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Specificity of Learning Curvature, Orientation, and Vernier Discriminations

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Training significantly improves the performance of many perceptual tasks. Different visual tasks share some "front-end" neuronal mechanisms but rely (partly) on different neuronal mechanisms for further analysis. Perceptual learning might occur on the early common levels of visual information processing or else on the later, more specialized levels. Eighteen observers trained in three visual hyperacuity tasks, namely curvature, orientation, and vernier discrimination that probably share a common first stage of analysis based on detection of oriented line elements. Speed of improvement did not differ significantly between these tasks. There was no transfer of improvement from one task to another, indicating that the neuronal mechanisms underlying the three tasks are at least partly non-identical and that learning does not take place on the first common levels of analysis. This result constrains the possible localizations, in the human brain, of perceptual learning. The study also demonstrates that perceptual learning can be used as a tool to increase our knowledge on the sequence of operations during (visual) pattern recognition. © 1997 Elsevier Science Ltd.

Hyperacuity learning   Transfer of learning   Perceptual training   Plasticity of function

INTRODUCTION

Orientation discrimination obviously relies on the precise detection, classification, and comparison of oriented contours. However, orientation discrimination might also play a major role in discriminating a vernier offset to the right from an offset to the left (cf. Sullivan, Oatley & Sutherland, 1972). In the case of a vertical stimulus, vernier offsets to different directions can be easily discriminated from each other in a low-pass filtered image, i.e. in a kind of blurred version of the stimulus: the "blurred" stimulus will appear to be tilted to the right or to the left, depending on the direction of offset and corresponding to the regression line through the stimulus (cf. Figure 1, angle α).

Presenting the vernier at variable orientations around the vertical significantly decreases performance compared to presentation at constant orientation especially for short stimuli, indicating that loss of the absolute orientation cue is detrimental especially for the detection of vernier offsets (Watt *et al.*, 1983; Watt & Campbell, 1985).

Recent results on the detection of slight curvatures in almost straight lines also suggest that curvature detection is subserved by mechanisms detecting orientation differences (angle α in Fig. 1) rather than displacements ("*d*" in Fig. 1), at least for slight curvatures (Kramer & Fahle, 1996). Hence orientation information plays an important role in all three tasks, and it is well known that the receptive fields of cortical neurons in the first visual area of the primate cortex, V1, have elongated receptive fields that are orientation specific (Hubel & Wiesel, 1959). Hence, the three tasks investigated in this study probably share a first level of analysis that is based on the detection of oriented line elements.

The last few years have brought a much better understanding of the scope of perceptual learning and of the underlying neuronal mechanisms. It appears that even a short training in a perceptual task such as a hyperacuity discrimination might significantly improve performance for this task (Poggio *et al.*, 1992; Ahissar & Hochstein, 1993; Fahle *et al.*, 1995). In spite of large inter-individual variability between observers (Fahle & Edelman, 1993; Kumar & Glaser, 1993; Fahle & Henke-Fahle, 1996) it has been possible to show that the improvement through training (here defined as "learning") in several perceptual tasks was specific for stimulus orientation (Poggio *et al.*, 1992; Fahle *et al.*, 1995), for visual field position (Fahle *et al.*, 1995), for the specific task that had been trained (Fahle & Morgan, 1996) and partly for the eye used during training (Karni & Sagi, 1991; Poggio *et al.*, 1992). The high specificity of perceptual learning, led me to speculate whether experiments using visual training can give information regarding the structure of visual information processing in the human brain.

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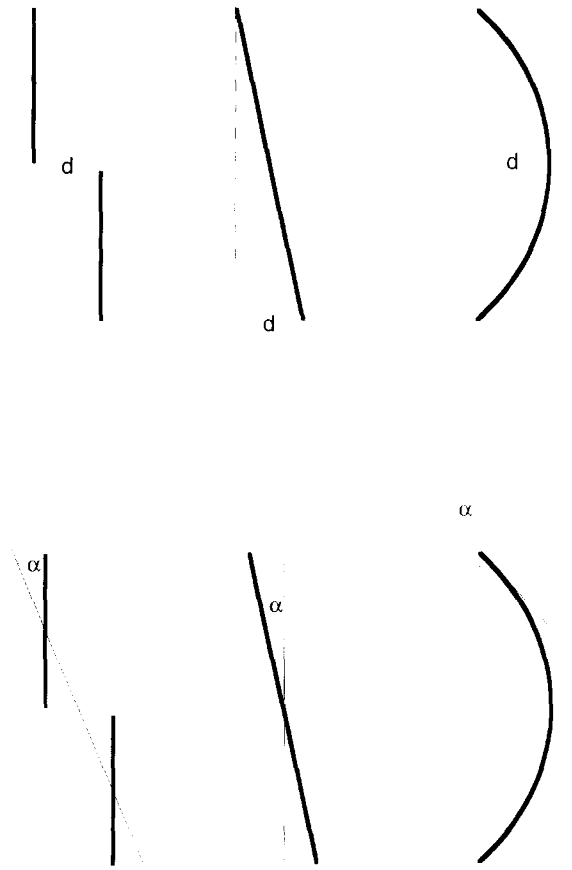


FIGURE 1. Schematics of the stimuli. The horizontal displacement is "*d*", the angle with the vertical is for all stimuli. Note that identical displacements d for the three types of stimuli result in quite different angles *a* between the (implicit) orientation of the stimulus and the vertical.

The present study intends to answer the question on which level perceptual learning of hyperacuity occurs: on an early level of orientation specific filters (Karni & Sagi, 1991; Saarinen & Levi, 1995) that is common to all three tasks, or on a subsequent, more specialised level of analysis? Initial thresholds as well as speeds of learning for orientation discrimination were compared with those of two other hyperacuity tasks, curvature detection and vernier acuity in 18 observers. The amount of transfer of improvement between the three tasks was evaluated to test whether or not perceptual learning takes place on a common level of analysis. The results indicate that learning does not predominantly occur on the same (early) level common to all three tasks.

