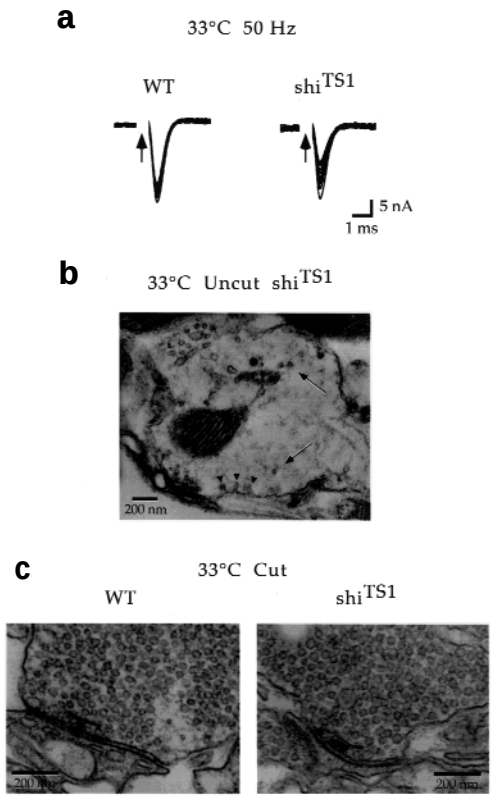

Fig. 2. ICLM synapses show a *shi* synaptic phenotype, but are not depleted of vesicles before stimulation. (**a**) Single-electrode voltage-clamp recordings at ICLM synapses from wild-type and *shi*^{TS1} flies, displayed as in Fig. 1a. Synaptic currents were elicited by 50-Hz stimulation of the cut ICLM motor axon. Holding potential, –50 mV. Similar results were obtained in six WT and four *shi*^{TS1} experiments. (**b**) Transmission electron microscopy (TEM) image from a *shi*^{TS1} preparation in which the ICLM motor axons were left intact (uncut). Arrows point to a few remaining synaptic vesicles. Arrowheads indicate endocytic intermediate structures as defined previously[2]. (**c**) TEM images from WT and *shi*^{TS1} preparations in which the ICLM motor axons were cut. ICLM synaptic currents were recorded as described[15]. TEM was done using conventional methods, essentially as described[14].

um-dependent refilling is reported as well[9]. One possibility is that fast refilling is occluded in *shi* by accumulation of endocytic intermediates at release sites. A role for dynamin in rapid clearance of these intermediates during repetitive stimulation would complement fast, calcium-dependent refilling and contribute to short-term maintenance of the releasable pool. Relevant findings in adrenal chromaffin cells indicate that retrieval of vesicle membranes after intense stimulation includes a calcium- and dynamin-dependent component with fast kinetics[10,11]. This may reflect a 'kiss-and-run' mechanism[12], in which exocytosis occurs without collapse of the vesicle into the plasma membrane. Additional work will address the mechanism of fast synaptic fatigue in *shi* in the context of the above working model.

Finally, dynamin activity is regulated by phosphorylation as well as by interactions with its binding partners[1,13], and these mechanisms are proposed to regulate synaptic function. The present finding that *shi* synapses exhibit rapid synaptic fatigue supports a role for dynamin in short-term synaptic plasticity.

ACKNOWLEDGEMENTS

Electron microscopy was done in the Penn State Electron Microscopy facility. The shi^{TS2} *mutant was provided by the Bloomington Stock Center. Supported by the National Science Foundation.*

RECEIVED 25 APRIL; ACCEPTED 28 JULY 2000

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Motor timing learned without motor training

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Improvements due to perceptual training are often specific to the trained task and do not generalize to similar perceptual tasks[1]. Surprisingly, given this history of highly constrained, context-specific perceptual learning, we found that training on a perceptual task showed significant transfer to a motor task. This result provides evidence for a common neural architecture underlying analysis of sensory input and control of motor output, and suggests a potential role for perception in motor development and rehabilitation.

Both tasks required processing of time. The perception task was to discriminate temporal intervals denoted by brief auditory stimuli, and the motor task was to produce successive finger movements separated by a target temporal interval. Evidence suggests a common neural substrate for time perception and motor timing[2]. Thus we tested the possibility that plastic modifications of such a substrate, induced by perceptual training, could affect motor timing.

Twelve right-handed adults participated in seven experimental sessions, with no more than two days between successive sessions. During the training period (sessions 2–6), each participant

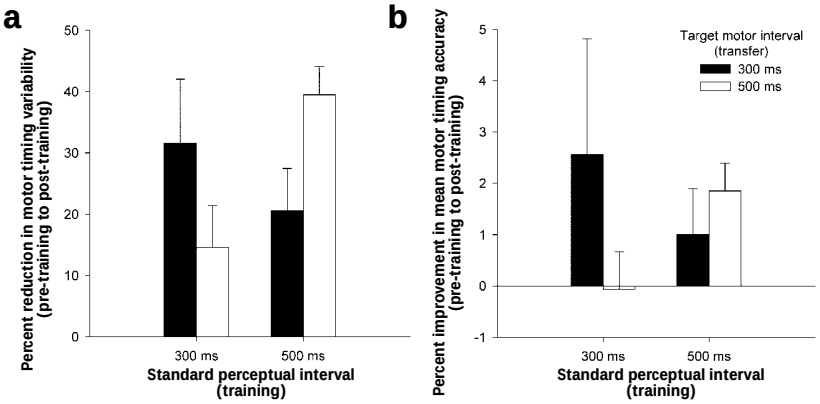

Fig. 1. Change in motor performance as a function of perceptual training condition. The motor tasks involved attempting to produce successive thumb presses separated by a target interval of time. Motor timing variability (**a**) was measured by the standard deviation of the interpress interval, and mean motor timing accuracy (**b**) was measured by the difference between mean IPI and the target IPI; note that mean IPI can correspond well to target IPI even when performance is highly variable (as in the pre-training session). Participants showed a greater reduction of variability (**a**) when the target interval matched the interval used in an auditory discrimination task during the training phase. Consistent with the measure of variability (**a**), participants showed a tendency toward greater improvement in mean accuracy (**b**) when the target interval matched the trained interval, although the interaction between perceptual and motor interval was not significant ($F_{1,10} = 2.66$). The lack of a significant effect was not surprising because mean IPI was close to the target IPI in the pre-training session; in other words, there was little room for improvement in mean accuracy.

