal of Ophthalmology, 41, 709-730.

Elklens, C. J. & Colleijn, H. (1985) Motion perception during dichoptic viewing of moving random-dot stereograms. Vision Research, 25, 583-588

Engel, G. R. (1970) An investigation of visual responses to brief stereoscopic stimuli. Quarterly Journal of Experimental Psychology, 22, 148-166.

Ewald, J. R. & Jaderholm, G. A. (1906) Auch Alle Gerauche geben, wenn sie intermittiert werden, Intermitenztone. Pflugers Arch. ges. Physiol, 115, 555.

Georgeson, M. A and Shackleton, T. M. (1989) Monocular motion sensing, binocular motion perception. Vision Research, 29, 1511-1523.

Green, M. and Blake, R. (1981) Phase effects in monoptic and dichoptic temporal integration: Flicker and motion detection. Vision Research, 21, 365-372.

Julesz B. (1971) Foundation of Cyclopean Perception. University of Chicago Press, Chicago, IL.

MacDonald, R. I. (1977) Temporal stereopsis and dynamic visual noise. Vision Research, 17, 1127-1128.

Mezrich, J. J and Rose, A. (1977) Coherent motion and stereopsis in dynamic visual noise. Vision Research, 17, 903-910.

Ogle, K.N. (1963) Stereoscopic depth perception and exposure delay between images to the two eyes. Jouunal of the Optical Society of America, 53, 1296-1304

Pantle, A. J. and Picciano, L. A. (1976) A multistable movement display: Evidence for two separate motion systems in human vision. Science. 193, 500-502.

Petersik, J. T. (1989) The two-process distinction in apparent motion. Psychological Bulletin, 106, 107-127.

Ramachandran V. S. and Anstis S. M. (1983) Displacement thresholds for coherent apparent motion in random-dot patterns. Vision Research 23, 1719-1724.

Ross, J. (1974) Stereopsis by binocular delay. Nature, 248, 363-364

Ross, J. and Hogben, J. H. (1974) Short-term memory in stereopsis. Vision Research, 14, 1195-1201.

Sato, T. (1990) Effects of dot size and dot density on motion perception with random-dot kinematograms. Paper given at 13th European Conference on Visual Perception. September, 1990, Paris.

Shadlen, M. and Carney, T. (1986) Mechanisms of motion perception revealed by a new cyclopean illusion. Science, 181, 877-879.

Shimojo, S., Silverman, G.H., & Nakayama, K (1989). An occlusion related mechanism of depth perception based on motion and interocular sequence. Nature, 333, 265-268.

Shipley, W.C., Kenney, F.A. & King, M.E. (1945). Beta movement under binocuar, monocular and interocualr stimulation. American Journal of Psychology, 58, 545-549.

Shipley, T. & Rawlings, S. C. (1971) Sensory direction in homogeneous binocular visual space. Perception and Psychophysics, 9, 335-337.

Tyler, C.W. (1974) Stereopsis in dynamic visual noise. Nature, 250, 781-782

Tyler, C.W. (1977) Stereomovement from interocular delay in dynamic visual noise: A random spatial disparity hypothesis. American Journal of Optometry and physiological Optics, 54, 374-386.

Westheimer, G. (1979) Cooperative neural processes involved in stereoscopic acuity. Experimental. Brain Research, 36, 585-597

## Acknowledgements

-- I wish to thank Dr. E. Yodogawa of ATR for providing the opportunity to do this research. I am also indebted to Mr. Masami Ogata and Dr. Satoshi Shioiri of ATR for many valuable discussions.

## Figure captions

Fig. 1 A schematic diagram of interocular-sequential (IS) presentation. The first of the two random-dot patterns is presented to one eye, then the second pattern is presented to the other eye. The temporal relationship of the two patterns is shown in the lower panel. Note that motion will be perceived if the two patterns are presented to the same eye (random-dot kinematograms), and depth will be perceived if they are presented simultaneously to the two eyes (random-dot stereograms).

Fig. 2 Motion direction performance under IS presentation. Performance of motion direction discrimination is plotted for two IOA values as a function of displacement with dot-density as parameter. Results with three dot density are shown for two subjects. Circles represent 0.1%, triangles represent 1%, and squares represent 50%. Each data point is based on 48 trials. The graph for TS at 240ms IOA includes results from no-shift (displacement = 0) and no-correlation (NC) conditions.

Fig. 3 The relationship between eye-order and perceived motion direction. Perceived direction is always towards the eye which received the first stimuli (first eye), regardless of the direction of physical shift in the patterns. Thus, the judgement is always correct when the physical shift is towards the first eye, or when the direction of eye-order effect and physical shift match, but is always incorrect when the shift is towards the second eye.

