

Timing Functions of The Cerebellum

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Abstract

This study investigated the effects of different types of neurological deficits on timing functions. The performance of Parkinson, cerebellar, cortical, and peripheral neuropathy patients was compared to age-matched control subjects on two separate measures of timing functions. The first task involved the production of timed intervals in which the subjects attempted to maintain a simple rhythm. The second task measured the subjects' perceptual ability to discriminate between small differences in the duration of two intervals.

The primacy of the cerebellum in timing functions was demonstrated by the finding that these were the only patients who showed a deficit in both the production and perception of timing tasks. The cerebellar group was found to have increased variability in performing rhythmic tapping and they were less accurate than the other groups in making perceptual discriminations regarding small differences in duration. Critically, this perceptual deficit appears to be specific to the perception of time since the cerebellar patients were unaffected in a control task measuring the perception of loudness.

It is argued that the operation of a timing mechanism can be conceptualized as an isolable component of the motor control system. Furthermore, the results suggest that the domain of the cerebellar timing process is not limited to the motor system, but is employed by other perceptual and cognitive systems when temporally predictive computations are needed.

Introduction

The concept of the motor program has proved useful to researchers attempting to explain how voluntary movements are controlled. As developed by Henry and Rogers (1960) and extended by Keele (1968) among others, the motor program is an abstract representation of an intended movement, containing not only the goal of the action and the existing environmental conditions, but also the possible means by which the movement could be achieved. The motor program is analogous to the role of software used by computers—flexible as a function of the input, but constrained within the limitations of the hardware. The program is the most general description of the capabilities of the system.

A logical extension of the computer metaphor is to consider the internal procedures or operations which may constitute the motor program. This would also be a prerequisite for developing a computational model of motor control. The highest level description of any model

must address the computational problems which need to be solved (Marr, 1982).

With this in mind, the work in our laboratory over the past few years has focused on delineating the basic components of coordination. The underlying premise is that the term "coordination" provides only a general characterization of skill. More insightful understanding can be obtained by decomposing this general term into a number of separable operations. In this sense, skilled behavior would be explained in terms of the successful execution of these independent procedures. For instance, computational modules might include procedures to control the sequence of actions and their locations, the selection of the appropriate muscles to implement each action, and the specification of the force and time parameters for each of the selected muscles (but see Stein, 1982; for a discussion of higher order control variables see Flash & Hogan, 1985; Soechting & Lacquaniti, 1981).

Our initial efforts to determine the validity of candidate components of coordination used a correlational ap-

proach. In our first study on timing control (Keele, Pokorny, Corcos, & Ivry, 1985b), we found that subjects who were good at maintaining an arbitrary rhythm with one effector such as the hand also tended to be good at the same task when using a different effector such as the foot. More surprising, a significant correlation was found between subjects' ability in timing production tasks and tests of timing perception when the durations of time are comparable across the two domains. Subsequent studies (Keele, Ivry, & Pokorny, 1987) showed the ability to control time to be largely independent of the ability to control force arguing for the separability of processes controlling force and time. These results were interpreted as providing evidence for a common timekeeping mechanism which is used in both production and perception functions which involve time-related decisions. Thus, the componential approach provides a more abstract definition of the organisms' capabilities. An operation may not be best thought of as part of the motor or perceptual system, but rather as an independent entity which is employed whenever its specific computation is needed.

Neuropsychological research provides a second way to investigate the validity of these hypothesized procedures. The correlational work has yielded model tasks which can assess the functioning of separable components. Different patient groups can then be tested in an effort to show dissociations between the patients' performance of these tasks as a function of the location of their neurological lesion. This paper will present results of our neuropsychological work on timing.

Previous research in our laboratory (Wing, Keele, & Margolin, 1984) had revealed a timing deficit, at least on the production task, in a patient with Parkinson's Disease. The primary neurological damage in Parkinson's Disease is presumed to be in the dopamine pathways of the basal ganglia. In another single subject study (Keele, Manchester, & Rafal, 1985a), a patient with damage to the cerebellum was also found to have difficulty in producing regular timed intervals. Taken together, the two case studies would appear to implicate both subcortical structures in timing functions and thus promote the argument that timing may involve some sort of pathway which passes through both regions. Alternatively, only one of these regions, or some other unexplored region may be critical for timing functions. If this were the case, the effects observed in the case reports may be due to indirect, modulatory effects that the basal ganglia and/or cerebellum exert on the timing mechanism. The perception of time task offers one way to test whether a particular neural structure plays a primary role in timing since the response requirements for this task are minimal and independent of those required in the production task.