MATERIALS AND METHODS

Stimuli were synthesized from single dots on an analogue monitor (Tektronix 608, P31) whose x and y inputs were controlled by a 32-bit computer via high accuracy (16 bit) digital-to-analogue converters. The stimuli were 20 arc min high and 2 arc min wide at the observation distance of 2 m, and consisted of 40 dots displayed at a distance of 0.3 mm from each other, corresponding to the dot size of the monitor. Relative spatial accuracy of positioning was around 0.008 mm, and luminance of the dots was approximately 150 cd/m^2 on a surround of 5 cd/m^2. Stimuli were presented for 150 msec, and observers had to respond by pressing one of two push-buttons within 2 sec after each presentation.

Three kinds of stimuli were presented, all oriented (almost) vertically. The *vernier* consisted of two vertical lines, each 9 arc min long and 2 arc min wide, with a vertical gap size between the segments of 1 arc min. Observers indicated the direction of horizontal offset (*d*). The stimulus to measure sensitivity for *curvature* consisted of an almost straight vertical line 20 arc min long and 2 arc min wide, bent slightly to the right or to the left. Observers indicated the direction of bend. The maximal deviation from straightness, *d*, of the line; i.e., the maximal linear deviation from straightness in the stimulus (cf. Figure 1) was chosen to correspond to the size of the vernier offset. We used a straight line, 20 arc min long and 2 arc min wide to test *orientation* detection. The line was rotated either clockwise or counter-clockwise from vertical in the plane of the monitor, and observers indicated the direction of rotation. The horizontal displacement *d* of the line-ends (cf. Figure 1) corresponded to the size of the vernier offset and the deviation from straightness of the curved stimulus, and was indicated in the graphs for each observer. Each data point was based on exactly 80 presentations. About 1% of the data were lost due to computer crashes or errors of the subjects. Missing data led to larger distances along the x-axis between the data points in the graphs, or to a rightward shift of the data curve's start.

The 18 observers volunteered to participate in the experiments. They were students of Tübingen University, in their early twenties with normal or corrected-to-normal visual acuity, no prior experience with psychophysical tests and were paid for participation. To counterbalance possible learning effects in the sequence of the tests, the observers formed six groups with three observers each. Each group trained wirh the three stimuli in a different order such that each possible sequence of testing was realised; the sequences were completely counterbalanced. Before the experiment proper, we performed one threshold estimation for the first kind of stimulus to be presented to the observer. The threshold estimate relied on a practice run with 80 presentations during which either offset, bend, or rotation was controlled by an adaptive staircase procedure (PEST; Taylor & Creelman, 1967). For better temporal resolution of the improvement through practice, all trial blocks during the experiment consisted of 40 presentations, each with fixed displacement, *d*. The size of displacement used during the experiment proper was based on the threshold estimate for the individual observer during the practice run, as well as on average performance of previous observers. Displacement was kept constant for each individual observer throughout the whole experiment but varied between observers. Percentages of correct responses are plotted in the graphs.