Fig. 4 The effect of eye order. The same data as in Fig. 2 is plotted separately for the two eye- order categories: motion towards the first eye (open symbols) and motion towards the second eye (filled symbols). The notation for dot density is as in Fig. 2. The eye order effect is also observed in no-shift (displacement = 0) and no-correlation (NC) conditions at 240 ms IOA for subject TS.

**Fig. 5** The relationship between motion and depth perception for random-dot patterns under IS presentation. (A) Relative frequencies of motion (open symbols) and depth (filled symbols) preference at 12 min displacement (disparity) are plotted as a function of IOA for three dot-densities. Each data point represents the percent preference for either motion or depth from 48 presentations. (B) The percentage of correct motion (open symbols) and depth (filled symbols) judgement.

**Fig. 6** Depth direction performance under IS presentation. Performance of depth direction discrimination (near / far) is plotted for 0.2% and 50% densities as a function of displacement with IOA as parameter. Each data point represents the percentage of correct discrimination from 48 trials.

**Fig. 7** Effect of dot density on upper IOA limit. Performance of depth discrimination at 12 min disparity for subject TS is plotted separately for each dot density.

**Fig. 8** The relationship between motion and depth perception with random-dot patterns under IS presentation. The IOA and density ranges within which correct motion, eye order dependent motion, and stereopsis are experienced are illustrated separately for short and long displacements.

**Fig. 9** Schematic diagrams of occlusion constraint. The diagrams illustrate (A) an object moving horizontally behind a hole in an occluding screen, (B) moving behind a narrow occluder, and (C) sequential stimulation of foveal receptors by an object moving off the holopter plane.

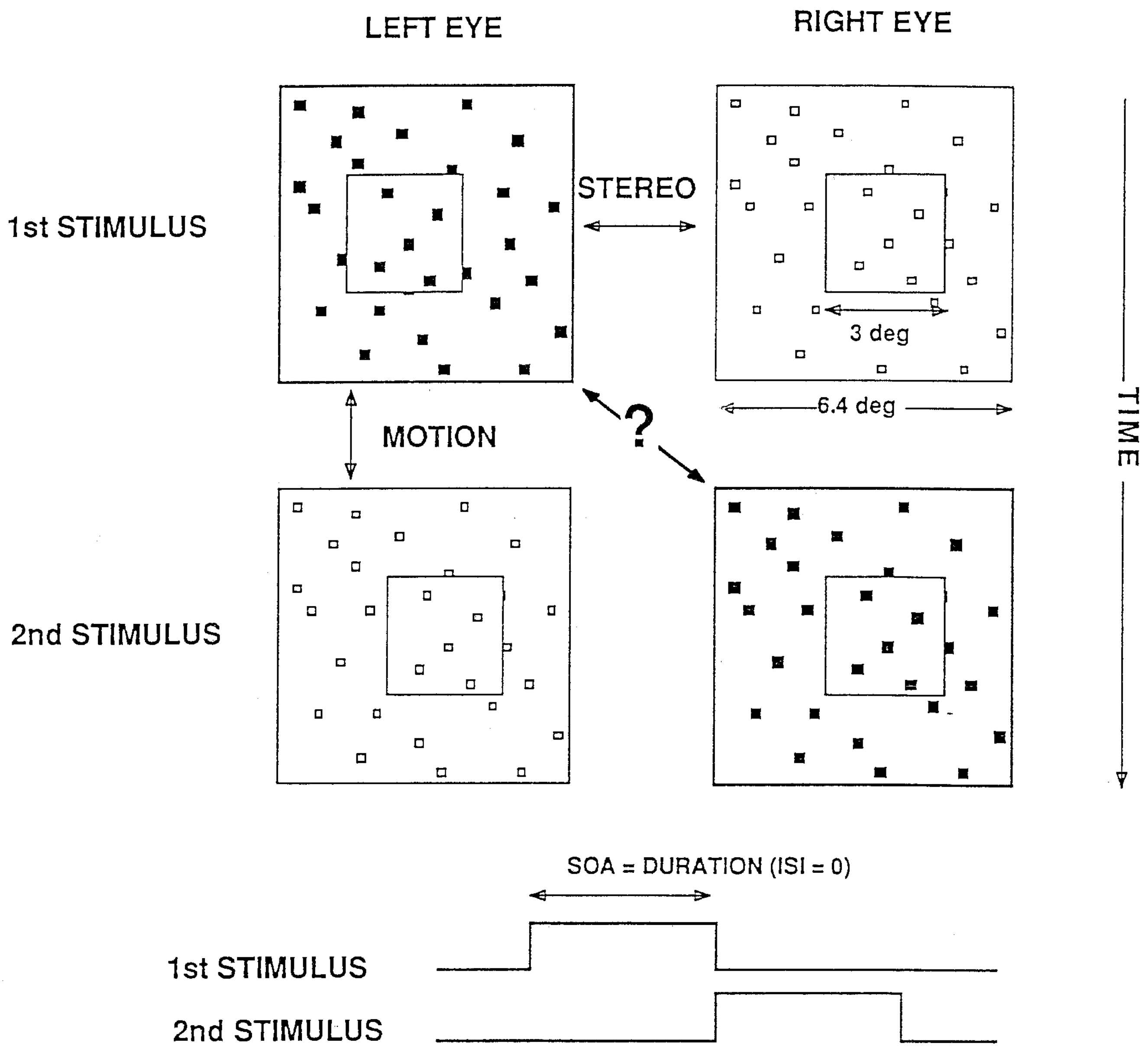
LEFT EYE
RIGHT EYE
1st STIMULUS
STEREO
3 deg
6.4 deg
MOTION
?
TIME
2nd STIMULUS
SOA = DURATION (ISI = 0)
1st STIMULUS
2nd STIMULUS

