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Motion-in-depth Direction Discrimination in Dynamic Random Dot Stereogram: The Role of Visual Perceptual Training*

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Abstract Stereopsis is not only the perception of static depth information, but also involves the ability to detect dynamic stereoscopic motion. This study investigated the motion-in-depth (MID) perception in dynamic random dot stereogram (DRDS) among the population of inexperienced normal vision observers, and the role of visual perceptual training for MID perception. There were three sessions in the main experiment: in the pre-training session, subjects were instructed to discriminate the motion direction of DRDS moving in depth (toward or away from the observer). Then subjects went through a perceptual training session to improve their sensitivity for the motion detection discrimination. A post-training session was carried out to evaluate the outcome of the training process. A control experiment involving only pre-training and post-training sessions was carried out to clarify the influence of repeated practice on visual performance improvement. Participants showed low direction discrimination ability for MID perception of DRDS in the pre-training session, their performance was significantly improved after the perceptual training session. However, large individual difference existed for fully perceiving the binocular disparity information during perceptual learning session. Moreover, the training effect was equivalently retained after six months. The subjects' performances in the control experiment did not show significantly difference between pre-training and post-training sessions. These findings demonstrate that difficulties for DRDS motion perception exist for inexperienced observers, and highlight the role of visual perceptual training.

Key words dynamic random dot stereogram (DRDS), motion-in-depth (MID), stereopsis, perceptual training
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We live in a 3D world, the ability to discern the relative position between objects and their motion in depth is fundamental for our daily life [1]. There are basically two types of 3D information: static depth information indicating the relative positions between objects and dynamic motion-in-depth (MID) revealing the direction of the movements. Previous studies have explored the neural processing regions and mechanisms for dynamic and static stereopsis in human vision. It is reported that static and dynamic disparities were processed by separated mechanisms. Subject who could answer normally to static disparity might have degraded performance with dynamic disparity [2-4]. An assessment of MID perception of strabismus patients was carried out by Watanabe to compare the dynamic stereopsis and static depth perception using a conventional stereo test, the result revealed low correlation between the two aspects[5].

Visual perception relies both on the optical quality of the eye and the neural processing in the brain [6]. In recent years, a growing number of studies have focused on how perceptual learning could help improving visual performances for static depth perception, particularly with regards to patients with stereopsis deficits and reported promising results [7-9]. Stereopsis is however only one aspect of binocular vision, observers with good stereopsis may not have a

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good dynamic stereo motion perception. Since individual differences among normal vision populations for MID perception were reported in the study of Nefs[10]. The aim of this study was to assess if practice and perceptual learning could help improve MID perception for observers with normal stereo acuity.

Dynamic random dot stereogram (DRDS) is an appropriate way to stimulate pure binocular perception, since it only provides disparity and motion information, eliminating the impact of monocular cues such as shade, and perspectives [11]. DRDS has been used in numerous studies such as motion aftereffect assessment (front parallel and 3 dimensions), perceptual training, MID perception features (stimulus eccentricity, velocity etc.)[12-13]. In the current study, we used DRDS as stimulus to examine the inexperienced observers' performance for MID perception. Based on previous results on perceptual learning and the adaptability of the visual system, it is demonstrated that a wide range of visual tasks could be improved through perceptual training, such as depth detection, figure discrimination in random dot stereograms [14-17]. The hypothesis of this study was thus that practice and perceptual learning can help improving motion direction discrimination in DRDS.

Three reasons motivated this study. Firstly, people with impaired stereo vision have worse performances on stereopsis visual tasks than their peers with normal stereo vision [18-19] with negative consequences on their quality of life. If MID perception can be trained through practice and perceptual learning, it could be a step towards a better treatment of binocular vision deficits.

Secondly, a large number of studies have focused on MID perception to elucidate the neural processing involve and to clarify how it relies on different input (changes in disparity, interocular velocity differences etc.)[20-21]. As usual in the field of neurophysiology and psychophysics, many studies relies on a small number of subjects (e.g. between 2 and 4 [12-13, 22-25]) often involving both trained and naïve observers. If MID perception can be improved by practice and perceptual learning then such groups of observers should not be mixed.

