# The time course of learning a visual skill

**Avi Karni* & Dov Sagi†**

Department of Neurobiology, Brain Research,
Weizmann Institute of Science, Rehovot 76100, Israel

**SEVERAL examples of experience-dependent perceptual improvement (perceptual learning) suggest that plasticity in specific neuronal loci could underlie the learning process[1-6]. For a basic visual discrimination task (using an optimal stimulus for 'automatic' preattentive texture segregation[7-10]), discrete retinal input-dependent changes within a very early stage in the stream of visual processing were indicated as the locus of a large and consistent learning effect[5]. When do these changes occur? Here we report that except for a fast, rapidly saturating improvement early in the first practice session, performance was very stable within sessions. Indeed, observers showed little or no improvement until up to 8 hours after their last training session (latent phase). But large improvements occurred thereafter. Finally, there was almost no forgetting; what was gained was retained for at least 2–3 years. We conjecture that some types of perceptual experience trigger permanent neural changes in early processing stages of the adult visual system. These may take many hours to become functional.**

Nine observers took part in these experiments. Stimulus parameters and procedure were as previously described[5] (Fig. 1). The observers' task was to decide whether a small target texture—an array of 3 diagonal line elements (bars) differing only in their orientation from a background of identical elements—was horizontal or vertical (Fig. 1*a*). Performance was measured as the mean per cent correct response for increasingly shorter time intervals between the briefly presented (10 ms) stimulus and a patterned mask (stimulus-to-mask onset asynchrony, SOA). A psychometric curve was then constructed, from which a threshold SOA for 80% correct discrimination could be derived (Fig. 1*b*, *c*). As previously reported[5], the main effect of practice is a leftward shift of the performance curves, indicating genuine increases in sensitivity, on consecutive sessions spaced 1–3 days apart. Where perception completely fails on the initial session, there is >90% correct discrimination on the following day (Fig. 1*b*). Thus the increments in performance refer to learning that was retained from one daily session to the next.

For most observers, a fast learning effect which quickly saturates could be shown (Fig. 2*a*). But this consistently occurred only during the first few practice blocks of the very first session or two in naive observers, and only with above-threshold (as defined by the psychometric curve for the session) novel stimuli. Following this short phase, performance was very stable for consecutive blocks of trials, and no amount of practice affected the psychometric curves or improved the discrimination threshold within a session (Fig. 2). Yet the psychometric curves (and perceptual thresholds) continued to improve, as shown on subsequent daily sessions (Figs 1*b*, *c* and 2*f*, *g*). Also, unlike the between-sessions improvement in discrimination thresholds[5], 'fast' learning did transfer from a trained eye to the other (although it too was specific for orientation and visual-field location).

* Present address: Laboratory of Neuropsychology, NIMH, NIH, Bethesda, Maryland 20892, USA.
† To whom correspondence should be addressed.