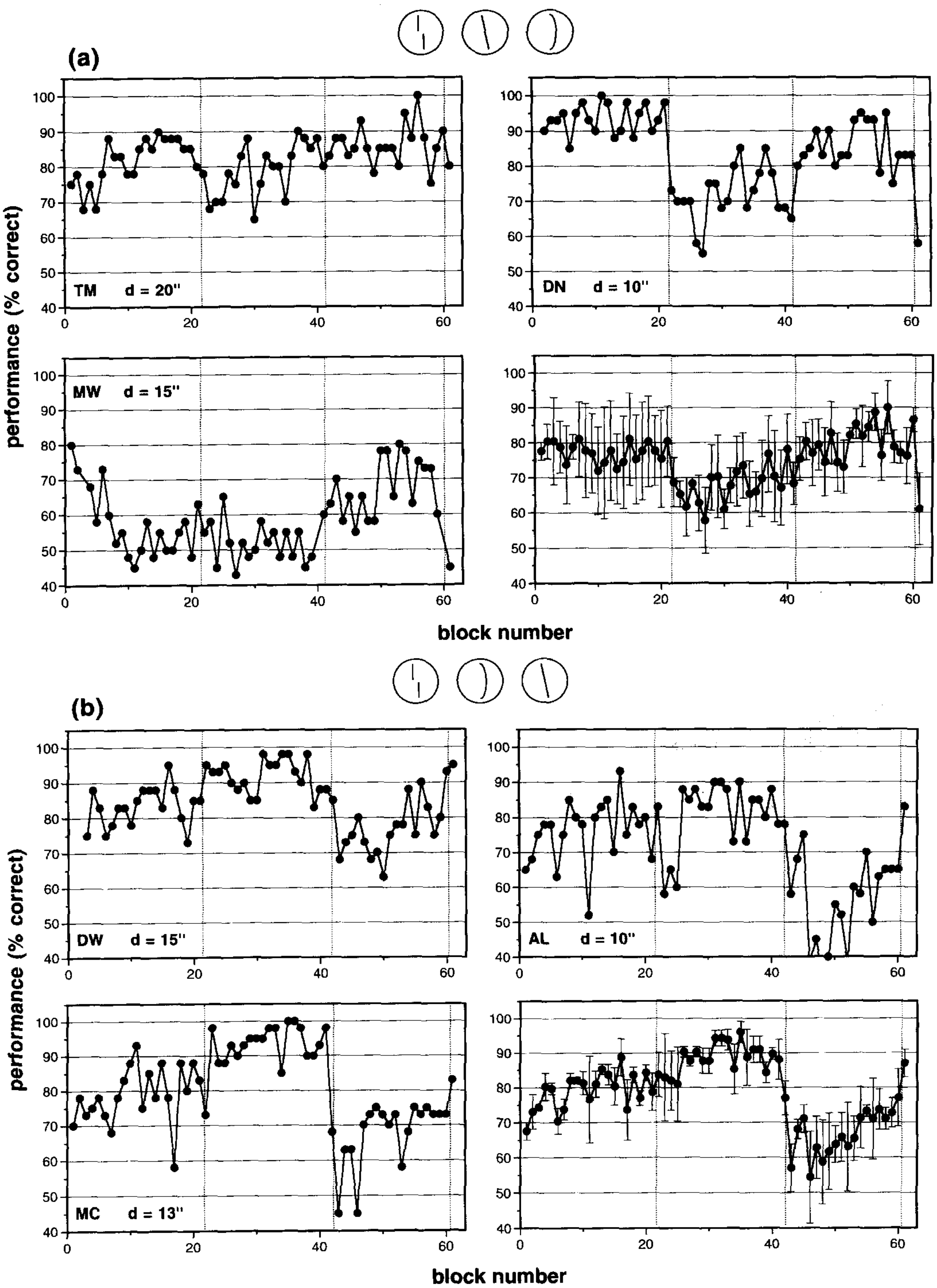


FIGURE 2. (a) Percentage of correct responses for the group of observers starting with the vernier discrimination task, followed by an orientation and a curvature discrimination task. Upper row and left (curves without error bars): Results of individual observers. Standard errors of the individual data points are typically around 6, and can be calculated according to $\sqrt{p(1-p)/n}$ 100 with $n = 40$ and p = per cent correct. Lower right: means and standard errors of the means of the three observers in this group. These standard errors are meant to given an impression of the variability of the results—they were not used for statistical evaluation. Total training time was 3 hr, distributed over 3 days with 20 blocks of 40 presentations each. Dashed vertical lines indicate transitions between tasks. The last point of each graph indicates results for the first condition (retest). The size of offset d varied between observers but was constant for each observer throughout the experiment and is indicated in each graph. (b) Percentages correct as in (a), but for the group starting with the vernier discrimination task, followed by the curvature and orientation discrimination tasks.

Testing of the first stimulus type lasted for around 1 hr and continued, usually on the next day, or the day after, with the second stimulus type, and on yet another day with the third kind of stimulus. The first block of 40 responses in the second and third sessions tested the first resp. second condition. That is, the change of conditions did not occur at the same point of the curves as the transition between subsequent sessions, in order to

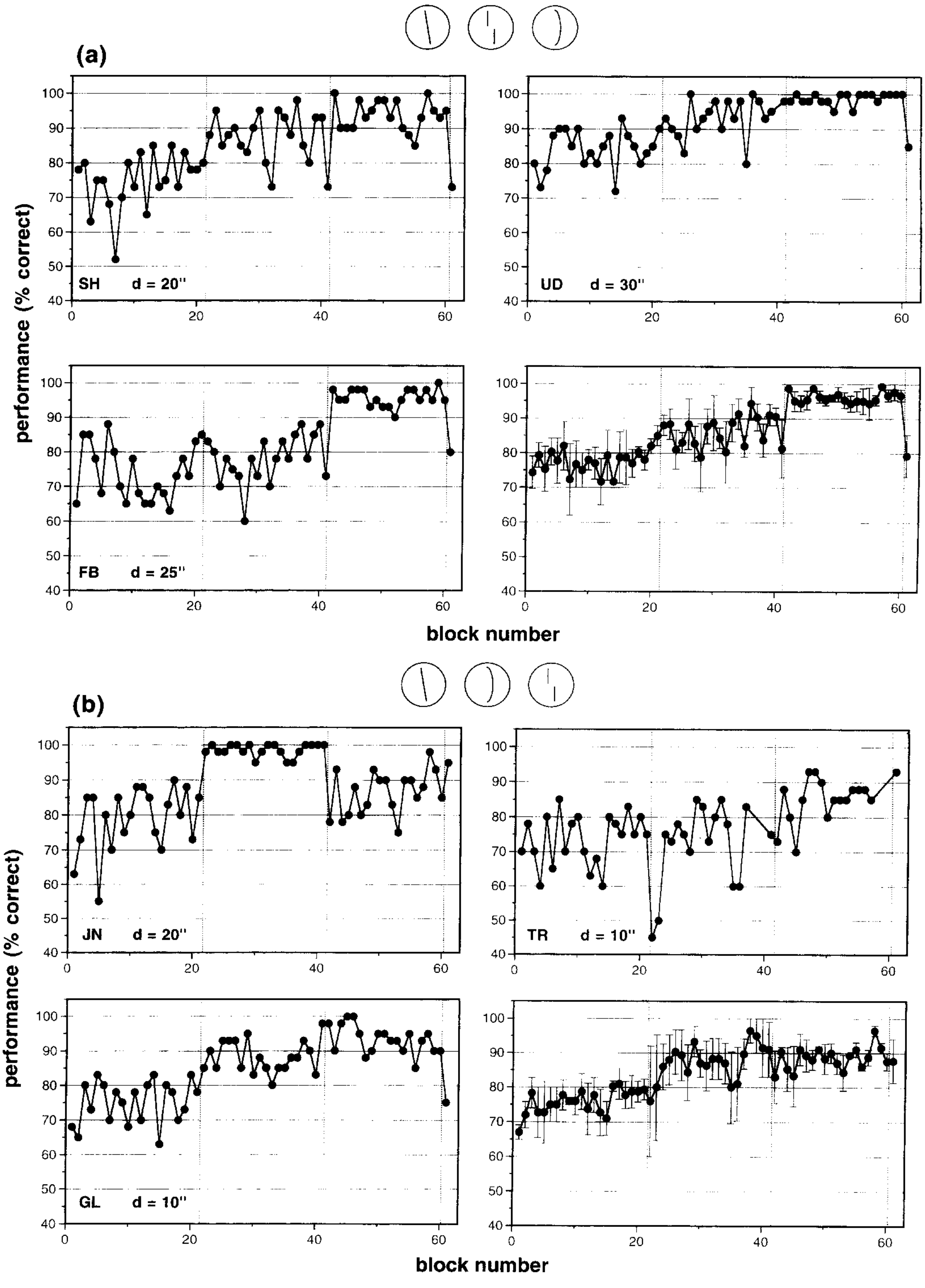


FIGURE 3. (a) Percentages as in Fig. 2, but for the group starting with orientation discrimination, followed by vernier and curvature discrimination. (b) Percentages as in (a) but for the group starting with orientation discrimination, followed by curvature and vernier discrimination.

separate the effects of rest and/or forgetting between sessions from the effects of stimulus type.