Lastly, it could be of interest for such studies if MID perception could be facilitated through training and perceptual learning. Although DRDS is an appropriate stimulus type for pure sensorial perception exploration, the use of DRDS stimulus to investigate MID perception is impeded by several issues: Perceiving MID with DRDS stimulus is not trivial[26-27]; protocols tend to be long and complex and not suited to a clinical environment; the associated large variability in MID perception sensitivity [10] leads to poor statistics or strong constraints on the number of subjects to be recruited. If practice and perceptual learning could help improving MID perception in DRDS, we could then possibly use larger number of patients with MID perception performances above chance level.

Here we first examined the discrimination ability of MID perception for observers with normal stereo acuity. In addition, we investigated if perceptual training could improve visual performance for MID perception. The performance of MID direction discrimination was compared by pre- and post-training experiments. Post training tests were carried out three times within 6 months to determine the time effect on perceptual learning of RDS MID discrimination.

1 Methods

1.1 Subjects

Fifteen healthy subjects ((24.1 ± 3.6) years old), inexperienced with RDS stimuli, were recruited. Subject vision inclusion criteria involved monocular visual acuity equal or better than 10/10, evaluated by a decimal scale chart; with no history of ocular pathology (functional and organic); no vertical or horizontal phoria (checked by fixation test), no glasses (contact lens were acceptable) to avoid prismatic effect, stereo acuity less than 60" (tested by Titmus Stereo Test). Approval was obtained according to the tenets of the Declaration of Helsinki. All subjects were naive to the experimental procedures and informed about the nature of the study. Written informed consent was obtained from all subjects.

1.2 Stimuli

The stimulus was displayed by a 3D projector at a viewing distance of 70 cm. 3D glasses synchronized with the projector (frame rate of 60 Hz) allowed stereoscopic viewing. The stimuli on the screen consisted of 80 RDS (40 white dots with luminance of 392 cd/m^2; 40 black dots with luminance at 20 cd/m^2) in a gray background (164 cd/m^2) centered on a lambertian white screen, as shown in Figure 1. Radius of the internal and external fields of RDS view were 3°

and 7°, each dot size was 0.15°, according to the fixed viewing distance. During the whole stimuli exposure time, observers were asked to fixate on the white cross in the middle of the RDS with a subtending angle of 0.5°. There were two kinds of dots among all the 80 RDS: signal dots and noise dots. The monocular velocity for signal dot was 0.6°/s, a randomly chosen motion direction: toward or away from observer was set in each trial for all the signal dots. We assigned to signal dots a random position in depth within the stimulus volume ± 0.6° and a randomly chosen dot lifetime within the range 0 –250 ms [13, 28]. The two requirements for replacement of each signal dot to its new randomly chosen position-in-depth were introduced: (1) as soon as lifetime reaches 250 ms, (2) if the signal dot reaches one of the borders (±0.6°). After the relocation, the same direction of motion and speed were assigned, the new initial lifetime was equal to 250 ms. The monocular velocity and dot lifetime for noise dots had to be less or equal to the signal dots velocity and lifetime. Initial position of noise dots was chosen randomly, as for signal dots. In addition, we implemented the linear change of the contrast from 100% to 0% visible color of all dots (signal and noise) on the grey background to achieve a smoother motion. Within the volume all dots were 100% visible and on the border we artificially increased the stimulus volume up to ±0.9°, i.e. we added ±0.3° to initial volume and within this part of stimulus volume we changed the contrast. Subjects would not perceive the changes of the dots directions due to the transparency procedure (linear change of contrast).

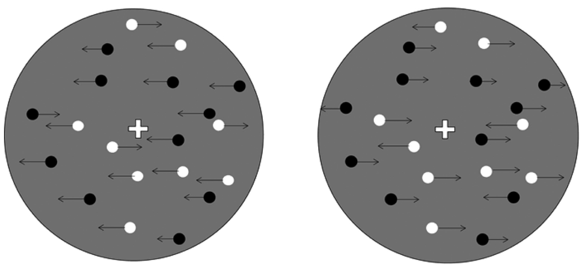

Fig. 1 Stimulus demonstration for the experiment

1.3 Procedure

The fifteen subjects were divided into two groups: nine in the experiment group and six in the control group. For the experiment group, there were four sessions in the whole experiment: pre-training session, perceptual training session, post-training session and training effect retention session. For the control group, subjects only went through pre-training session and post-training session. There was an interval between the two sessions to reduce the effect of visual fatigue (at least 1 h). Without the training session, the subjects’ performance could be compared with the experiment group, thus to clarify whether the improvement of the MID detection was due to the training or the repetition of the tests.