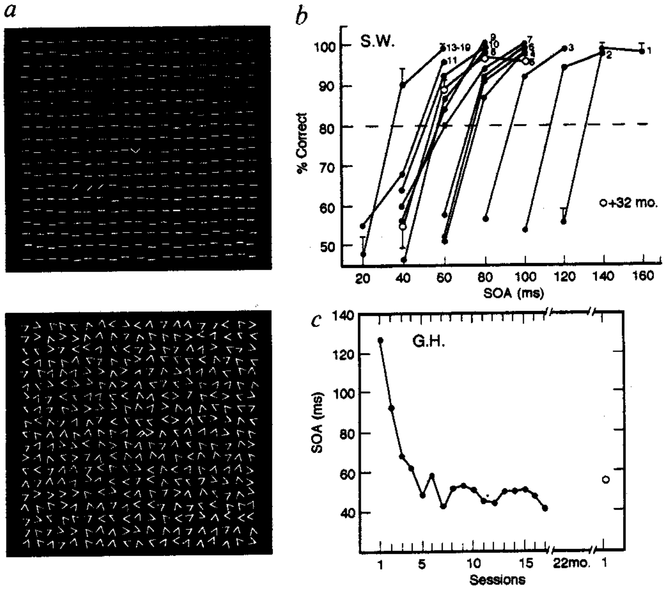



FIG. 1 Computer-generated displays. *a* Top, a test stimulus with a small target texture (3 diagonal bars) embedded within a background of horizontal elements. Display parameters were set as previously described[5]. Display size was 14° by 14° of visual angle viewed from a distance of 110 cm, with an array of 19 by 19 slightly jittered line segments (subtending 0.42° × 0.03° each, with a luminance of 35 cd $m^{-2}$ and spaced 0.70° apart). A small rotated letter (either T or L) at centre of display served as the fixation target. The target texture's position was varied randomly from trial to trial but always within a specific display quadrant and within 2.5°–5° of visual angle from centre of display. Bottom, mask pattern made of randomly oriented V-shaped micropatterns and at the centre, a compound micropattern of superimposed T and L. *b*, Psychometric curves for performance on consecutive daily sessions (spaced 1–3 days apart) for observer S.W. (●), and on a probe session 32 months later (○) (S. W. had no further psychophysical experience with visual textures in the interval, although she participated in some experiments involving random-dot stereogram depth perception). Results indicate persistent day-to-day improvements and almost no forgetting on a timescale of years. Each data point represents the mean per cent correct responses (± s.d.) from 3–5 consecutive blocks (150–250 trials) for a specific SOA. The initial performance curve is on the right; as learning occurs, the curves are displaced to the left (shorter processing times needed for task performance), indicating improved sensitivity. The far left curve represents asymptotic performance. Dashed line, 80% correct (threshold) performance. *c*, Learning curve for observer G.H. SOA required for threshold discrimination on consecutive daily sessions (●), and for a probe session 22 months later (○). Each point refers to a single session, interpolated from the respective psychometric curve. The large learning effect has not decayed in the interval (where no psychophysical testing or training was done).

METHODS. Each session consisted of 16–24 blocks of 50 trials (stimulus presentations) each. Observers were instructed to fixate a small central cross and then activate the trial sequence: blank screen interval (250–300 ms), the stimulus (10 ms), blank inter-stimulus interval (calculated from the onset of the stimulus display, SOA), the mask (100 ms), blank screen until response (no time limit). For each display the observers were required first to identify the letter at fixation point and then to decide whether the foreground texture target was vertical or horizontal. Immediate auditory feedback was given only for the fixation control task. Because stimuli were presented for only 10 ms, no eye movement could displace the stimulus on the retina, ensuring that the target texture consistently appeared in a specific retinotipic location. In the initial session for each observer, the SOA was set at 240–300 ms to establish above 95% correct texture discrimination. On all following sessions the initial SOA was set to the lowest SOA, for which 95% correct discrimination was obtained in the previous session. Then, on each session, 3–5 consecutive blocks of trials were run per SOA, which was then decreased by a step of 20 ms and another group of 3–5 blocks were run. This successive stepwise reduction in SOA was repeated until perception failed (less than 60% correct discrimination on 3–4 consecutive blocks).

If perceptual performance does not change during the training session, when does learning occur? To follow the time course of this change, the test procedure was repeated in probe sessions spaced from 20 minutes to 10 hours after the completion of the initial training session of the day. In Fig. 3, the gain in performance for 9 observers is plotted as a function of time elapsed since the termination of the practice session. No improvement was found on retesting within the first 8 hours (latent phase). Only after 8 hours did some observers show a learning effect. By the following day, however, large improvements had occurred (discrimination threshold lowered by 43 ± 11 ms (mean, s.d.). The additional practice during the latent phase did not induce larger gains than those found in our original observations with no intermediate probe sessions (38 ± 7 ms (mean, s.d.), 5 observers) (*t*-test, n.s.). This suggests that training during the latent phase was superfluous, and that learning was driven by the sensory experience acquired at the initial session.

