

TRANSMITTER POTENTIALITY OF HOMONYMOUS AND
HETERONYMOUS MONOSYNAPTIC REFLEX CONNEC-
TIONS OF INDIVIDUAL MOTONEURONS

BY DAVID P. C. LLOYD AND A. K. MCINTYRE

*(From the Laboratories of The Rockefeller Institute for Medical Research, New York, and
the Department of Physiology, University of Otago, Dunedin, New Zealand)*

(Received for publication, March 2, 1955)

Monosynaptic reflex transmission from the afferent fibers of one fraction of a synergic unit (such as triceps surae) to motoneurons of another fraction, which is to say heteronymous monosynaptic reflex transmission, has been found to occur in certain circumstances (1-4, 7), of which post-tetanic potentiation of transmitter action is the most readily established and controlled (6, 7). Only a small fraction of a motoneuron population appears to participate in response to potentiated heteronymous afferent volleys (7). The experiments to be described are designed to inquire into the circumstances that predispose certain motoneurons to heteronymous response. It seemed at the outset that such an inquiry would demand the study of motoneurons as identified individuals and, indeed, it was for this reason that the observations presented in the antecedent paper (9) and here were begun.

The population of 110 individual tricipital motoneurons discussed in the antecedent paper (9), which contains the relevant details of method, has been examined for the incidence of response to maximal heteronymous monosynaptic reflex afferent volleys. The experimental plot has been to compare homonymous and heteronymous monosynaptic reflex performance of each motoneuron in search of such correlation as might exist. Initial surmise was that variation in mean postsynaptic threshold could predispose certain motoneurons to heteronymous response, which then should be coupled with a high homonymous firing index, or alternatively, that details of presynaptic organization at the synaptic junctions would prove the significant determinant of heteronymous response, in which case coupling with high homonymous firing indices would seem unlikely.

RESULTS

In the otherwise resting state one of the 110 tricipital motoneurons responded once to maximal heteronymous afferent volleys. Having done so it failed to respond again in any of a subsequent 432 trials. It is of interest that this motoneuron was the most persistent responder to post-tetanicly potentiated heteronymous volleys. It and fourteen others, in all 15 of 110, responded to one

or more of the low frequency series (*i.e.* 25 per minute) of heteronymous test stimuli subsequent to tetanization at *ca.* 500 per second for 12 seconds.