Fig. 1

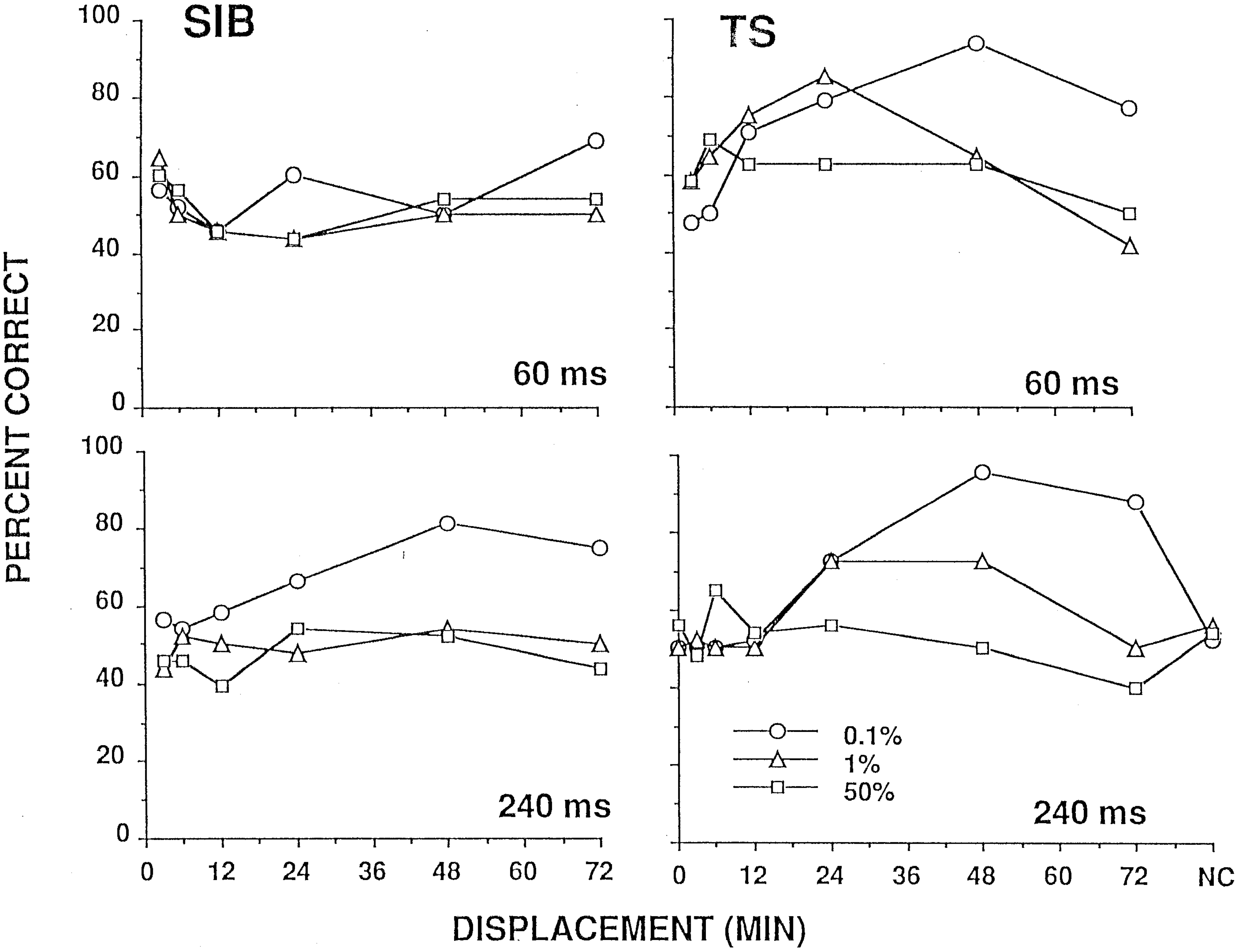SIB
TS
PERCENT CORRECT
100
80
60
40
20
0
60 ms
240 ms
0
12
24
36
48
60
72
NC
0.1%
1%
50%
DISPLACEMENT (MIN)