Once discrimination thresholds have improved, there seems to

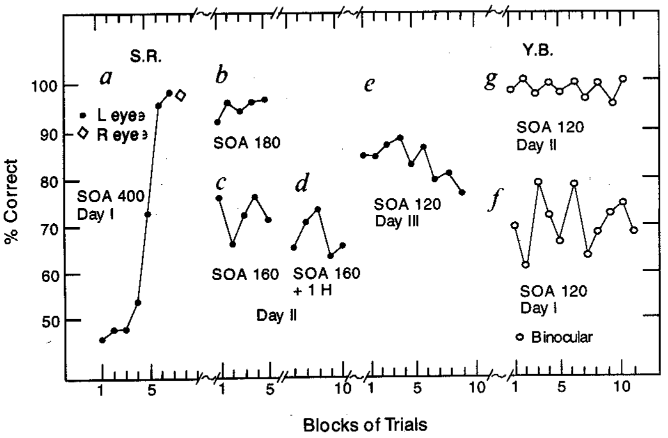
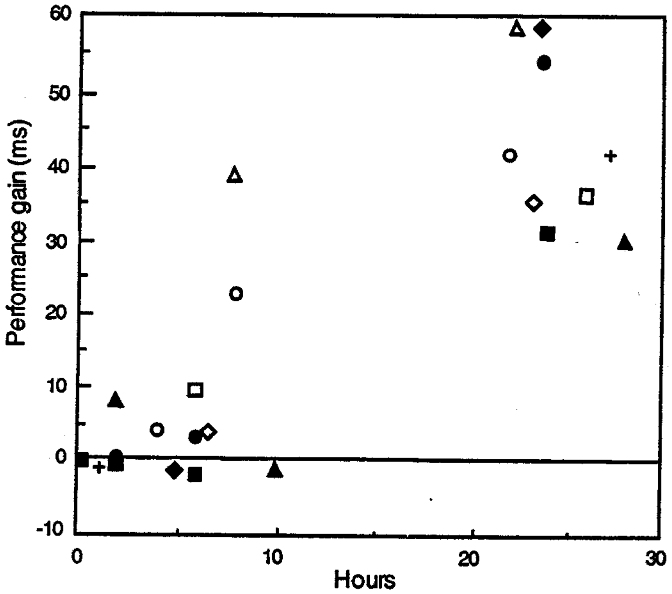



FIG. 2 Fast (within-session) and slow (between-session) learning. Performance for consecutive blocks of 50 trials each, on consecutive daily sessions. The procedure was modified in that the initial SOA was set to 260–400 ms (two to three times the previously determined mean threshold for 10 naive observers) and was not changed until performance stabilized. The completion of a single block of trials took 2–4 min, so performance changes within a timescale of a few minutes were assayed. *a*–*d*, Observer S.R. *a*, Fast improvement on the very first blocks of trials at above threshold stimulus presentation (SOA at 400 ms). ●, Left-eye viewing; ◇, right-eye viewing. Unlike the slow learning effect[5], there is complete interocular transfer of the fast learning effect. *b*, *c*, Stable performance above and below threshold (SOA at 180 and 160 ms, respectively) indicating saturation of the fast learning effect by the second session. *d*, An hour later performance is stable and there is no improvement (SOA at 160 ms). *e*, 20 h later, performance at 120 ms SOA shows a more than 40 ms gain to have occurred in the interval from (*d*). *f*, *g*, Observer Y.B. SOA is at 120 ms. Performance is very stable within each session, but there is marked improvement on retesting after an interval of 24 h. *f*, Performance at threshold on the first training session, following above threshold experience and the saturation of the fast learning effect. *g*, Performance 24 h after the initial session.

FIG. 3 Slow (latent) improvement in perception several hours after visual experience was terminated. Performance gain (in terms of threshold SOA, in ms, each extrapolated from a complete psychometric curve (see Fig. 1) at different time intervals from the initial training session (normalized at zero). Nine observers. Each symbol represents a single observer exposed to a set stimulus configuration, probed 1–3 times in the first 10 h interval after the initial session, and once again after an interval of 20–30 h. Two observers (○, △) show a performance gain of more than 20 ms, after an 8 h interval whereas another (▲) is still within the latent phase after 10 h. For up to 6 h there is no gain in performance (mean change, $2\pm5$ ms). By 22–28 h after the initial training session all observers have gained in visual sensitivity. The gain was not related to the number of intervening test-practice sessions. The gap in data for the time interval between 10 and 20 h after the training session, stands for night time. Experiments to be reported in detail elsewhere have shown that the process of consolidation occurs also during normal sleep, and depends on the integrity of stage REM sleep[22].




be no forgetting over periods of many months. Figure 1*b* depicts the discrimination performance of S.W. on consecutive daily sessions during September–October 1989, and her performance on a probe session 32 months later, with no training in the interval. Almost three years later most of the gain was retained. This was also the case for G.H., after an interval of 22 months (Fig. 1*c*).

It has been assumed that perceptual improvement closely follows practice, and the ability to detect or discriminate visual stimuli improves over the course of the training session; some tasks require more training[2,4], whereas for others the effects of practice occur rapidly, within a few tens of trials[1,3,6]. Long-term perceptual learning effects, on a slower timescale, have also been ascribed to within-session improvements carried over from one session to the next[2-4,8,11]. But perhaps for the first time, our results show that not all human learning is concurrent with practice. The psychophysical evidence suggests that two stages, possibly two processes, subserve texture discrimination learning. Each has a distinct time course (evolution and saturation) and although both show a high degree of stimulus specificity, only the slow, between-sessions, learning effect is monocular. This finding implies that slow learning is mediated by earlier stages of processing[12,13]. Although fast learning may reflect the setting up of a task-specific routine[6,14] for solving the perceptual problem, slow learning may indicate the ongoing long-term, perhaps structural, modification of basic perceptual modules.