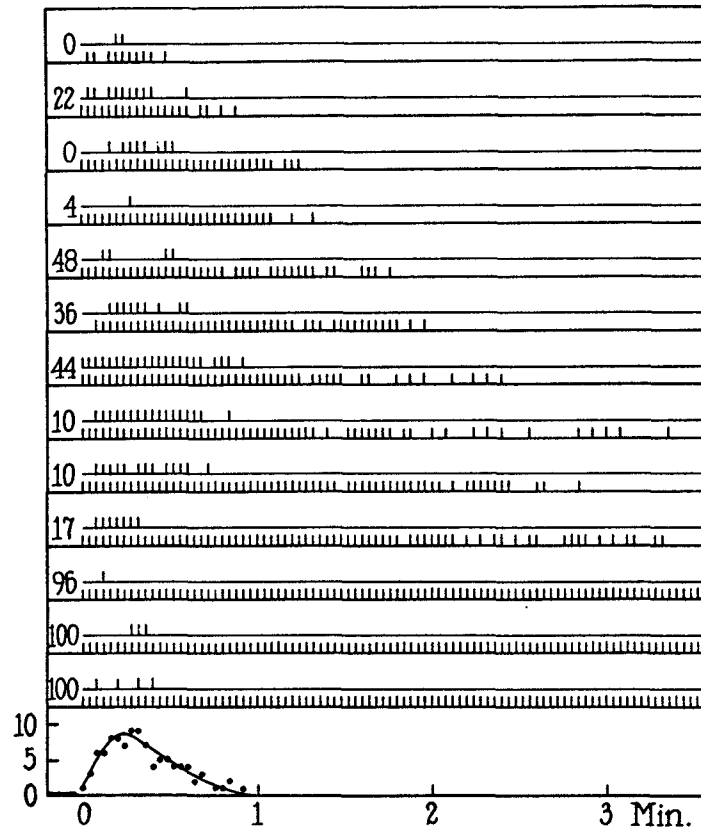


FIG. 1. Patterns of heteronymous and homonymous post-tetanically potentiated response of individual motoneurons. Each motoneuron is represented at the left by a number that gives its resting homonymous firing index, and along the abscissa by vertical lines each of which by its position indicates the order number in the post-tetanic sequence of trials at which a response occurred. For each neuron the upper response series represents heteronymous firing, the lower homonymous firing. Heteronymous trials were continued until the motoneurons failed to respond further. All the homonymous trials were continued at least 2 minutes and longer. At bottom is a synthetic post-tetanic potentiation curve of heteronymous response constructed from the response patterns above. Ordinate, number of neurons responding to each trial in the post-tetanic series. Abscissa, time in minutes after close of tetanus.

Fig. 1 presents the post-tetanic response patterns of 13 motoneurons. Pattern of heteronymous response of the remaining two motoneurons was lost through accident to the recording film, although the number of responses is

known from parallel notebook entries. Each of the 13 is represented at the left by a number expressing its resting firing index to maximal homonymous afferent volleys at a test repetition rate of 25 per minute (*cf.* reference 9). For each motoneuron, extending to the right from zero time, which represents the end of tetanization, are two linear time plots indicating by the presence or absence of a vertical line, at each test interval, the presence or absence of response to the particular test volley. The upper plot in each instance describes the pattern of heteronymous post-tetanic response, the lower that of homonymous post-tetanic response. From above downwards the individual motoneurons are ranked in order of increasing intensity of homonymous post-tetanic response. At the bottom is a plot of the sum of the heteronymous responses constructed in the manner of the summated homonymous post-tetanic response in Fig. 6 of the antecedent paper.

Post-tetanic heteronymous response of these individuals was confined to the first post-tetanic minute which is in accord with findings relative to the behavior of natural pools at near normal temperatures (7). Further, the summated heteronymous response curve is one of the expected form with its peak at the time when potentiation of natural pool response is maximal.

Fig. 2 identifies, in terms of their resting homonymous firing indices, those individual motoneurons in the series of 110 that did respond to post-tetanicly elicited heteronymous volleys. The plot of Fig. 2 thus is essentially that of Fig. 1A in the antecedent paper with the exception that the individual motoneurons are represented by filled and open circles, the latter having reference to those motoneurons that responded to potentiated heteronymous volleys. The number associated with each open circle gives the total number of responses elicited by iterative test at 25 per minute during the post-tetanic period. The numbers encircled refer to the two motoneurons the response of which in number is known, but in pattern is not. Three of the motoneurons that responded to potentiated heteronymous volleys had resting homonymous firing indices of zero and so cannot be ranked on the basis of resting firing indices alone. These three have been assigned order numbers 45, 76, and 84 respectively on the basis of their individual post-tetanic homonymous firing indices relative to those of the other 63 motoneurons having a resting $F_i = 0$. The assignment can be considered only approximate.

A striking feature of Fig. 2 is that most of the motoneurons that responded at all to post-tetanicly elicited heteronymous volleys, and of these the individuals that responded with the highest incidence, are to be found in the intermediate range with respect to response incidence to homonymous afferent volleys in the otherwise resting state.