1.3.1 Pre-training session

Subjects were instructed to focus on the fixation cross at the center of the stimuli and assess the general MID direction of the dot cloud. There were three coherence levels with different MID direction: ±0.05, ±0.30, ±0.50, where “+” stands for motion toward, and “–” stands for motion away from observers. Coherence level here defines the portion of signal dots among all the dots. For a coherence level of 0, all the dots move in random directions. For a coherence level of 1, all the dots are moving in the same direction, either toward or away from the subjects. For every subject, each coherence level had 12 trials during the whole experiment, the trial number for the whole test was 72. The order of trials was randomized. The sequence for one trial includes two periods: test stimulus (TS) of 1s, inter-stimulus interval (ISI) of 1.25s. RDS with signal information was displayed during test stimulus period, no dots were displayed on the screen during the ISI, except the fixation cross and a grey background. In each trial, subjects used a joystick to give their answer for motion-toward or motion-away immediately when they perceived the dots motion during the period of TS and ISI. The answer was recorded as null if they cannot give the response within the trial time. The session lasted around 3 min.

1.3.2 Training session

The training session was carried out 1 h after the pre-training session. In this session, all the dots were moving at the coherence level of 1, which means that all the dots moved in a consistent motion direction in each trial (toward or away from the subjects). The number of the dots changed from trial to trial: 8 dots, 24 dots and 40 dots. There were two periods in one trial, TS and ISI, as described in pre-training session. The training session had three subsections. There were 300 trials in one subsection, the first 240 trials were with feedback indicating the correct MID direction at the end of each trial (a voice audio). In the last 60 trials, subjects needed to give their answer with a joystick without feedback. The training session was stopped until subjects' correct answer percentage arrived at 90%. If one could not achieve 90% correct answer, another subsection was carried out after 10 min rest. If the subjects could not achieve the required accuracy after three subsections, two more training sessions would be carried out depending on their convenience in the following days. This strategy was chosen because we aimed to train rapidly the participants without affecting negatively their degree of participation.

1.3.3 Post-training session

It was a repetition of the pre-training session after the training session, carried out one day after the training session. The protocols of this session were the same with the pre-training session. No feedback was given in the pre-training and post-training sessions.

1.3.4 Training effect retention session

Three subjects whose performance had significantly improvement in the post-training session repeated the post-training test after 6 months to test whether the training effect could be maintained over a long time.

1.4 Data analysis

To fit the MID discrimination performance as a function of coherence levels, psychometric function (PF) was used by implementing Psignifit Toolbox 3.0[29] for Python 2.7. Bootstrap was applied to fit the psychometric function (PF). The following logistic function was used:

$$F(x;\alpha,\beta)=\frac{1}{1+e^{-(\frac{x-\alpha}{\beta})}} \quad (1)$$

Where x stands for the coherence levels of the stimulus (±0.05, ±0.30, ±0.50), α corresponds to the shift of the curve and β corresponds to the slope of the curve. Output data of each observer for further analysis represents the correspondence of percentage of motion-toward answers to each coherence level.

The training curve (i.e., accurate answer percentage as a function of trial number [in log unit]) for each subject was fit with a linear function:

$$C = A\log(\text{trial number}) + C_0 \quad (2)$$

Where C stands for the correct answer percentage and A is for the slope of the training curve.

2 Results

2.1 Learning course

The performance of MID perception in the training session is illustrated in Figure 2, correct