Observers received auditory error feedback after each incorrect response, and each observer contributed approximately 2500 responses, leading to more than 40,000 responses for all observers of this study. Means for the three observers of each group were calculated on a Macintosh computer using Statview and JMP software to demonstrate the stepwise reduction of noise through averaging. The group means were subsequently averaged using the same software. To obtain quantitative statistical measures, we calculated linear regressions through the results of all individual observers and tested the hypothesis that the slopes of these regression functions were significantly above zero. Moreover, an analysis of variance (ANOVA) served to evaluate the effect of

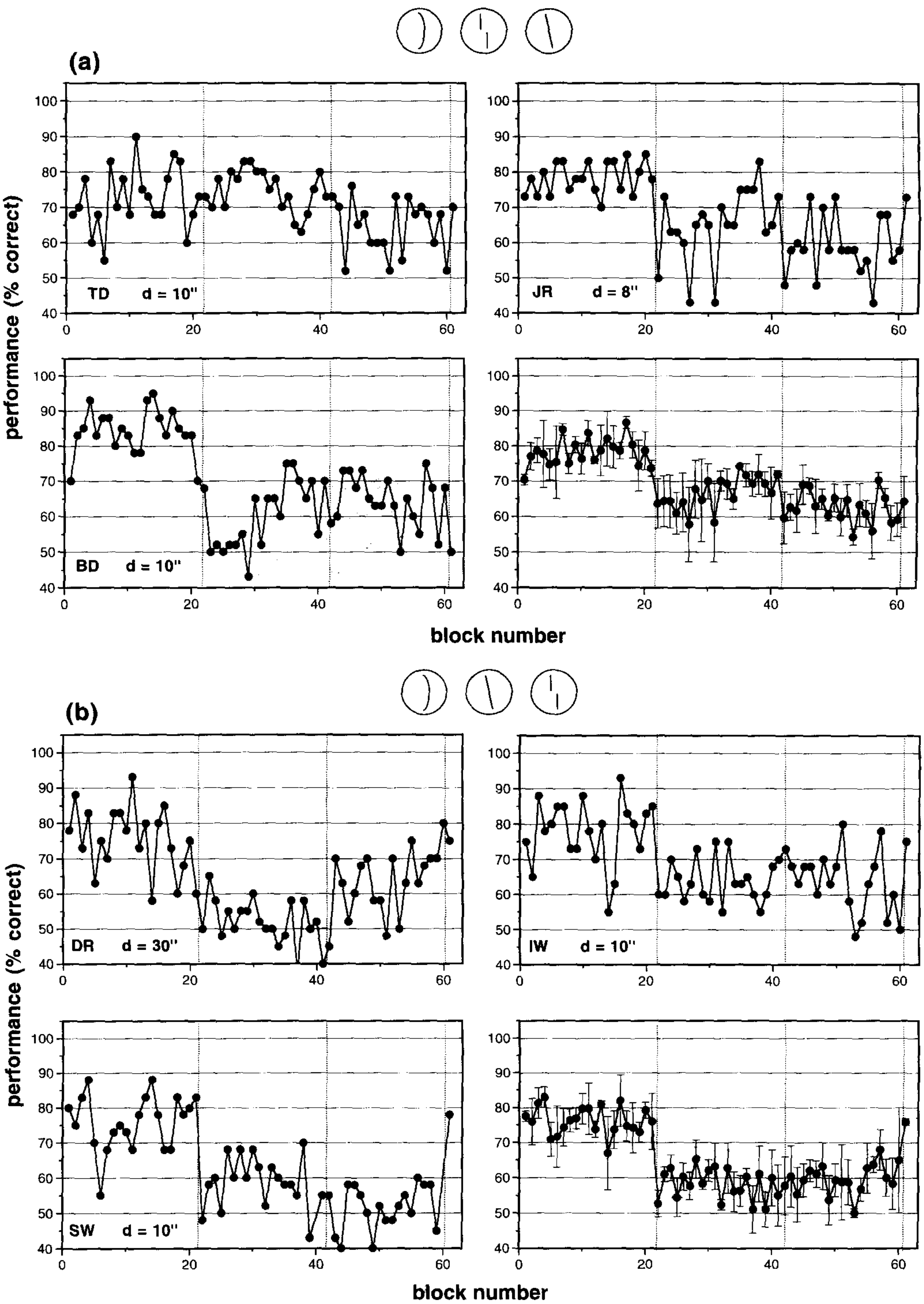


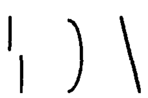
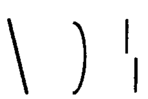
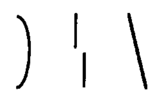
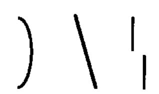
FIGURE 4. (a) Percentages as in Fig. 2, but for the group starting with curvature discrimination, followed by vernier and orientation discrimination. (b) Percentages as in (a), but for the group starting with curvature discrimination, followed by orientation and vernier discrimination.

training on performance, using the same software. These programs calculate r^2 as the sum of error squares (variation) explained by the model divided by the total sum of error squares in the data.

RESULTS

Since the variation of results between these unselected and untrained observers was high (cf. Fahle & Edelman, 1993; Kumar & Glaser, 1993; Fahle & Henke-Fahle, 1996), it was necessary not only to present means but the overall results of all observers. Therefore, Figs 2–4 show the results of individual observers as well as the means for each of the six groups of observers. As in previous studies on perceptual learning, inter-observer variance in these groups of observers was much higher than is usual in psychophysical studies with experienced observers.