Without the need for prior tetanization of the monosynaptic reflex pathways five of 62 motoneurons responded to volleys in either gastrocnemius nerve when incident upon a background of long spinal reflex activity consequent to

stimulation of the brachial plexus. Brachial plexus stimulation in the sort of preparation here employed provokes a vigorous discharge of interneurons in the ventral horn (5) and facilitation of motoneuron response over a period of some 25 msec. (5, 8). Near the peak of the facilitation period motoneuron discharges

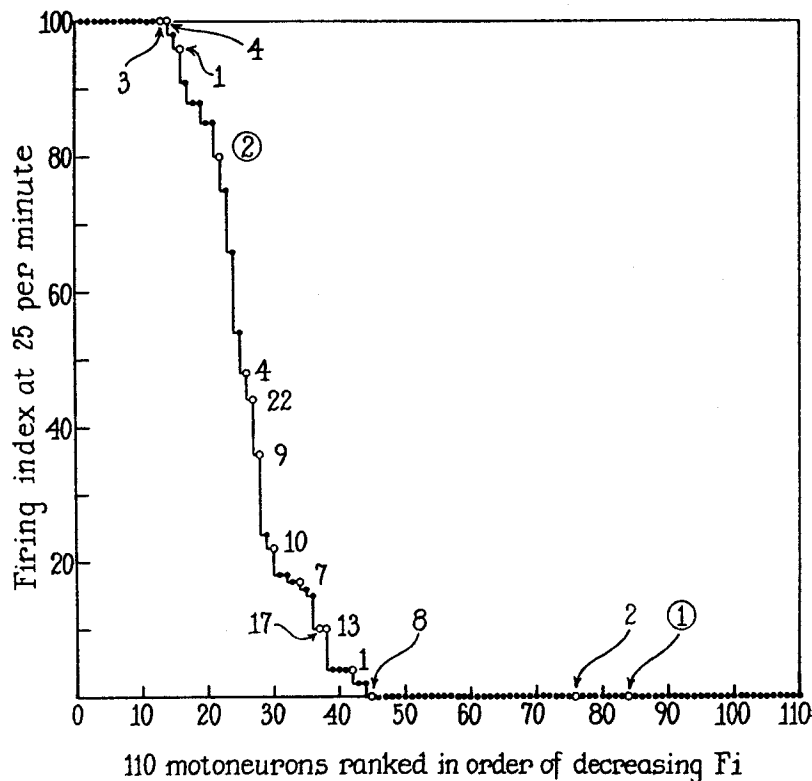


FIG. 2. The population of 110 motoneurons has been ranked in order of decreasing homonymous firing indices. Filled circles represent the individuals that did not respond post-tetanicly to heteronymous volleys, open circles those that did. Numbers associated with the latter give the total number of post-tetanic responses elicited by potentiated heteronymous volleys in a trial series.

may occur, and it has been shown that tripital motoneurons partake in the response (8). In the present experiments shock interval (*ca.* 12 msec.) has been so adjusted that the monosynaptic reflex volleys, homonymous or heteronymous as the case may be, fell in the period of facilitation, but prior to the onset of motoneuron response to unaided long spinal reflex volleys.

With the use of homonymous afferent volleys the unitary responses that appeared by virtue of the long spinal reflex facilitatory convergence, or those that assumed a higher firing incidence therefore, did so in the strictest short

latency monosynaptic reflex time with respect to the homonymous stimulation. There can be little doubt that the homonymous volleys were in essential control of the motoneurons.

On the other hand, with the use of heteronymous volleys, neither these nor the brachial plexus volleys in isolation being effective, latency of response with respect to the heteronymous nerve stimuli occasionally was prolonged. That exact monosynaptic reflex time relationships between stimulus and response was not always maintained is of considerable interest, since in other known instances of heteronymous transmission it is (1, 3, 4, 7). Seemingly the conditions for extension of delay *relative to the heteronymous monosynaptic reflex stimulation* must be that the combination with long spinal reflex activity be ineffective at the short latency reflex time and that the long spinal reflex barrage increase at some rate greater than that of the decay of heteronymous monosynaptic reflex facilitatory influence so that discharge time is determined by certain of the long spinal reflex impulses incident upon the motoneurons.

Once heteronymous afferent volleys are potentiated by prior tetanization and combined with long spinal reflex activity the incidence of heteronymous monosynaptic reflex response rises sharply. In the population of 62 motoneurons studied with the use of long spinal reflex activity six individuals responded to potentiated heteronymous volleys without long spinal reflex influence. Addition of the latter raised the number to 22 or just over one-third of the population.