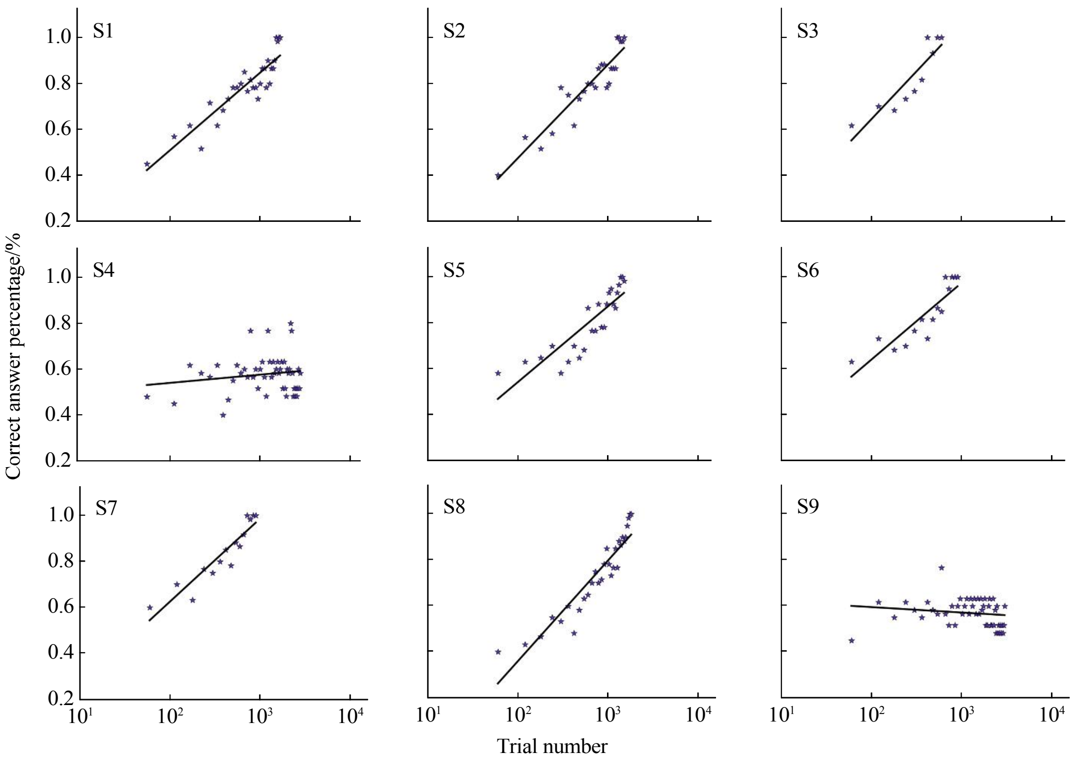

Fig. 2 Individual and group average learning curves in the training session

Data were fitted with a Log-linear function. Each dot in the figure corresponds to the averaged correct answer percentage for each 60 trials in the training session, e.g. S3 had passed 600 trials, so there are 10 dots in the figure.

answer percentage improved significantly in 7 of 9 subjects over training process. Averaged across observers, the correct answer percentage increased from 51% to 91% (t = 6.615, P = 0.0002). The average slope of the training curve was 13% per log unit of trial number. Different trial numbers had been applied to subjects according to their speed of perceptual learning. Three subjects had their performance improved to the required accuracy in the first training session (S3, S6, S7). Among them, S3 was the fastest learner, achieved 90% accuracy in the second subsection (600 trials). S6 and S7 passed three subsections (900 trials). For S1, S2, S5, S8, their accuracy reached 90% in the second round training session. For S2 and S5, it took 1 500 trials, for S1 and S8, it took 1800 trials. Two subjects did not reach the required accuracy even after three training sessions (S4, S9). Their detection of MID direction at the end of the third training session was still at chance level (50%).

2.2 Psychometric functions

The results of the pre-training and post-training sessions were calculated by the percentage of toward answers as a function of coherence level, as plotted in Figure 3. Theoretically, at the coherence level of 0, all the dots are moving in randomly chosen direction (toward or away from the subject), so the percentage of toward answer should be around the chance level (0.5). When the coherence level is 1, all the dots move toward the subjects, so the toward answer percentage should be 1, similarly, at the coherence level of −1, the toward answer percentage should be 0 since all the dots are moving away from the subject.