Fig. 2

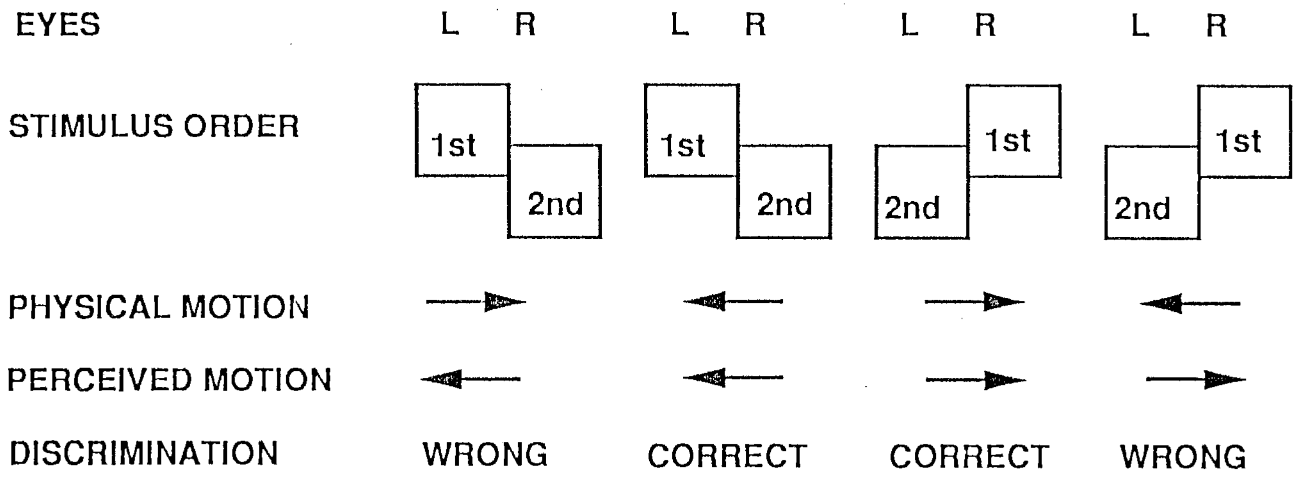
EYES
L R
L R
L R
L R
STIMULUS ORDER
1st
2nd
1st
2nd
1st
2nd
1st
2nd
PHYSICAL MOTION
PERCEIVED MOTION
DISCRIMINATION
WRONG
CORRECT
CORRECT
WRONG