Unlike the basal ganglia, there are a number of converging lines of evidence which suggest that one of the functions of the cerebellum involves timing control. The most explicit statement of the cerebellum as an internal clock was put forward by Braitenberg over twenty years

ago (Braitenberg, 1967, 1965; Braitenberg & Onesto, 1962). Braitenberg argued that information concerning the common source (i.e., mossy fiber input) generating a specific parallel fiber pulse would be lost unless the output system accounts for the different time delays introduced as the parallel fiber traverses an orthogonal array of Purkinje cells. For this operation, Braitenberg (1967) proposed a scheme based on delay lines which vary as a function of the distance between the input and output signal. Since the conduction velocity within these fibers is a relatively slow 0.5 mm/sec. (Braitenberg & Atwood, 1958), a 100 mm. chain of fibers extending across the cerebellum could provide a delay signal as long as 200 ms. Shorter chains could presumably be activated for shorter temporal intervals.

Despite the elegance of the theory, Braitenberg has since come to view the basic conception of simple delay lines as inadequate. Neurophysiological data indicated that somatotopic representations within the cerebellar cortex span relatively short distances (Oscarsson, 1980; Robertson, 1985). The maximum delay signal which could be achieved in this distance is too small to be meaningful in motor coordination (Fahle & Braitenberg, 1984).

Nonetheless, Braitenberg has not entirely dismissed the role of timing in his recent conjectures on cerebellar function. A recent model (Fahle & Braitenberg, 1984) postulates that the cerebellum establishes synchrony between the dynamic events associated with multi-joint movements and the subsequent mechanical consequences. In the same spirit, Pellionisz and Llinas (1982) have argued that the cerebellum can be viewed as a neuronal device for jointly mapping space and time onto a common dimensional space. In both of these models, time is part of the computational process since the cerebellum needs to anticipate the multiple joint positions which will be achieved during the course of a movement.

While the preceding arguments were based on anatomical observations, many clinical and experimental results can also be interpreted as supportive of the hypothesis that the cerebellum may function as a timing device. The pioneering work of Holmes (summarized in Holmes, 1939; see also Dichgans & Diener, 1984) identified two of the more common symptoms of cerebellar dysfunction: dysmetria and dysdiadochokinesia. Following lesions of the cerebellar hemispheres or the deep cerebellar nuclei, particularly the lateral zones and the dentate nucleus, the patient's movements are usually hypermetric. Dysdiadochokinesia, the inability to rapidly alternate between a pair of movements involving antagonist muscles, is generally seen in these same patients (Eccles, 1977). Both of these cerebellar signs have been interpreted as being the result of a breakdown in the patient's ability to time the onset and offset of antagonist muscles. For instance, hypermetric movements may overshoot the target because the agonist activity is not properly terminated.

Evidence from researchers using electromyography

(EMG) supports this hypothesis (Hallett, Shahani, & Young, 1975; Marsden, Merton, Morton, Hallett, Adam, & Rushton, 1977). Hallett et al., (1975) examined the EMG records of patients who had incurred various forms of cerebellar lesions. They found that cerebellar patients did not tend to show any deficit in making smooth, slow movements which only required the continuous activation of the agonist muscle. However, when the movements of the same amplitude were made ballistically, almost all of the patients showed EMG abnormalities. In general, the EMGs associated with rapid movements appeared normal in terms of the initial onset of the agonist burst. However, the duration of this burst tended to be longer than normal. In addition, the onset time of the antagonist and the duration of the antagonist were disturbed. Marsden et al., (1977) have reported similar results. Lengthening of either the duration of the first agonist burst and/or an increase in the delay of the antagonist burst could account for both dysmetria and dysdiadochokinesia.

Animal models have further linked the cerebellum to timing control. Arshavsky and his associates (Arshavsky, Gelfand, & Orlovsky, 1983) have argued that the cerebellum must be the generator of rhythmical activity observed in subcortical motor nuclei during locomotion since these signals are abolished following cerebellar lesions. Furthermore, the rhythmic cerebellar output in intact animals remains stable even when perturbations are introduced which disrupt the rhythmic afferent signals to the cerebellum. Other animal research has demonstrated that dysfunction in either the cerebellar hemispheres or deep nuclei can disrupt the kinematics of rapid movements (Beaubaton & Trouche, 1982; Conrad & Brooks, 1974; Meyer-Lohmann, Hore, & Brooks, 1977; Vilis and Hore, 1980). These results have generally shown that permanent or temporary lesions are more disruptive for the antagonist response, the muscular burst which is assumed to provide the braking force in rapid movements. Vilis and Hore (1980) postulate that the intentional tremor seen in cerebellar pathology is a consequence of this disruption in the braking system. The cerebellar subject, unable to anticipate when to initiate the braking process, becomes dependent on afferent input in order to trigger the antagonist response. The inherent delays involved in any closed loop process lead to the oscillations seen in intentional tremor.