The main result uncovered by following the time course of texture discrimination learning is a latent phase of several hours duration, during which the perceptual skill evolves. This result has now been observed in two other examples of perceptual learning. For untrained observers, contrast detection is improved when masks are positioned at a short distance from the target[15]. But, this distance can be more than tripled by practice, a learning effect that shows strong retinotopy, orientation-specificity and monocularity[16] and follows a two-phased time course with a latent phase of about 8 hours duration (U. Polat and D.S., manuscript in preparation). Second, although fast stereofusion learning has been previously described[1], a slow, between-session improvement in stereo-fusing random dot displays across increasing disparities has been recently found (I. Kovács and B. Julesz, personal communication). In all three examples, long-term, experience-driven improvements in the perceptual skill occur following a latent period of several hours. We suggest the term 'consolidation' for the process, presumably initiated during the practice session, which underlies the improvement of perceptual sensitivity several hours after visual experience was terminated. Consistent with this interpretation of our human data are the kinetics of early-life (critical period) cortical plasticity[17], and patterns of mammalian memory consolidation that have shown a latent phase of several hours before the long-term retention of a specific skill[18,19]. One example of a possible neural mechanism of latent-phase learning is given by the experience-induced (imprinting) changes in NMDA receptor binding in chick brain which follows a latent phase of 6–8 hours[20]. This may be pertinent to perceptual learning, because NMDA receptor blockade had been shown to disrupt mammalian visual cortex plasticity[21]. We conjecture that slow learning reflects a functional property of basic neuronal mechanisms of memory storage within the adult sensory system. These may subserve the long-term retention of some perceptual skills. □

Received 30 April; accepted 24 June 1993.


1. Ramachandran, V. S. & Braddick, O. *Perception* **2,** 371–376 (1973).
2. McKee, S. P. & Westheimer, G. *Percept. Psychophys.* **24,** 258–262 (1978).
3. Fiorentini, A. & Berardi, N. *Vision Res.* **21,** 1149–1158 (1981).
4. Ball, K. & Sekuler, R. *Vision Res.* **27,** 935–965 (1987).
5. Karni, A. & Sagi, D. *Proc. natn. Acad. Sci. U.S.A.* **88,** 4966–4970 (1991).
6. Poggio, T., Fahle, M. & Edelman, S. *Science* **256,** 1018–1021 (1992).
7. Julesz, B. in *Dynamic Aspects of Neocortical Function* (eds Edelman, G. M., Cowan, W. M. & Gall, W. E.) 585–612 (Wiley, New York, 1984).
8. Beck, J. (ed.) in *Organization and Representation in Perception* 285–317 (Erlbaum, Hillsdale, New Jersey, 1982).
9. Nothdurft, H. C. *Vision Res.* **25,** 551–560 (1985).
10. Sagi, D. & Julesz, B. *Science* **228,** 1217–1219 (1985).
11. Gurnsey, R. & Browse, R. A. *Percept. Psychophys.* **41,** 239–252 (1987).
12. Zeki, S. M. *Nature* **274,** 423–428 (1978).
13. Hubel, D. *Nature* **299,** 515–524 (1982).
14. Ullman, S. *Cognition* **18,** 97–157 (1984).
15. Polat, U. & Sagi, D. *Vision Res.* **33,** 993–999 (1993).
16. Polat, U. & Sagi, D. *Invest. Ophthalmol. Vis. Sci.* **34** (suppl.), 776 (1993).
17. Buisseret, P., Gary-Bobo, E. & Imbert M. *Nature* **272,** 816–817 (1978).
18. McGaugh, J. L. *Science* **153,** 1351–1358 (1966).
19. Matthies, H. *Progr. Neurobiol.* **32,** 277–349 (1989).
20. Horn, G. & McCabe, B. J. *J. Physiol.* **423,** 92 (1990).
21. Bear, M. F., Gu, Q., Kleinschmidt, A. & Singer, W. *J. Neurosci.* **10,** 909–925 (1990).
22. Karni, A. & Sagi, D. *Neurosci. Abstr.* **18,** 387 (1992).


ACKNOWLEDGEMENTS. We thank M. Mishkin, L. Ungerleider, R. Desimone, B. Richmond, L. Chelazzi and P. De Weerd for discussions and suggestions, and Y. Barbut and M. Adams for graphical help. This work was supported by the Israeli Center for Psychobiology.