Fig. 3

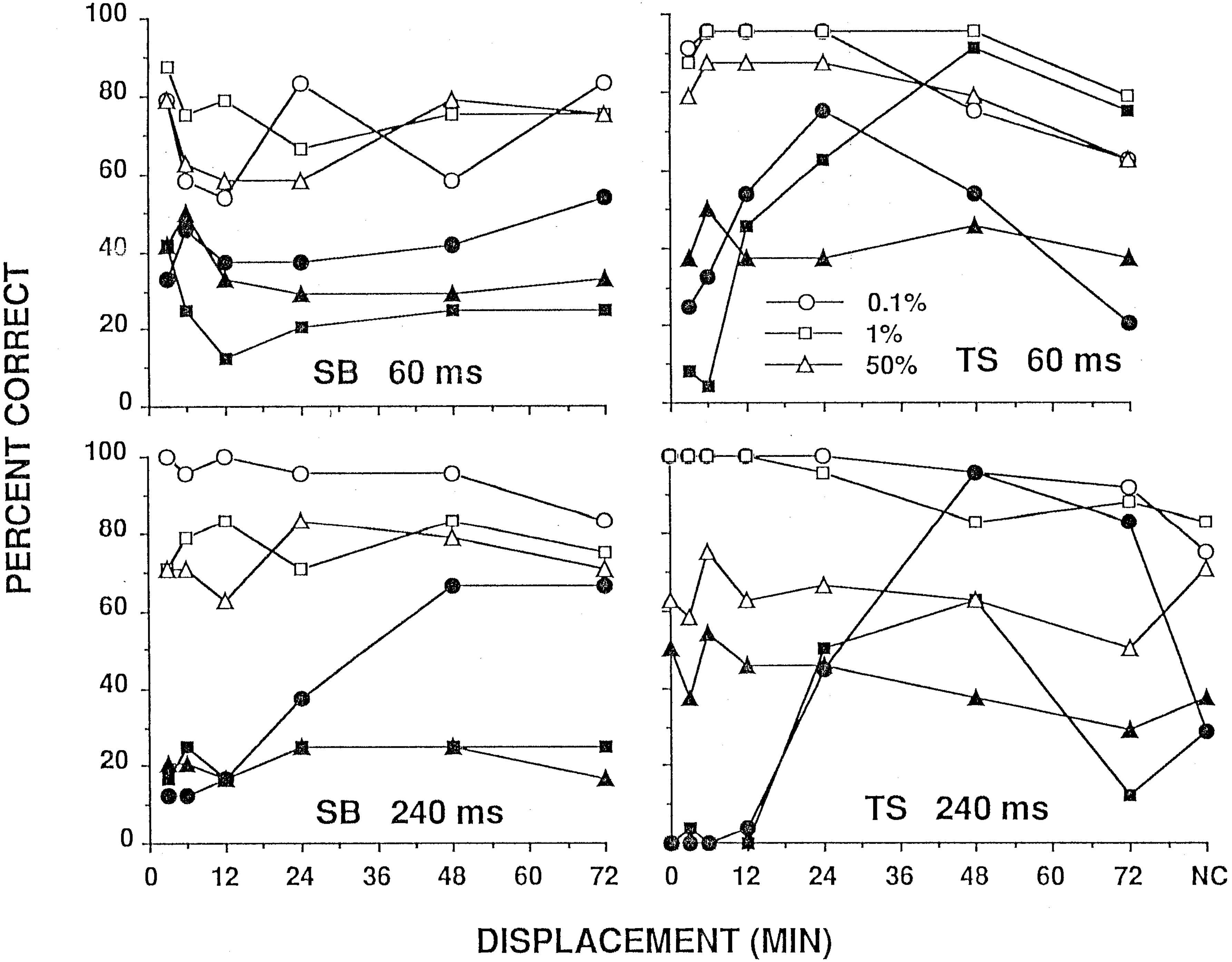
PERCENT CORRECT
100
80
60
40
20
0
SB 60 ms
0.1%
1%
50%
TS 60 ms
SB 240 ms
TS 240 ms
0
12
24
36
48
60
72
NC
DISPLACEMENT (MIN)