TABLE 1. Regression lines through the individual results of all observers ("Initials") from Figs 2–4

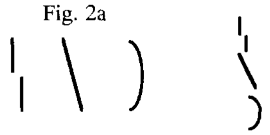
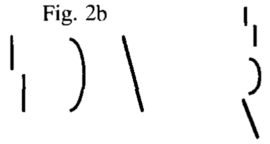
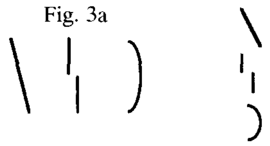
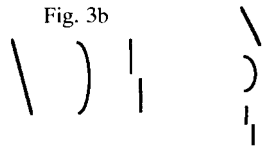
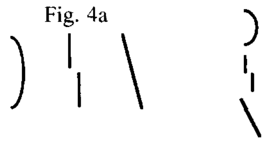
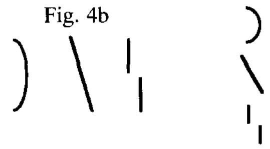
	Initials	Intercept	Slope	SE slope	r^2	P
Fig. 2a	TM	72.889	0.839	0.175	0.561	0.0001
		70.544	0.825	0.26	0.372	0.006
		85.438	0.065	0.275	0.003	0.816
	DN	92.405	0.068	0.178	0.009	0.706
		67.246	0.47	0.31	0.119	0.148
		85.216	0.065	0.29	0.003	0.825
	MW	70.089	−1.197	0.292	0.497	0.0007
		54.464	−0.283	0.25	0.074	0.275
		61.686	0.612	0.354	0.157	0.1
Fig. 2b	DW	80.025	0.268	0.261	0.062	0.32
		92.614	−0.051	0.204	0.004	0.806
		71.98	0.476	0.311	0.127	0.146
	AL	69.9	0.6	0.335	0.151	0.09
		73.281	0.751	0.398	0.173	0.0761
		55.985	0.04	0.616	<0.001	0.949
	MC	74.005	0.452	0.315	0.103	0.169
		88.246	0.439	0.257	0.147	0.106
		58.144	0.973	0.368	0.31	0.018
Fig. 3a	SH	69.863	0.451	0.307	0.107	0.1585
		87.456	0.081	0.274	0.005	0.77
		94.34	−0.065	0.203	0.006	0.753
	UD	82.442	0.129	0.223	0.018	0.569
		90.379	0.282	0.251	0.073	0.278
		97.954	0.087	0.075	0.077	0.264
	FB	76.337	−0.28	0.307	0.044	0.375
		72.298	0.591	0.266	0.225	0.04
		95.49	0.036	0.12	0.006	0.768
Fig. 3b	JN	72.747	0.553	0.344	0.125	0.126
		98.614	−0.014	0.078	0.002	0.859
		81.163	0.55	0.267	0.209	0.056
	TR	70.226	0.302	0.292	0.056	0.315
		63.8	0.972	0.635	0.143	0.148
		80.3	0.524	0.329	0.154	0.133
	GL	72.958	0.185	0.245	0.031	0.461
		89.09	−0.135	0.18	0.032	0.428
		96.804	−0.348	0.172	0.203	0.061
Fig. 4a	TD	69.3	0.286	0.351	0.035	0.427
		77.614	−0.277	0.246	0.069	0.276
		65.301	−0.026	0.348	<0.001	0.942
	JR	75.774	0.241	0.179	0.092	0.195
		56.456	0.823	0.402	0.198	0.056
		58.954	−0.001	0.403	<0.001	0.998
	BD	82.363	0.223	0.227	0.051	0.34
		50.825	0.912	0.342	0.295	0.0163
		67.542	−0.361	0.334	0.068	0.295
Fig. 4b	DR	80.284	−0.413	0.35	0.072	0.254
		56.07	−0.36	0.246	0.112	0.162
		56.033	0.657	0.38	0.158	0.103
	IW	77.526	−0.012	0.371	<0.001	0.9645
		64.018	−0.054	0.266	0.002	0.841
		69.15	−0.495	0.384	0.094	0.215
	SW	74.258	0.128	0.319	0.009	0.693
		59.255	−0.027	0.35	<0.001	0.939
		48.752	0.278	0.289	0.054	0.32

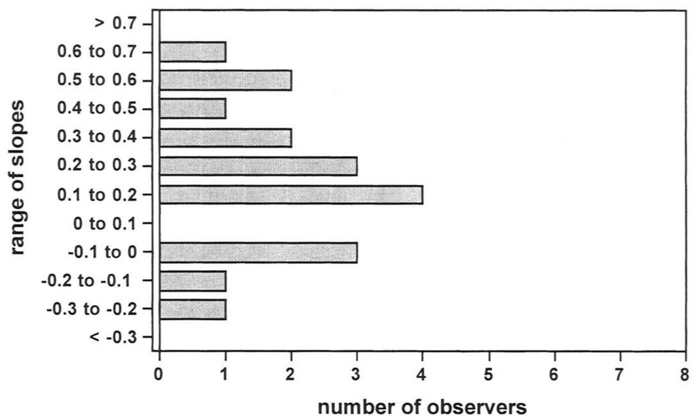
Intercepts, slopes, standard errors of the slopes, regression coefficient (r^2) and error level (P) are listed for the first condition (upper row of each observer's data), second condition (second row), and third condition (third row). The speed of learning was comparable to that found in other hyperacuity experiments (e.g. Fahle *et al.*, 1995). SE, standard error.

Both baselines (intercepts) and the speed of learning (slope) varied widely (Table 1).