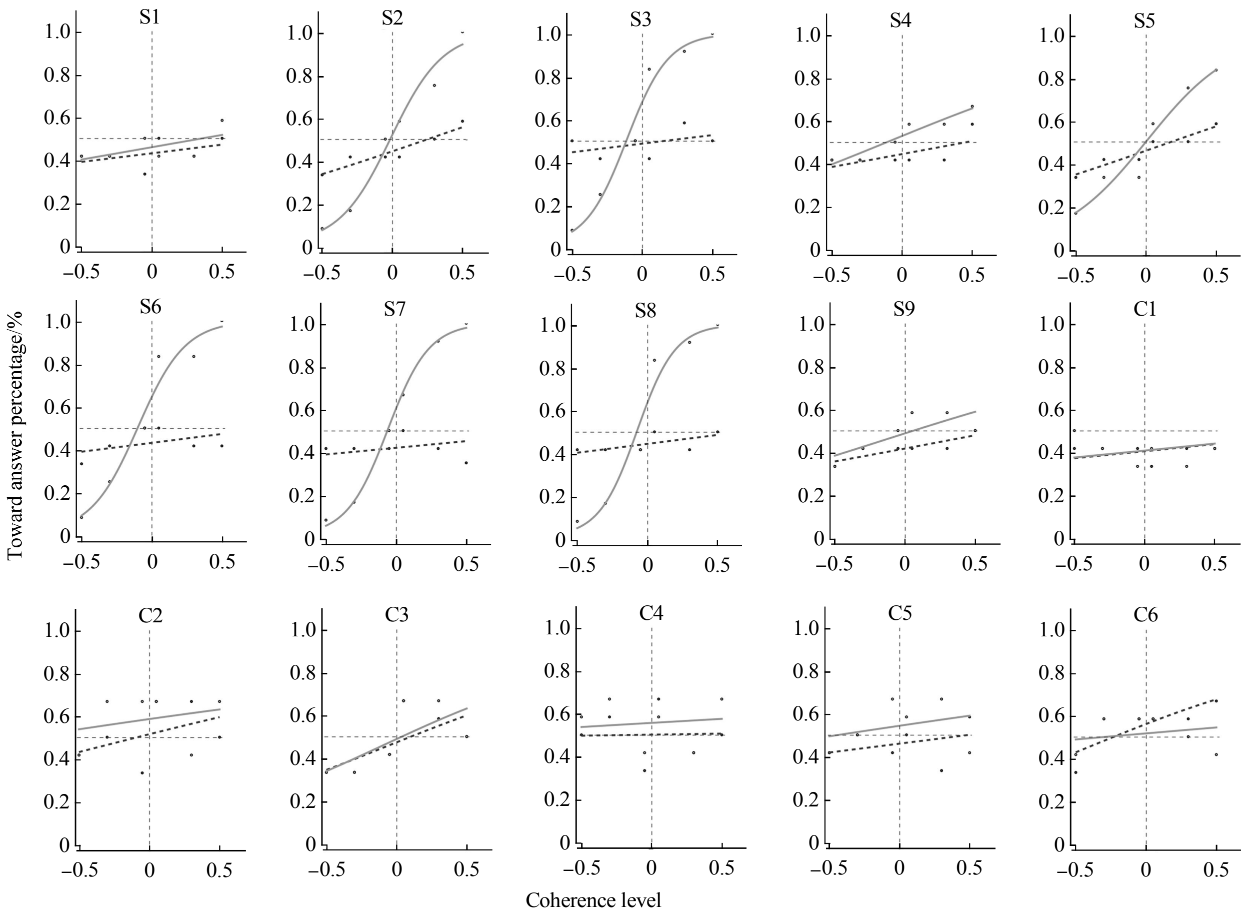

Fig. 3 Fitted psychometric functions for the performance of pre-training session and post-training session

S1−S9 demonstrate the subjects' performances in the main experiment, C1−C6 demonstrate the subjects' performances in the control experiment. ●·····● : Pre-training; ●—●: Post-training.

In the pre-training session, the subjects in the experiment group could hardly perceive MID direction (S1 –S9 in Figure 3). As shown by the dot line in Figure 3, the toward answer percentage fluctuated at the chance level (0.5), even when the dot coherence was 0.5. The subjects were asked about the difficulty of the experiment at the end of the session (simple, normal, difficult), 100% subjects reported that the task was difficult, and most of their answers were given by guessing. The performances of the nine subjects in the post-training session were draw with solid line in Figure 3. The seven subjects that had reached the required threshold in the training session were S1, S2, S3, S5, S6, S7, S8, but the training effect was not completely transferred to the post-training task, since S1 could hardly detect the MID motion in the post-training session, the performance was similar to the pre-training session. For the other six subjects, their performances were significantly improved in the post-training session. For S4 and S9, who did not reach the threshold in the training session, their discrimination of MID direction in the post-training session was not significantly changed. The improvement of MID perception due to perceptual training was shown in Table 1, the performance improvement of motion direction detection for each subject in the experiment group was calculated according to the dot coherence level (the accuracy of toward and away direction detection was averaged). It reveals that the performance of six subjects has been largely improved (S2, S3, S5, S6, S7, S8).