Fig. 3 identifies, in terms of their resting homonymous firing indices, (*a*) the individuals among the group of 62 motoneurons studied with the use of long spinal reflex activity that responded to post-tetanicly potentiated heteronymous afferent volleys in isolation (filled circles), (*b*) those responding to a combination of long spinal reflex activity and unconditioned heteronymous volleys (arrows), and finally (*c*) the motoneurons in addition to those already identified that responded to the combination of long spinal reflex activity and potentiated heteronymous volleys (open circles). Order numbers assigned to motoneurons that yielded resting homonymous $Fi = 0$ are approximate, and were obtained by reference to relative post-tetanic homonymous firing indices.

In the first two categories (*a* and *b* above) 5 of 6 and 4 of 5 respectively are in the intermediate range with respect to resting homonymous Fi . However, the motoneurons that respond to the combination of potentiated heteronymous volleys and long spinal reflex activity are much more evenly distributed, although still skewed in favor of the intermediate range of resting homonymous Fi . That the intermediate homonymous range is not now fully occupied by responders to the facilitated, potentiated heteronymous drive means that motoneurons of the intermediate homonymous range are not uniformly more accessible to heteronymous volleys than are those of the subliminal fringe. In short some are high on the scale of heteronymous transmitter potentiality, others are very low.

When the entire extensor synergic unit of the ankle, namely triceps surae, is fractionated into the medial and lateral components and either of these is stimulated with the aim of evoking a monosynaptic reflex response it is usual

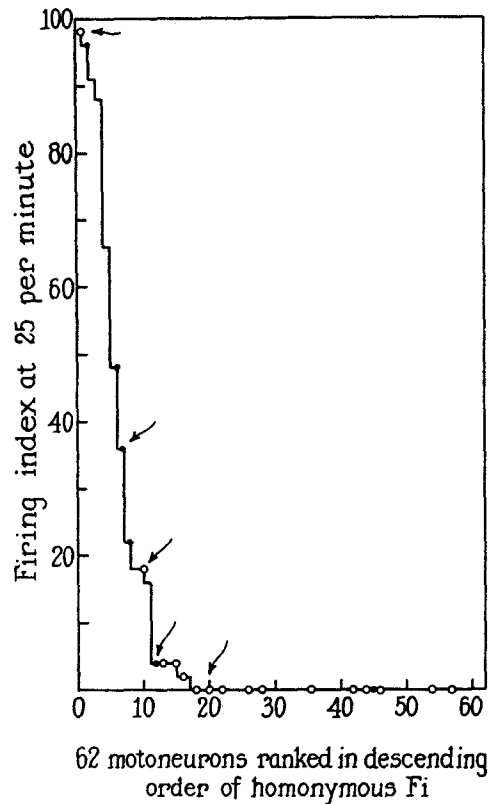


FIG. 3. A population of 62 motoneurons has been ordered according to decreasing homonymous firing indices. Those that failed to yield any heteronymous response are not individually identified. Filled circles indicate the individuals that responded to post-tetanicly potentiated heteronymous volleys, arrows those that responded to unpotentiated heteronymous volleys in combination with long spinal reflex drive, open circles those additional motoneurons that responded to potentiated heteronymous volleys in combination with long spinal reflex drive.

to find that response confined to motoneurons of the fraction stimulated. Average transmitter potentiality of homonymous connections is much greater than that of heteronymous connections. The same is true of other fractionated synergic units. Autochthony of fractional monosynaptic reflexes is not absolute (7), which is to say that the transmitter potentiality of heteronymous connections has finite although relatively speaking low values. There is evidence to

show that motoneurons are graded with respect to transmitter potentiality of their heteronymous connections (7) as indeed they are with respect to transmitter potentiality of their homonymous connections (9).

The present observations indicate that the motoneurons are not similarly ordered with respect to intensity of response to standardized homonymous and heteronymous volleys. It seems, therefore, a warrantable conclusion that variation in mean intrinsic motoneuron thresholds is not a significant factor in gradation of transmitter potentialities, which in turn leads one to suppose that mean threshold is a fairly uniform property of motoneurons.