Fig. 4

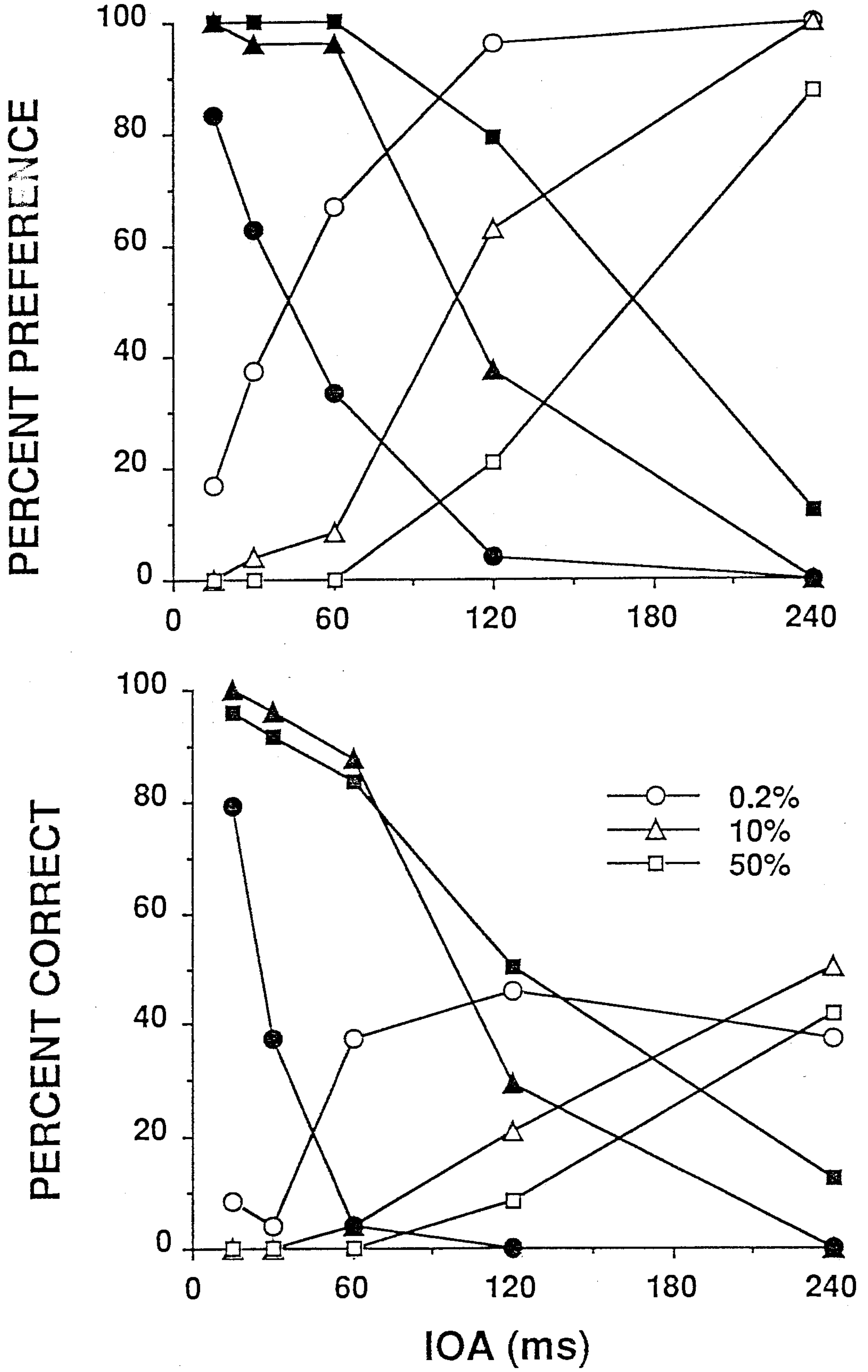
PERCENT PREFERENCE
100
80
60
40
20
0
0
60
120
180
240
PERCENT CORRECT
100
80
60
40
20
0
0
60
120
180
240
0.2%
10%
50%
IOA (ms)

Fig. 5

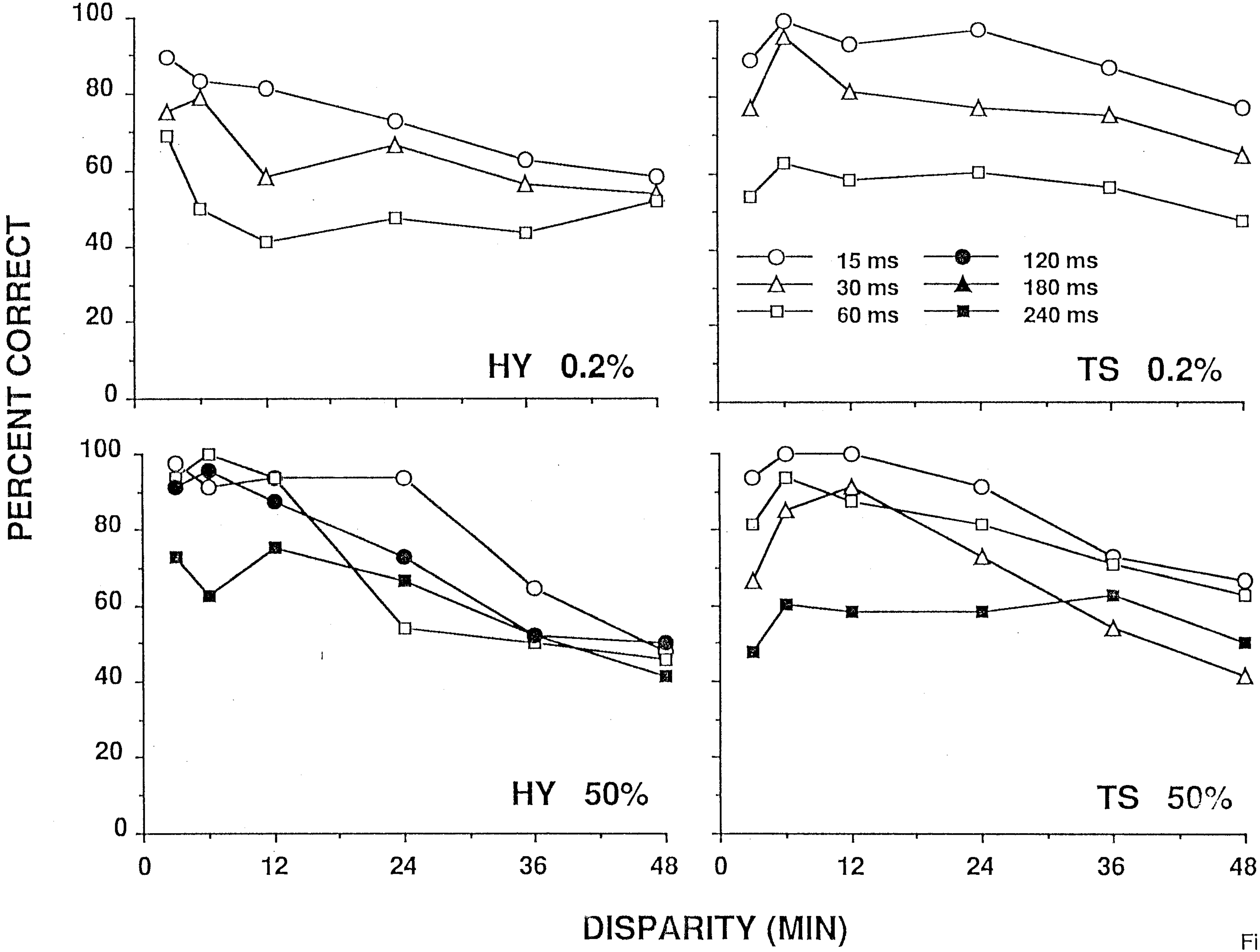
PERCENT CORRECT
DISPARITY (MIN)
100
80
60
40
20
0
12
24
36
48
HY 0.2%
TS 0.2%
HY 50%
TS 50%
15 ms
30 ms
60 ms
120 ms
180 ms
240 ms