Table 1 The performance improvement of MID perception for each subject after the training session, CL stands for dot coherence level

CL	S1	S2	S3	S4	S5	S6	S7	S8	S9
0.5	4.17%	33.33%	45.83%	4.17%	20.83%	37.50%	45.83%	37.50%	0.00%
0.3	0.00%	25.00%	25.00%	4.17%	16.67%	29.17%	33.33%	29.17%	8.33%
0.05	–12.50%	4.17%	20.83%	4.17%	8.33%	16.67%	8.33%	12.50%	4.17%

We averaged the data across the subjects in in the experiment group to compare the performance of pre-training and post-training performances. Paired t-test was applied for statistics analysis. The averaged performance between pre- and post-training was compared, as a function of the coherence level. The statistics indicates that subjects' capability of MID direction discrimination was significantly improved by perceptual training (t = 2.519, P = 0.015).

2.3 Retention

Three subjects (S3, S6, S8) were retested using the same protocols 6 months after the first post-training session. The data is demonstrated in Figure 4. All the three subjects remained precise direction discrimination over a long period. According to paired t-test, the visual performance did not change significantly comparing to the post-training six months before (t = 0.182, P = 0.859).

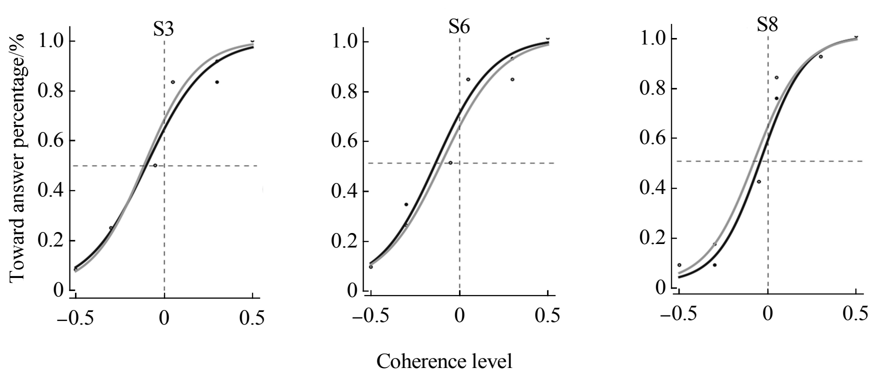

Fig. 4 Fitted psychometric functions for the performance of post-training sessions in 6 months

●—● : Post-training after six months; ●—● : Post-training.

2.4 Control group

The results of the control group is shown in Figure 3 C1 –C6, this group only went through the pre-training session and the post-training session, their performances in the post-training session were not statistically distinct from the pre-training session (t = 0.813, P=0.485). The comparison between experiment group and control group indicated that the MID perception performance improvement was due to the training session, the repetition of the test did not affect MID direction perception.

3 Discussion and conclusion

The possibility to improve static depth discrimination through perceptual training, both for normal human adults and patients with strabismus and amblyopia has already been demonstrated in previous studies[9, 14, 30]. In this study, we show, firstly, that MID detection in DRDS for inexperienced normal vision observers is a difficult task and, secondly, that the subjects' capacity to perceive MID could be efficiently improved through training and that this training can have a long lasting influence.

The results of the control group allowed us to assess the influence of the feedback given during practice compared to the sole repetition of trials. In view of the large number of trials taken, it is actually theoretically possible that the changes observed in the experiment group were only due to repeated practice and that the feedback given in the training phase had limited influence. However, in the current study, the post-training test performance in the control group did not significantly differed from the pre-training test, while the performances was apparently improved after the training in the experiment group. This eliminated the influence of repetition on MID perception improvement.