made 2500 discrimination judgments. On each trial, subjects indicated which of two successive temporal intervals was perceived to be longer in duration. The beginning and end of each interval were marked by auditory tones of constant duration (25 ms), frequency (1 kHz) and amplitude. The shorter of the two intervals (the standard interval) was 300 ms on every trial for six of the participants, and 500 ms on every trial for the other six participants. The duration of the longer interval (the comparison interval) was determined by a weighted up–down method[3], which estimated the temporal threshold at which the standard and comparison intervals could be discriminated with 75% accuracy. Consistent with a previous report[4], participants had lower thresholds after the training period than before; an ANOVA with trained interval (300 or 500ms) and session (pre-training and post-training) as factors yielded only a main effect of session ($F_{1,10} = 12.94$, $p < 0.005$).

The purpose of the auditory training was to enhance the neural representation of the standard interval. To assess whether this training affected performance on a motor task, participants performed two motor tasks before (session 1) and after training (session 7). Only one of the two motor tasks involved a temporal interval matched to the standard used during the perceptual training task. In both tasks, participants used the right thumb, which was covered from view, to press a button twice in succession. Following the second press, the interpress interval (IPI) was displayed on a monitor as feedback. Participants attempted to produce a target IPI of 300 ms in one task and 500 ms in the other. There were 3 blocks of 50 trials in each task, and the 6 blocks occurred in random order.

As is customary in studies of discrete motor timing[5], we used variability (standard deviation of IPI) as the dependent measure; we also report the correspondence between mean IPI and target IPI (Fig. 1b). Motor learning was gauged by the reduction in timing variability from before to after training. If this motor learning were the result of perceptual training, then it would be present only for the perceptually trained interval. This prediction was supported by a significant interaction between trained perceptual interval and target motor interval (Fig. 1a; $F_{1,10} = 24.57$, $p < 0.001$). Specifically, participants trained at 300 ms showed greater reduction of motor timing variability in the 300-ms task than the 500-ms task ($t_5 = 2.69$, $p < 0.05$), whereas participants trained at 500 ms showed greater reduction of motor timing variability in the 500-ms task than the 300-ms task ($t_5 = 5.36$, $p < 0.005$). In other words, participants showed more motor improvement when the temporal requirements of the motor task matched the temporal characteristics of their perceptual training.

We suggest that this motor learning was a byproduct of an enhanced representation of a particular temporal interval, induced by auditory training, in a plastic network shared by sensory and motor systems. Alternatively, one might suggest that unintended motor training occurred during the training period, or that auditory feedback aided motor performance in the post-training session. Some methodological constraints were implemented in anticipation of such concerns. For example, in auditory training, the onset of tones was unpredictable, eliminating the possibility that subjects used rhythmic bodily movement to aid in auditory discrimination. Also, participants listened to white noise while performing the motor tasks, thereby eliminating any auditory feedback from the movement (such as button depression). Despite the white noise, participants possibly could have deliberately used auditory memory during the post-training session to aid motor timing at the trained interval. However, during debriefing after the experiment, they were surprised to learn of the temporal relationship between their training task and one of the motor tasks.

Behavioral evidence for a common sensory and motor timer has been indirect[6,7]. For example, performance declines similarly at increasing temporal intervals for perception and motor tasks[6]. Such correlational evidence has left open the possibility that sensory and motor systems merely represent time in a similar fashion, rather than sharing a common neural mechanism. The anatomical correlate of this view might have sensory and motor timers located in sensory and motor cortices, respectively. A compromise view[2] is that temporal representations for perception and motor control, although anatomically distinct, are located more proximally (for example, adjacent regions of the cerebellum[8]). There is mounting evidence for a cerebellar role in both sensory and motor timing[9,10], particularly for the range of durations used in the present study[11]. The cerebellum also is important in learning skills that require precise timing[12], such as the coordination of the individual components of multi-component movements[13], or the anticipation of temporally modulated sensory stimuli[14]. Therefore it seems reasonable to hypothesize a cerebellar contribution to the generalized learning reported here. Whatever the anatomical loci of sensory and motor timers, our results suggest that they are closely interconnected, such that plastic modifications of sensory temporal representations automatically affect motor temporal representations.

The finding that motor learning can occur without motor training has interesting implications for development and rehabilitation. In cases where the neural or musculoskeletal control of movement is underdeveloped or incapacitated, exposure to sensory input matched temporally to some future motor goal might accelerate the attainment of that goal once motor production becomes possible. One example is speech development, where speech perception could conceivably train the neural control of speech production before the vocal apparatus reaches the requisite level of maturity.

ACKNOWLEDGEMENTS

This work was supported by NIH grants T32-MH19942 and R29- MH54770, and NSF research grant SBR-9873477.

RECEIVED 5 JUNE; ACCEPTED 3 AUGUST 2000

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