Synchrony Dominates Motor Cortex Post-Spike Effects in Monkeys Trained Long Term to Perform a Large Repertoire of Skilled Finger Movements.

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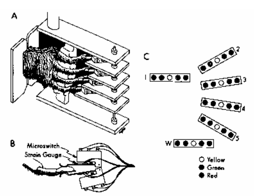
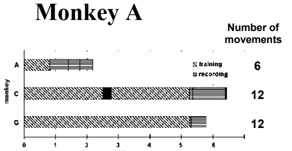
1. Introduction

Synchronous discharge among neurons increasingly is thought to play an important role in information processing by the CNS. Whereas synchrony can be examined most directly in the pairwise cross-correlation of simultaneously recorded neuron spike trains, spike-triggered averaging (SpikeTA) of rectified EMG (rEMG) affords an opportunity to examine synchrony among larger groups of premotor neurons that provide input to pools of spinal α-motoneurons. Some effects in SpikeTAs show discrete peaks (or troughs) with i) an onset latency after the trigger spike, and ii) a peak width, appropriate for input from the trigger neuron alone. Other effects, however, have too early an onset, or too wide a peak, to represent input from just the trigger neuron. Such effects reflect near synchronous (± several msec) discharges of other neurons that also have inputs to the same motoneuron pool. Here I report studies of synchrony in the SpikeTAs of neurons in the primary motor cortex (M1) hand representation in 3 monkeys studied as each monkey performed visually cued individuated finger movements (below).



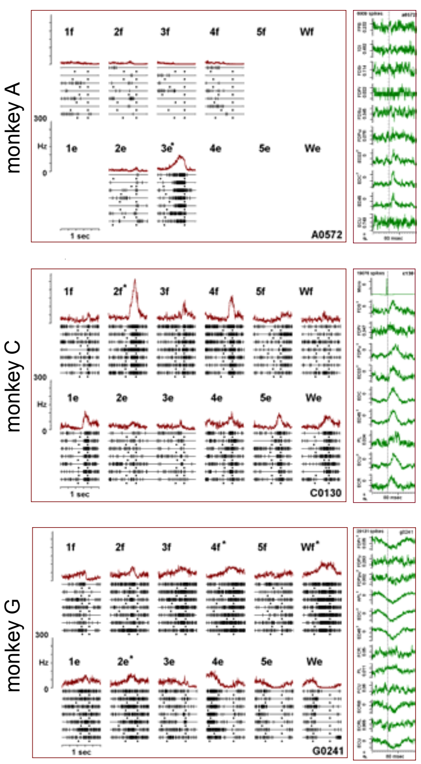
2. Monkeys C and G trained longer and performed more movements than Monkey A



3. Example M1 Neurons

Neuron activity in rasters and histograms

Spike-triggered averages



4. More Effects in Monkeys Trained Longer

Multifragment statistical analysis (Poliakov & Schieber, 1998) was applied to each spike-triggered average to identify significant peaks or troughs in a 6-16 msec post-spike window.

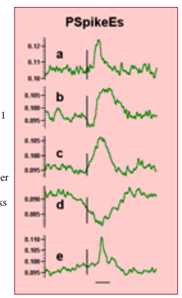
More M1 neurons in monkeys C and G than in monkey A had at least one significant effect (χ^2 $p < 0.00001$).

M1 Neurons	A	C	G	Total
With SpikeTA Effects	27	159	53	239
Without SpikeTA Effects	139	159	83	381
Total	166	318	136	620
Percent with Effects	16.27	50	39	38.55

More Neuron-EMG pairs in monkeys C and G than in monkey A had a significant effect (χ^2 $p < 0.00001$).

Neuron-EMG pairs	A	C	G	Total
With SpikeTA Effect	47	467	212	726
Without SpikeTA Effect	1602	3064	2552	7218
Total	1649	3531	2764	7944
Percent with Effect	2.85	13.23	7.67	9.139

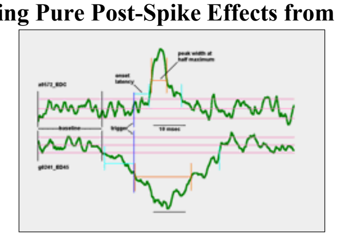
5. Variety of Effects Reflect Variations in Synchrony of Inputs to Motoneuron Pools



(**a**) onset latency after the trigger (vertical bar) consistent with inputs from the M1 neuron to the motoneuron pool, as well as a narrow width consistent with inputs from only one neuron, i.e. "pure" post-spike effects.
(**b**) onset latency consistent with inputs from the M1 trigger neuron, but peak too wide to reflect inputs from only one premotor neuron, suggesting that additional inputs reached the motoneuron pool after those of the M1 trigger neuron.
(**c** and **d**) onset latency too early to be caused by the M1 trigger neuron, and peaks too wide to come from a single input neuron, suggesting that additional inputs from other premotor neurons arrived at the motoneuron pool synchronously (± several msec) with the input from the trigger neuron in M1.
(**e**) "pure" post-spike effect riding on an underlying "synchrony" effect.