Even in the group-means, improvement was not obvious for all groups and all stimulus types (Table 2). However, when the results were collapsed over all observers, it became clear that significant improvement occurred during all three sessions (Fig. 5), and for all three types of stimuli (Fig. 6). This is to say that

TABLE 2. Regression lines as in Table 1, but averaged over all observers of each group (1–6)

	Stimulus	Intercept	SE intercept	Slope	SE slope	*p*
Fig. 2a		78.461	7.02	−0.097	0.59	0.089
		64.085	4.9	0.337	0.33	0.131
		77.447	7.88	0.247	0.18	0.333
Fig. 2b		74.643	2.94	0.44	0.096	0.627
		84.714	5.85	0.38	0.233	0.586
		62.036	5.01	0.496	0.27	0.643
Fig. 3a		76.214	3.632	0.1	0.212	0.044
		83.378	5.604	0.318	0.148	0.078
		95.928	1.066	0.019	0.045	0.547
Fig. 3b		71.977	0.878	0.347	0.109	0.132
		83.835	10.388	0.274	0.351	0.937
		86.08	5.363	0.242	0.295	0.317
Fig. 4a		75.812	3.771	0.25	0.019	0.154
		61.632	8.155	0.486	0.382	0.291
		63.932	2.572	−0.129	0.116	0.373
Fig. 4b		77.356	1.742	−0.099	0.162	0.173
		59.781	2.309	−0.147	0.107	0.287
		57.978	5.968	0.147	0.339	0.829



Data indicate means of the individual regression lines rather than regression lines through the mean results of all observers. The lower part of the table summarizes the distribution of slopes of all 18 observers, averaged, for each observer, over all three tasks. SE, standard error.

regression lines through the *averaged* results of all observers have slopes significantly above zero for all sessions and all conditions (cf. upper insets of Figs 5 and 6). Given the large inter-individual variation, the *means* of the individual slopes through the results of all individual observers, separated for the three conditions, i.e., different perceptual tasks or subsequent sessions of testing (1–3), are more important and are indicated in the graphs. The underlying distribution of individual slopes of all observers was normal ($W = 0.97$; $P = 0.67$; Shapiro–Wilk test). The mean of the distribution of slopes was above zero for all but one conditions, at least at the 95% level of confidence (cf. insets of Figs 5 and 6; Wilcoxon signed-rank test: $P < 0.03$ with the exception

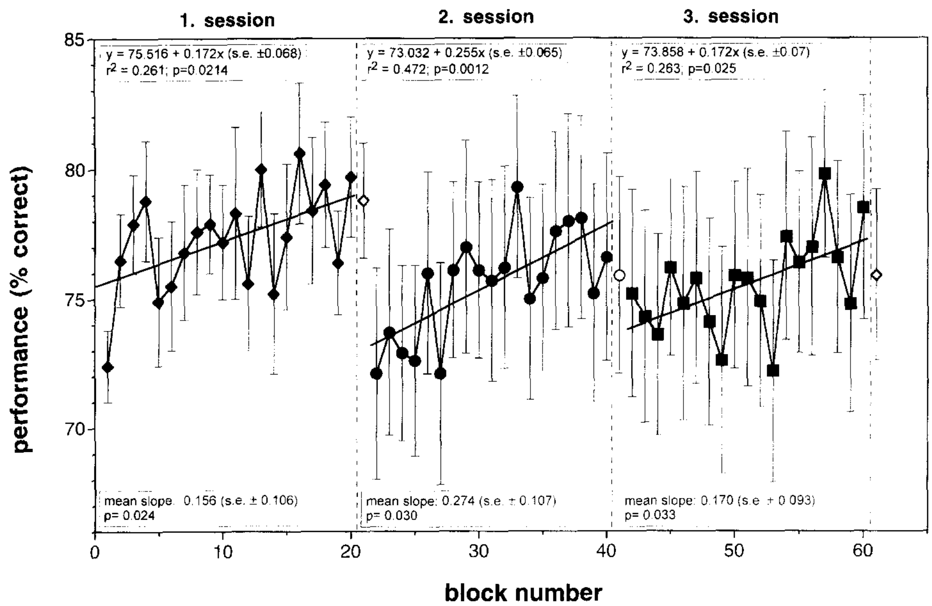


FIGURE 5. Percentages of correct responses averaged over all observers, i.e., data of Figs 2–4. Rhomboids indicate first stimulus type, circles symbolize results for the second stimulus type, and squares indicate the third stimulus type. Line symbols plot the re-test of one stimulus type at the beginning or end of the following session. Means and standard errors of the means of all 18 observers. Standard errors are given for illustrative purpose only and are based on SE = SD/$\sqrt{n}$, where $n = 18$. The insets indicate the intercepts, slopes, and standard errors of the slopes, as well as the regression coefficient (r^2) of the regression lines. The P-values indicate the error probability for the mean of the distributions of slopes to be above 0 (Wilcoxon signed-rank test).

of orientation discrimination: $P = 0.071$). The distribution of mean slopes for all three tasks is indicated in Table 2 for all observers.

A repeated measure analysis of variance (ANOVA) with factors stimulus condition and time of testing within stimulus condition (i.e., block number within each condition: 1–19), yielded no significant effect of condition ($F(1, 17) = 0.21$; $P = 0.66$; linear polynominal contrast) but a highly significant effect of time of testing ($F(1, 17) = 8.1$; $P = 0.01$). Absolute block numbers (1–60), on the other hand, failed to show a significant effect in the same type of ANOVA ($P = 0.21$). The interaction between condition and block number, too, failed to reach significance ($F(1, 17) = 0.009$; $P = 0.93$). Higher order fits yielded lower levels of significance in all cases.

The last block of the first type of task was measured at the start of the second session, and the last block of the second type of task was measured at the start of the third session. Both results are indicated by line symbols rather than solid symbols in Fig. 5. At the very end of the third session, the first condition was retested. Obviously, training in the second and third session did not improve performance for the task trained for during the first session: if there was a change, it was towards deterioration.

Figure 7 plots performance for the first block of the new session as a function of performance for the last block of the old session. Data points above the oblique line in Fig. 7 indicate an improvement of performance during the period of rest, while data points below the line indicate a deterioration of performance during this period. The period of rest between the first and second, respectively, between the second and third sessions does not, on average, improve performance, since almost the same number of points are above (15) and below (16) the line, and their mean distances to the line are very similar, with only a slight bias for larger distances from the line in the lower part of the figure (Fig. 7).