Fig. 6

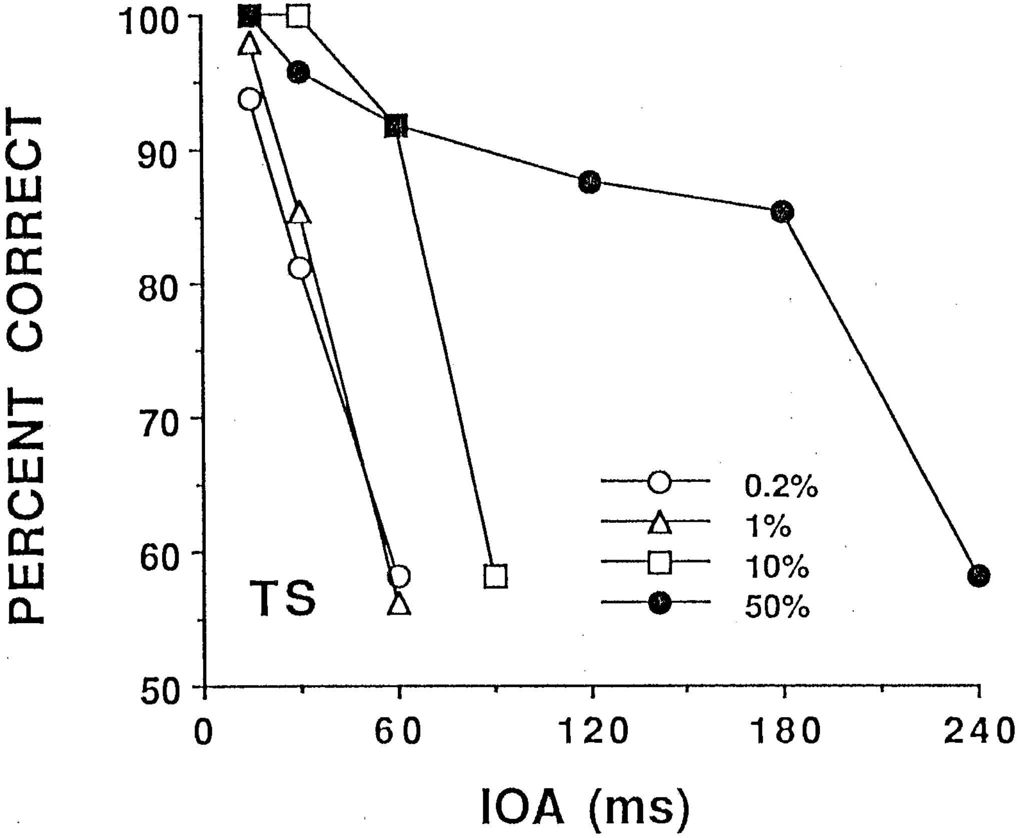
PERCENT CORRECT
100
90
80
70
60
50
0
60
120
180
240
IOA (ms)
TS
0.2%
1%
10%
50%