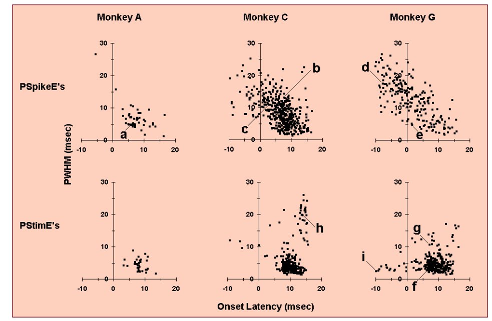
6. Distinguishing Pure Post-Spike Effects from Synchrony

Pure post-spike effects may be differentiated from synchrony effects using onset latency and/or peak-width at half maximum (PWHM) (e.g Baker & Lemon, 1998)..



7. More Synchrony in Monkeys Trained Longer

Using onset latency > 5 msec and PWHM < 9 msec as criteria to separate pure post-spike effects from synchrony effects, in monkey A, only 21% (10/47) were synchrony effects; in monkey C, 52% (225/467); and in monkey G, 78% (165/212) were synchrony effects. Chi-square testing confirmed that the frequency of pure versus synchrony effects differed among the 3 monkeys ($p < 0.0001$), while the frequency of **stimulus-**triggered effects with such features did not differ among monkeys ($p > 0.2$).

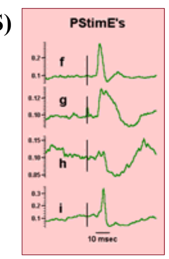


The ***top row*** of the panel at left shows scatter plots of PWHM versus Onset Latency for each significant effect in the three monkeys-- A, C and G. In monkey A, the majority of effects had onset latency and PWHM consistent with pure post-spike effects. But in monkeys C and G, the majority of effects had onset latency too early and/or PWHM too long to reflect pure effects, instead indicating synchrony. No clear bimodal separation between pure and synchrony effects was evident.

The ***bottom row*** of the panel at left shows similar measurements made on populations of **stimulus**-triggered effects recorded in the same monkeys. In all three monkeys the majority of these effects had both onset latency and peak width consistent with monosynaptic EPSPs arriving from directly stimulated M1 neurons.

8. Single-Pulse Intracortical Microstimulation (sICMS)

Three types of stimulus-triggered effects that suggest relatively long-lasting effects of sICMS pulses on motoneuron pools (**g, h,** and **i**) were seen almost exclusively in monkeys C and G, further suggesting differences in physiological connectivity of M1 in these two monkeys as compared to monkey A.
(**f**) typical stimulus-triggered effects had onset latency and PWHM consistent with inputs from directly stimulated M1 neurons
(**g**) PWHM too wide to reflect inputs from only directly stimulated neurons, suggesting additional inputs from indirectly (i.e. trans-synaptically) stimulated neurons, which might include both indirectly activated corticospinal and sub-cortical neurons .
(**h**) late onset and wide PWHM. These were particularly common in monkey C, where they all consisted of relatively late post-stimulus suppression of EMG with little or no preceding facilitation.
(**i**) narrow peak, but a paradoxically early onset. These were found exclusively in monkey G. Such effects consistently showed relatively long lasting suppression following a narrow facilitation peak, suggesting that the effects of a single ICMS pulse on the motoneuron pool lasted longer than 50 msec. Given that the single ICMS pulses were delivered at intervals of 60-80 msec, varied by hand turning a potentiometer, I infer that in these cases inputs to the motoneuron pool became entrained by the quasi-rhythmic sICMS stimuli, resulting in some degree of rhythmical recovery from suppression preceding many stimuli.



9. Conclusions

1. Long-term training at a motor skill and/or development of a large repertoire of related movements is associated with increased synchrony among the discharges of M1 neurons and other neurons with relatively direct inputs to spinal motoneuron pools.

2. Atypical effects obtained with sICMS may reflect altered efficacy of interconnections in the motor system with long-term training.

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