That the motoneurons are differently ordered with respect to intensity of homonymous and heteronymous transmitter potentiality is new evidence that presynaptic organization of any given junction between an afferent fiber and motoneuron is the significant determinant of transmitter potentiality. One might reasonably have expected an inverse distribution of motoneurons with respect to homonymous and heteronymous transmitter potentialities. As it is, those motoneurons subjected to the highest grades of heteronymous drive for the most part are located in the intermediate segment of the motoneuron pool with respect to homonymous drive.

In no instance has a distinct asymmetry in response of a given motoneuron to homonymous and heteronymous volleys failed to appear. Degree of asymmetry is variable, the highest degree represented by any one of the motoneurons yielding $Pi = 100$ to homonymous test in the resting state and not firing heteronymously in any circumstance (9), the lowest degree exemplified by the motoneuron the post-tetanic responses of which are illustrated at the top of Fig. 1. Thus the disparity in *average* transmitter potentiality of homonymous and heteronymous connections to a fraction of the natural pool is recapitulated, in greater or lesser degree, by the transmitter potentiality of the individual homonymous and heteronymous connections to each of the constituent motoneurons. However, there are in the subliminal fringe of homonymous connection some motoneurons that respond to maximal homonymous volleys, potentiated or facilitated (by long spinal reflex action) in a manner that compares with, or falls short of, the response of some other motoneurons to heteronymous volleys in otherwise similar circumstances. Otherwise stated, some heteronymous connections with respect to transmitter potentiality are as potent or more potent than some homonymous connections. This holds true for motoneurons of a single preparation as it does for the entire group of motoneurons studied. Hence the relation cannot be ascribed to differences in "reflex status" of individual preparations. This means that the manner in which the transmitter potentiality of *one afferent fraction* (say medial gastrocnemius) is distributed throughout the motoneuron population of the *entire* synergic unit (*i.e.* triceps surae) no longer can be represented by a unimodal curve as was done in the first approximation concerning grading of transmitter potentiality (Fig. 1C, reference 7). According

to present evidence the distribution is bimodal, one peak of potentiation being located among homonymous motoneurons (medial gastrocnemius in the present argument), the other among heteronymous motoneurons (*i.e.* lateral gastrocnemius). The information contained in Fig. 2 serves to locate the peak of heteronymous potentiality in relation to that of homonymous potentiality.

Fig. 4 has been designed to bring together in a simple and orderly fashion the various items of information that are now available concerning the comparative behavior of motoneurons to homonymous and heteronymous volleys.

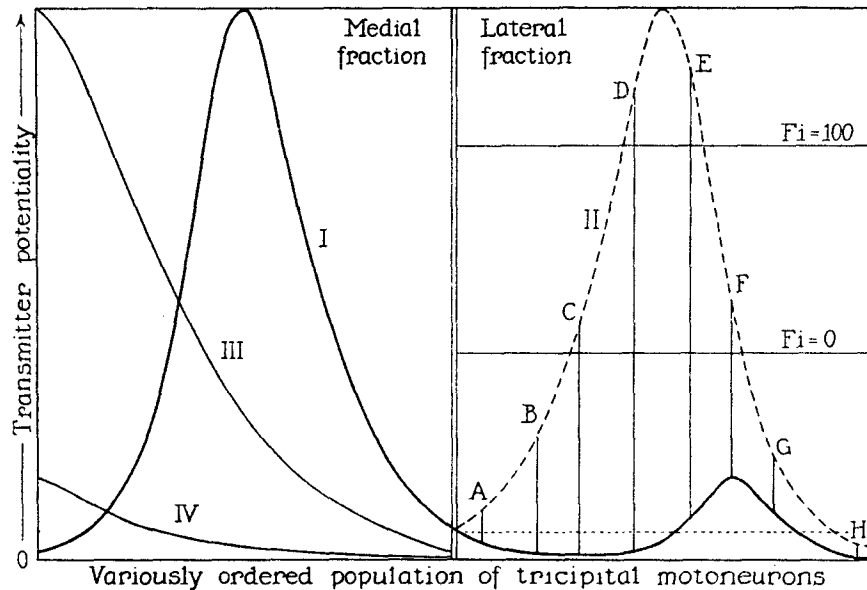


FIG. 4. Diagram to summarize and interpret in terms of distributed transmitter potentialities findings with respect to homonymous and heteronymous response of individual motoneurons. Described in text.