One final line of evidence that the cerebellum is involved in timing functions comes from the recent work of Thompson and his colleagues in the area of motor learning (reviewed in Thompson, Clark, Donegan, Lavond, Lincoln, Madden, Mamounas, Mauk, & McCormick, 1984). Their studies lead them to believe that the interpositus/dentate nuclei play a critical role in the storage of conditioned responses during classical conditioning (but see Yeo, Hardiman, & Glickstein, 1985a; 1985b). Moreover, they have found that lesions of the cerebellar hemispheres may not abolish the conditioned response, but will seriously disrupt the timing on this response

(McCormick & Thompson, 1984). Note that the conditioned response (CR) is linked to the onset of the aversive stimulus (US) which follows the CR rather than to the conditioned stimulus (CS) which precedes the CR. The anticipatory nature of the CR strongly suggests explicit timing. Disruption of the timing of the CR following lesions of the cerebellar hemisphere further supports the hypothesis that the cerebellum plays a primary role in timing.

It should be made clear, though, that the abnormalities in the EMG profile and the conditioning results can only be viewed as indirect evidence for timing deficits and alternative explanations may prove viable. Moreover, in each of the above studies, timing has been explored in the context of an explicit motor task. As such they provide no evidence regarding whether the timing capabilities of the cerebellum are utilized for more general purposes.

The experimental tasks employed in the present studies were designed to provide a more direct test of the role of the cerebellum in timing performance. In this paper, we report the results of different patient groups on two tasks requiring precise timing: a production task in which the subjects perform rhythmic tapping and a perception task in which their perceptual acuity of comparable temporal intervals is tested. A following paper will explore the performance of a select group of cerebellar patients in greater detail (Ivry, Keele, & Diener, in press).

Results

In the statistical analyses to be reported below, t-tests were employed in order to compare each of the patient groups with the control subjects. Given our previous results (Ivry & Keele, 1985; Keele et al., 1985a; Wing et al., 1984) showing that various lesions led to deficits in the tapping task, it seemed appropriate to replace omnibus significance tests (Hertzog & Rovine, 1985) with a series of planned comparisons. A consequence of this procedure is that the probability of falsely rejecting the null hypothesis is elevated. To offset this, we adjusted the criterion significance level with the modified Bonferroni test (Keppel, 1982). The significance level was set at .02 and .033 for the tapping and perception tasks, respectively. The levels differ because the peripheral neuropathy patients were not tested on the perception tasks, thus creating fewer comparisons. One-tailed t-tests were used in all comparisons involving patients and healthy subjects since the hypotheses center on whether certain patient groups are impaired in the different tasks. However, there were no a priori predictions regarding the different patient groups, and thus two-tailed tests were employed in any comparisons between patient groups.

Overall Performance

Tapping Results: No differences were observed between the German and Oregon cerebellar patients and thus their data has been pooled in the tables presented

below. Similarly, no differences were observed between the German and Oregon Parkinson patients, and between these two groups and the On-Off patients when medicated. Therefore, these scores were also pooled.

Table 1 presents the results for each control and patient group tested on the tapping task. As can be seen in the second column, there were some differences in the subjects' ability to maintain the target tapping speed. In fact, all of the groups produced a shorter mean interval than that observed for the elderly control group. This tendency is most apparent with the Parkinson patients, with some of these subjects averaging under 500 ms. As a group, their mean interval was significantly shorter than the elderly control subjects ($t(48)=3.47, p<.01$). At present, no strong insights concerning this finding can be offered. The hypothesis that tremor frequency may exert an effect on tapping speed has been tested (unpublished results), but the data is not supportive. Subjects who speed up when tapping with a 550 ms. pace also speed up at all other tapping rates. This issue is further clouded by the finding that the college age controls were also significantly faster than their elderly counterparts ($t(43)=3.70, p<.01$).

The third column of Table 1 presents the mean standard deviation of the IRIs for each group. The two control

groups demonstrate that there is a considerable increase in variability as a function of age ($t(43)=3.86, p<.01$). Given these differences between the two control groups, the patients' performance will only be compared with the elderly control group in subsequent analyses. Of primary interest are the results of the subcortical and cortical groups. As can be seen in the table, the Parkinson patients performed as well as the age matched control group. The cerebellar and cortical groups, however, were much more variable in the tapping task than the elderly control group ($t(46)=-5.03, p<.001$ for the cerebellars; $t(26)=-3.44, p<.001$ for the corticals). In addition both patient groups were significantly impaired in comparison to the Parkinson patients ($t(54)=-4.88, p<.001$ and $t(34)=-2.58, p<.02$ for the cerebellars and corticals, respectively). The standard deviation of the inter-response intervals was approximately 50% greater for the cerebellar patients and 33% inflated for the cortical patients. There was no difference in terms of tapping variability between the cerebellar and cortical groups.