Baseline performances for the three types of stimuli differed significantly from each other but the speed of learning did not (repeated measures ANOVA with factors condition and time of testing within condition: $F(1, 17) = 0.28$; $P = 0.6$). Mean initial thresholds, mean performance and mean improvement of performance of all observers are listed in Table 3. Please note that a given threshold for displacement d as listed in Table 3 corresponds to quite different orientation cues for the different tasks as illustrated in Fig. 1. The orientation cue at constant displacement d is smallest for the orientation discrimination task, larger by a factor of 2 for the vernier displacement (if the regression line is drawn through the middle of the segments), and larger by a factor of 4 for the curved stimulus (if a tangent would be drawn as indicated in Fig. 1). The real differences between thresholds are expected to be less pronounced since for curvature detection, a secant rather than a tangent to the stimulus is probably used (cf. Kramer & Fahle, 1996).

The amount of improvement during training depended, on average, on the initial level of performance (Fig. 8): the higher the initial percentage of correct responses, the smaller was (on average) the improvement through learning.

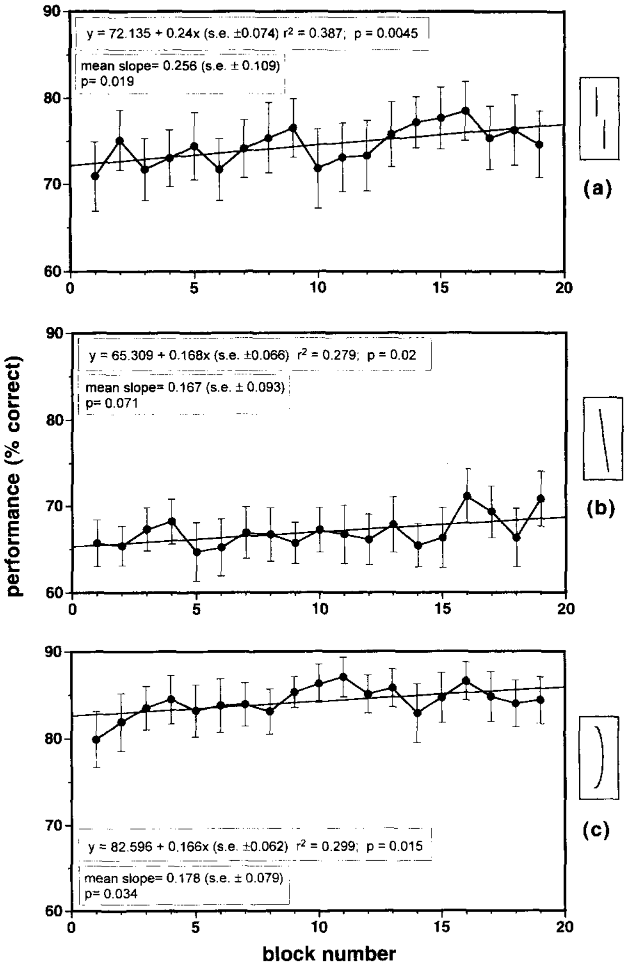


FIGURE 6. Percentages of correct responses of all observers, separated according to the type of test, irrespective of when it was performed during the experiment. Results for (a) vernier-, (b) orientation-, and (c) curvature-discrimination. Insets as in Fig. 5. The p-values again indicate the error probabilities for mean slopes of all observers to be above 0.

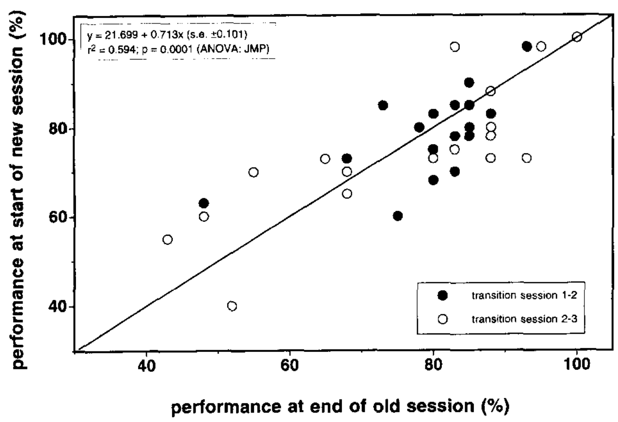


FIGURE 7. Influence on performance of the period of rest between the sessions. The abscissa indicates the level of performance at the end of the old session, i.e., the first session (for solid symbols) and the second session (for line symbols). The ordinate indicates the starting level, after the period of rest, for the same stimulus type as at the end of the old session. The oblique line indicates equality of performance. Data points above the line symbolize improvement of performance during the period of rest, while points below the line indicate deterioration of performance during the period of rest. The inset gives the equation for a regression line through all the data. Results of all 18 observers.

DISCUSSION

In the present context, the term "learning" denotes an improvement of performance as a result of training. In line with earlier reports, inter-observer variance in the present group of inexperienced psychophysical observers was high, both regarding the initial level of performance and the speed of learning. When the degree of improvement was plotted as a function of initial threshold (Fig. 8), the results could be approximated by a regression line with a slope of -0.21 (± 0.082 SE; one factor ANOVA with factor starting level ($F(1, 63) = 6.2$; $P = 0.015$). This is to say that improvement of observers depends on their initial performance: as to be expected, the better the initial performance, the less pronounced is the improvement. This is true even if the ordinate is transformed logarithmically, but the effect is relatively weak and requires large data sets to become significant (cf. Fahle & Henke-Fahle, 1996).