In the training session of the study, all the dots were signal dots, so the coherence level was 1. The MID direction discrimination was improved at lower coherence level (0.05, 0.30, 0.50) through the training at high coherence level (1), this result confirmed the fact that the transfer of training effect was efficient from simple task to more difficult and specific tasks[14]. It is reported in previous studies that the improvement through training was due to the reduced noise in the neurons in the disparity processing or the learning mechanisms that beyond the early disparity processing stage where high level cognitive process was involved[31–32]. However, with more experience and knowledge of the stimuli, the improvement of attentional learning might be an additional reason that leaded to better performance of MID perception. The effect of training with clear (low noise or without noise) and noisy displays has been investigated in previous studies. It is reported by Dosher and Lu[33] that the training on clear display had unique advantage, which could not only improve the enhancement of the stimulus, but also facilitate the performance in noisy display, since the noise filtering was also improved by exposure to the stimulus in clear display. The training session in the current study was carried out on a clear display, and the results confirmed the previous conclusion that the performance was improved in noisy display. Besides, we observed that the performance improvement decreased when high level of noise was applied on the display (different coherence level demonstrated in Table 1).

The observers' capability of MID perception in DRDS is not always deficit in previous studies[34]. In the experiment of Chang, the percentage of correct answers for the motion direction detection of DRDS was higher than the data obtained in the current study. This difference was due to the manipulation of the DRDS stimuli. In Chang's study, all the signal dots were located in the same depth of the volume, when all the dots moved in depth, subjects had the impression of a moving plane in the volume. The edge of the plane might provide monocular cues for the motion detection, which facilitated the MID perception. In the current study, we located the signal dots in different depth position in the volume, so the impact induced by the relative disparity was removed. Nevertheless, such stimuli would increase the difficulty of the visual task and leaded to relatively low performances.

All the observers in this study had good stereo acuity according to the Titmus Stereo Test (stereaocuity less or equal to 80" [17, 35]). Their poor discrimination ability for MID direction before training indicated that static depth perception and dynamic stereo motion perception was not related. This confirmed the importance of 3D motion evaluation for clinical diagnosis by doing a systematic comparison of static and dynamic cues for depth perception[34]. Three out of our nine subjects did not improve their performances through training. This was not related to any vergence issues since all subjects had good eye vergence function (far distance: more than 10 prism diopter, near distance: more than 30 prism diopter). One possible explanation could be their ability to fixate on the central cross. If subjects could not focus well on the central cross, the reduction of relative disparity would affect MID perception. The stimulus design might have also played a role. Nefs reported that subjects' sensitivity for motion detection was individually different for the cues of changing disparity (CD) and interocular velocity differences (IOVD)[10]. In our experiment, we used full cues which combine the cue of CD and IOVD. CD and IOVD are turned to different stimuli features, since IOVD mechanism might be sensitive for the speed processing, and we did not change speed in the whole experiment, the subjects who favored IOVD for MID perception might not get improved through the training session. DRDS is a common stimulus for the investigation of MID perception, due to its elimination of the monocular cue. Comparing with static RDS, it is more difficult for the subjects to perceive the information since the target is always moving in depth, which requires more concentration of the subjects. Besides, the experience of the participants plays an important role in such visual task. The method of perceptual training proposed by the current study provides a way to improve subjects' performance in related visual tasks and thus enlarge the sample size and improve the statistical validity of the experiment.

In summary, we have shown that inexperienced normal vision observers have limited perception for stereo motion discrimination in DRDS stimuli. However, MID perception could be trained to some extent to achieve better performances. This also highlights that the subjects' experience is a critical parameter for the sample selection of such experiments. In previous experiments, where professional observers have been commonly used, the small size of the sample has limited the statistical significance of the study and the facilitation of experimental duplication. The current study proposes an efficient method to rapidly train inexperienced subjects, which could be applied in the investigations of visual perception and cognition studies.

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视知觉学习对于识别动态随机点立体图深度运动方向的作用*

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摘要　立体视觉不仅指对静态深度信息的感知，也包括对物体在三维空间中的运动方向的判断．本研究记录了人眼对于动态随机点图运动方向的辨别能力以及视觉训练在提高对动态信息分辨能力的作用．实验结果表明，对于没有任何相关经验的视力正常的受试者，很难分辨出动态随机点的深度运动方向，而视觉训练可以大大提高人眼对物体深度运动方向判断的敏感度．此外，这种视觉训练所达到的效果具有较长时间的持续性(至少 6 个月)．这种通过视觉训练提高受试者对立体运动信息敏感度的方式，为立体视觉相关的实验和研究提供了新的视角．

关键词　动态随机点立体图，深度运动，立体视觉, 视知觉学习

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