The solid line curve (I) indicates a distribution throughout an ordered population of motoneurons, representing the tricipital synergic unit, of the summed transmitter potentialities of the medial gastrocnemius monosynaptic afferent fibers. To the left of the midline is represented the medial fraction, to the right the lateral fraction, of the synergic unit. Thus that portion of the solid line curve to the left of midline depicts the distribution of homonymous transmitter potentialities, that to the right the distribution of heteronymous transmitter potentialities. The broken line curve (II) repeats the distribution of homonymous potentialities with respect, however, to the lateral gastrocnemius monosynaptic afferent fibers. In the right half, then, the homonymous and heteronymous contributions to a fractional motoneuron pool may be compared.

The distribution has been drawn to satisfy certain requirements: (1) Average homonymous transmitter potentiality must be much greater than average heteronymous transmitter potentiality (7). (2) There must be homonymy-favoring asymmetry of greater or lesser degree, between homonymous and heteronymous transmitter potentialities at each individual motoneuron (p. 795). (3) There should be an approximately linear gradation of transmitter potentiality over a considerable range of intermediate values to accommodate an approximately uniform (*i.e.* rectangular) frequency distribution of motoneurons with respect to intermediate grades of synaptic drive (*cf.* reference 9). It is premature to define the extremes of distribution, although considerable deviation from linear gradation (and hence from rectangular frequency distribution of motoneurons with respect to synaptic drive) is permissible, and may be indicated, as the limiting values are approached. (4) The distribution must be bimodal to permit some heteronymous potentialities to be greater than some homonymous potentialities. (5) The peak of heteronymous transmitter potentiality must occur at an intermediate grade of homonymous transmitter potentiality (Fig. 2). (6) There must be a floor, here represented by a horizontal broken line, below which transmitter potentiality, homonymous and heteronymous alike, is so low that the most drastic measures are required to evoke any response (*cf.* reference 9, Table I motoneuron No. 52).

Lettered vertical lines joining the homonymous and heteronymous transmitter potentiality curves will serve rather well to describe, in terms of relative transmitter potentiality of their homonymous and heteronymous connections, the types of motoneurons that have been encountered. In effect the length of each vertical line is a measure of the degree of asymmetry characteristic of the motoneuron in question.

Neuron D, homonymous $Fi = 100$, does not respond to heteronymous volleys in any circumstance (Fig. 2).

Neuron E, homonymous $Fi = 100$, responds at a low post-tetanic heteronymous incidence (*cf.* lowermost two neurons in Fig. 1).

Neuron F, in the intermediate range of homonymous indices, is among the most easily discharged by heteronymous volleys, potentiated, or facilitated by long spinal reflex impingement (Figs. 2 and 3).

Neuron C, represents those motoneurons in the intermediate range of homonymous indices that cannot be discharged by potentiated, facilitated heteronymous volleys (Fig. 3).

Neuron B, resembles *neuron C* except for being in the $Fi = 0$ range of homonymous drive (Fig. 3).

Neuron A, will respond, perhaps 3 or 4 times, to post-tetanicly potentiated homonymous volleys, but not in any of the circumstances provided to heteronymous volleys (*cf.* neuron 58, reference 9, Table I).

Neuron G, with a low degree of asymmetry will respond to either homony-

mous or heteronymous volleys in the post-tetanic state, but to neither in the resting state (*cf.* uppermost neuron in Fig. 1).