Fig. 7

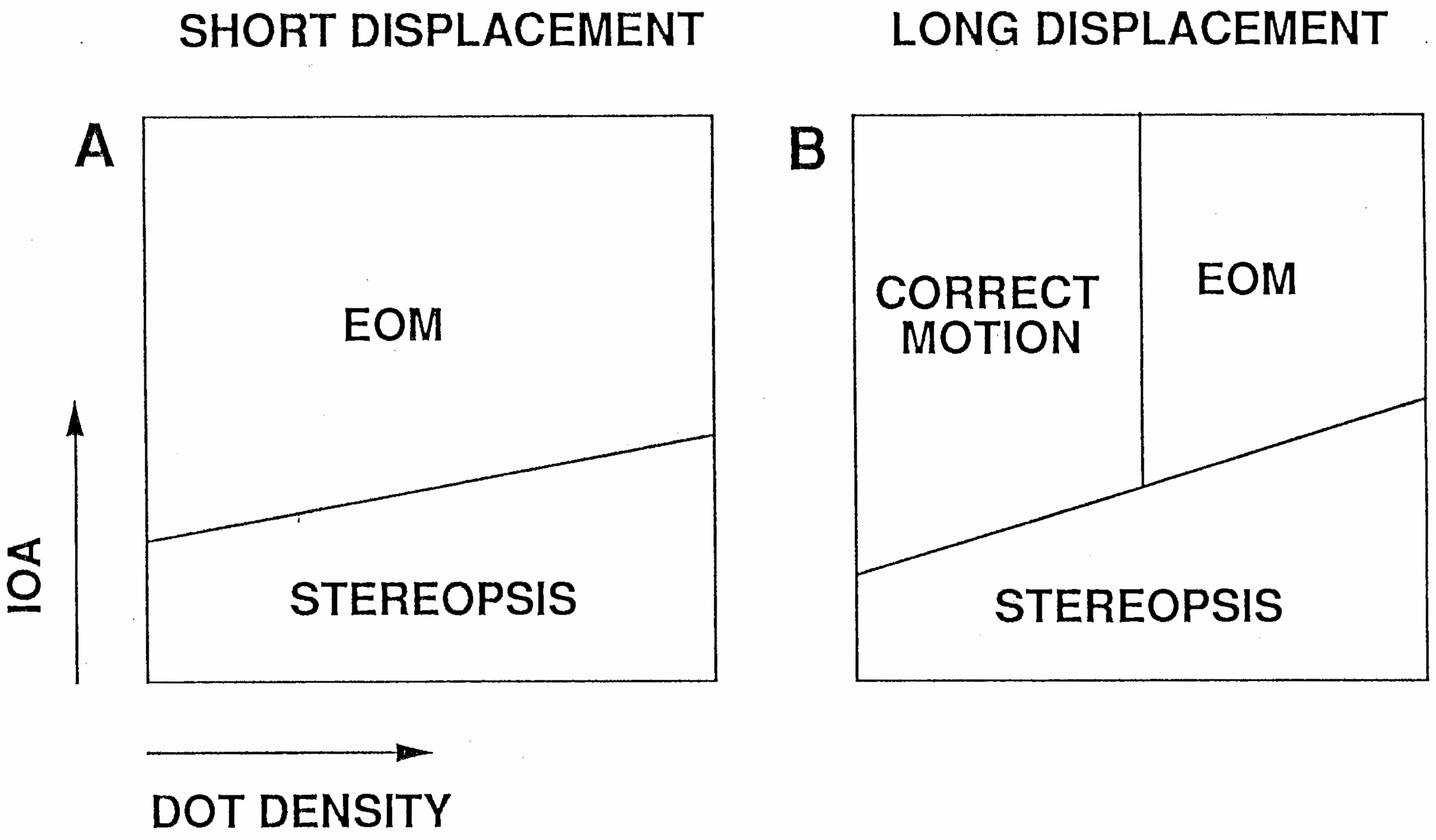
SHORT DISPLACEMENT
LONG DISPLACEMENT
A
EOM
STEREOPSIS
B
CORRECT MOTION
EOM
STEREOPSIS
IOA
DOT DENSITY

Fig. 8