While the improvement through training in more complex figure–ground discriminations seems not to take place during the task but during the period of rest and/or sleep thereafter (Karni & Sagi, 1991; Karni & Sagi, 1993), performance improves during the training but not during the period of rest (cf. Figure 7). This finding is fully compatible with earlier results on learning in hyperacuity, where we found no improvement during the period of rest, but a faster slope of improvement in the first blocks immediately after the period of rest (cf. Figure 3 in Fahle *et al.*, 1995). These results can be interpreted as indicating that two processes are superimposed during training, namely perceptual learning (improving performance), and fatigue (decreasing performance). While learning might be more prominent

TABLE 3. Mean performance, mean initial threshold, and mean improvement for all groups of observers and all stimulus types used in the experiment

	Mean initial threshold	SE ±	Mean performance	SE ±	Mean improvement	SE ±
Vernier acuity	22.10	1.55	74.6	0.50	4.8	1.5
Orientation discrimination	21.62	4.87	67.0	0.41	3.4	1.3
Curvature detection	10.69	1.5	84.3	0.39	3.3	1.2

The initial thresholds of the observers starting with different tasks differ significantly (Welch ANOVA: $F(2) = 12.96$; $P = 0.008$; Wilcoxon signed rank: $P = 0.035$). SE, standard error.

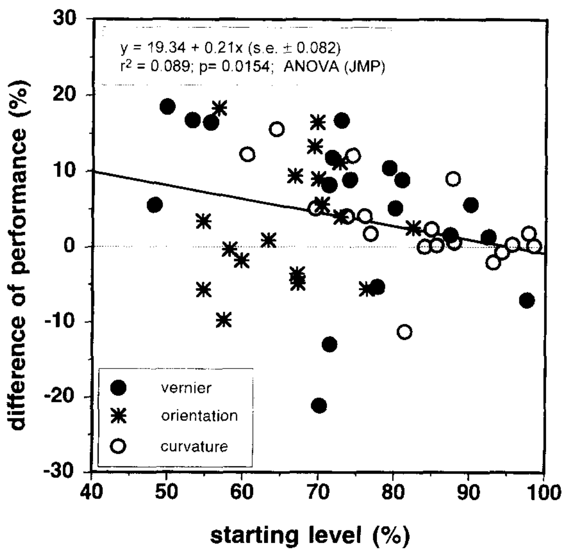


FIGURE 8. Improvement during training of individual observers for each kind of stimulus as a function of the initial level of performance. Data of all observers. Inset indicates the parameters of the regression line through the data.

during the early stage of the session, fatigue can be expected to dominate towards the end of the training sessions.

Performance differed significantly and strongly between the three hyperacuity tasks (cf. Table 3; $P < 0.008$). Averaged results of all observers for identical displacements "*d*" were best for the curvature detection task, lower for vernier discrimination and poorest (but still in the hyperacuity range) for orientation discrimination. This difference corroborates the notion that the three tasks are not subserved by a single common mechanism based on displacement detection, since if they were, performance should be similar. The differences in performance between the three tasks might be due to the fact that the same displacement d leads to larger orientation differences for vernier compared with orientation discrimination, and to orientation differences for curved stimuli that are clearly larger than for verniers. These results indicate that the relevant parameter might indeed be orientation rather than displacement.

The lack of transfer of improvement between the three tasks argues strongly for at least partly different mechanisms (even if all are based on some form of orientation analysis) rather than a single unitary one underlying the three types of visual hyperacuity. As is most evident from Fig. 5, observers improved during the training in one of the tasks but results deteriorated to baseline performance after the transition to the next task. As mentioned above, a repeated measure analysis of variance shows that the sequence of testing has no significant influence on the speed of learning, that is, it does not matter whether results are obtained during the first, second or third session. In other words, it makes no difference whether the task is learned first during the experiment or whether the observer has previously trained one or two similar hyperacuity tasks. Moreover, the transition from the first to the second task marks a significant decrease of performance in Fig. 5 (comparison between the last block of the first task and the first block of the second task: paired *t*-test: $P = 0.016$; Wilcoxon signed-rank: $P = 0.036$). And while an ANOVA demonstrates significant improvement within the 20 blocks of the individual tasks, there is no improvement throughout the whole experiment (see above, Results). From this difference between improvement during each of the three conditions and lack of significant improvement of performance over the course of the whole experiment, we can again conclude that performance does not transfer significantly from one task to the next. A third argument for a lack of transfer between the conditions is the fact that mean performance is higher for the first condition (77.43%) than for the second (75.7%) and third (75.6%) condition while transfer of improvement should lead to an *increase* of performance in the later conditions.

The fact that the improvement through training does not significantly transfer from one of these apparently similar visual hyperacuity tasks to another one has implications beyond the conclusion that these tasks rely at least partly on different neuronal mechanisms. The results imply that the improvement through learning involves those parts of the neuronal pathways that differ for the three tasks. This finding, in turn, excludes a possible explanation for perceptual learning, namely that the bandwidth of peripheral orientation filters decreases or that orientation discrimination improves due to an improved signal-to-noise ratio. Quite to the contrary, perceptual learning must rely on more sophisticated processes, such as improved recognition as postulated, e.g., by the model of Hyper Radial Basis functions (HBF; Poggio *et al.*, 1992). However, it will not be easy to suggest one isolated level of processing in the cortex where neurons are sufficiently specific to separate between orientation, vernier, and curvature detection tasks and at the same time are specific for visual field position, stimulus orientation and partly for the eye used during training. One might speculate that perceptual learning involves more than one level of (visual) information processing and that the different levels interact, including feedback (top-down) influences (cf. Herzog & Fahle, 1995).

In summary, the results show that curvature-, vernier- and orientation-discrimination yield quite different results for an identical displacement "*d*"—possibly since the same displacement d translates into quite different orientation cues in the three types of stimuli, with a much larger deviation from vertical in the curved than in the vernier and an even smaller one in the orientation target. But even if all three tasks indeed use orientation information, they must use it in different ways since there is no significant transfer of learning from one of the tasks to another. An analysis of variance does not detect differences in the results for the first vs second or third session of observers, and there is a pronounced dip in performance at the transition from one task to the next. These results imply that even if orientation discrimination subserves the three tasks investigated here, learning does not just sharpen the peripheral orientation filters but must operate on a somewhat more specific level of visual information processing.

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