Neuron H, will not respond to either homonymous or heteronymous volleys separately elicited, even in the post-tetanic period and convergent with long spinal reflex activity (*cf.* neuron 52, reference 9).

Remarks on the Ordering of Motoneurons with Respect to Transmitter Potentiality.—At the present state of knowledge concerning the synaptic relations of primary afferent fibers and motoneurons it has seemed advantageous for the most part to represent motoneuron pools as series of motoneurons ranked in order according to some quality (firing index for example). It is clear that transmitter potentiality exerted upon individual motoneurons by a standard maximal homonymous volley varies widely in degree. That a considerable degree of autochthony is maintained by a fractional monosynaptic reflex implies as earlier stated (7), a relation between transmitter potentiality and anatomical propinquity of receptor origin and effector termination. From this it may be supposed that natural orderings of motoneurons could be developed were the appropriate information available. It is not. Thus ordering is arbitrary and selected according to purpose. The essential feature of curves I and II in Fig. 4 is that a single ordering has been established that satisfies certain empirical relations between homonymous and heteronymous transmitter potentialities of motoneurons. For other purposes the chosen order is quite illogical. Obviously more logical ordering then would be according to decreasing (or increasing) transmitter potentiality. On the left of Fig. 4 are two plots additional to those already discussed. One of these (III) represents the distribution throughout a fractional pool of homonymous transmitter potentiality with the motoneurons reordered according to decreasing homonymous potentiality. The other (IV) represents the distribution throughout a fractional pool of heteronymous transmitter potentiality with the motoneurons further reordered to decreasing heteronymous potentiality. Although these curves describe in the first approximation some empirical relations between primary afferent fibers and motoneurons of triceps surae their precise and proper configurations are not yet sufficiently known to warrant use at this time for theoretical elaboration.

SUMMARY

An assemblage of 110 individual tricipital motoneurons has been examined with the aim of determining those factors that predispose certain motoneurons to heteronymous response in post-tetanic potentiation.

Motoneurons that respond most readily to homonymous volleys are not those that respond most readily to post-tetanicly potentiated heteronymous volleys. Hence differences in presynaptic organization rather than differences in mean postsynaptic threshold determine differences in readiness for response.

Every motoneuron exhibits a distinct asymmetry in transmitter potentiality

of homonymous and heteronymous monosynaptic reflex connections. The range of transmitter potentialities is wide and that of heteronymous connections to some motoneurons is greater than that of homonymous connections to some other motoneurons.

REFERENCES

1. Alvord, E. C., Jr., and Fuortes, M. G. F., Reflex activity of extensor motor units following muscular afferent excitation, *J. Physiol.*, 1953, **122**, 302.
2. Beswick, F. B., and Evanson, J. M., Irradiation of the monosynaptic reflex during post-tetanic potentiation, *J. Physiol.*, 1954, **124**, P 60.
3. Granit, R., and Ström, G., Autogenic modulation of excitability in single ventral horn cells, *J. Neurophysiol.*, 1951, **14**, 113.
4. Job, C., Monosynaptische Impulsübertragung zwischen Synergisten, *Arch. ges. Physiol.*, 1953, **256**, 391.
5. Lloyd, D. P. C., Mediation of descending long spinal reflex activity, *J. Neurophysiol.*, 1942, **5**, 435.
6. Lloyd, D. P. C., Post-tetanic potentiation of response in monosynaptic reflex pathways of the spinal cord. *J. Gen. Physiol.*, 1949, **33**, 147.
7. Lloyd, D. P. C., Hunt, C. C., and McIntyre, A. K., Transmission in fractionated monosynaptic spinal reflex systems, *J. Gen. Physiol.*, 1955, **38**, 307.
8. Lloyd, D. P. C., and McIntyre, A. K., Analysis of forelimb-hindlimb reflex activity in acutely decapitate cats, *J. Neurophysiol.*, 1948, **11**, 455.
9. Lloyd, D. P. C., and McIntyre, A. K., Monosynaptic reflex responses of individual motoneurons, *J. Gen. Physiol.*, 1955, **38**, 771.