Perception Results: Tables 2 and 3 present the results from the perception tasks. Table 2 shows those groups in which the perception of loudness was included as a

Table 1

TAPPING TASK: GROUP MEANS AND STANDARD DEVIATION					
GROUP	N	INT	SD	CL	MD
Controls					
Elderly	21	550.1 (14.7)	30.6 (7.4)	24.3 (8.1)	11.0 (6.9)
College Aged	24	535.4 (11.9)	23.6 (4.6)	17.9 (4.0)	9.6 (5.0)
Parkinsons	29	524.4 (31.5)	32.2 (8.9)	27.7 (8.1)	9.3 (6.2)
Cerebellars	27	542.0 (26.0)	46.8 (13.2)	38.1 (13.6)	14.0 (11.8)
Corticals	7	543.9 (22.0)	41.5 (16.8)	30.1 (8.3)	18.3 (6.0)
Peripherals	4	529.2 (21.8)	34.0 (3.1)	23.2 (1.2)	17.2 (2.7)
Sensory Loss	2	529.4	29.2	21.4	13.6

Note: Three cerebellar, one Parkinson, and one cortical patient were unable to produce any trials in which all of the intervals were within the criterion of +/- 50% of 550 ms.
Abbreviations: N - Number of subjects; INT - Mean inter-response interval; SD - Standard deviation of inter-response intervals; CL - Clock estimate; MD - Motor delay estimate.

control for general auditory deficits. The perception of frequency was used as a control with the epileptic patients and the results for these groups are shown in Table 3. The mean scores represent an estimate of one standard deviation on the subjects' response distribution. These numbers were calculated by taking the number of steps between the upper and lower threshold points and converting this difference into an estimate of 1.0 standard deviation. Technical problems prevented us from testing three cerebellar, one Parkinson, and four cortical patients on the perception tasks.

Contrary to what was observed in the tapping task, there does not appear to be any decrease in acuity as a function of age in normal populations. Neither task yielded a reliable difference ($t(43)=0.59$ for duration; $t(43)=0.37$ for loudness) between the two control groups although the mean scores were lower for the college age subjects. More interesting is the finding that the two perception tasks appear to be measuring separate processes since there was little correlation between performance on them within the healthy control groups. The correlation coefficient was .14 for the younger subjects and .24 for the elderly group, neither of which is reliably different from zero.

The results of most interest in Table 2 can be summarized quite easily. Only the cerebellar group shows a deficit in the perception of duration task. A comparison with the elderly control subjects revealed a significant difference ($t(46)=-2.31$, $p<.02$). A similar comparison between the cerebellar and Parkinson group only approached significance ($t(53)=-2.07$, $p<.05$). It should be reemphasized that comparisons involving the control group utilized a one-tailed test whereas comparisons between patient groups were based on two-tailed tests. (4) No other comparisons between any of the groups on the perception of duration approached significance. It thus appears that only the cerebellar subjects are impaired in the ability to make time-based perceptual judgments. While this result is in accordance with our hypothesis about the existence of a clock which is used in both production and perception, the results were surprising given the absence of any previous studies reporting purely perceptual deficits associated with cerebellar disorders. In fact, the novelty of this finding was our primary motivation for testing the cerebellar subjects in Oregon. The pattern of results was remarkably consistent across the two cerebellar groups. The mean for the 17 German patients was 44.0 ms. and the mean for the 10 Oregon patients was 48.8 ms. The success of this replication work is quite convincing of the validity of this finding. Furthermore, we have recently retested eleven of the German patients on this task. The eighteen month test-retest reliability correlation was .78 or, when corrected for attenuation, .88.

It is important to note that the cerebellar deficit in the perception of duration task can not be attributed to some sort of general auditory deficit. There were no differences in performance between the cerebellar patients and either

the Parkinson or elderly control subjects in the perception of loudness task. In fact, the pooled mean for the cerebellar groups is slightly lower than that obtained by combining the results of these two comparison groups.

Surprisingly, the results showed that the cortical group was impaired in the loudness task. This difference was significant when comparing their performance to the elderly control group ($t(27)=-2.35$, $p<.02$) and the cerebellar patients ($t(33)=-2.91$, $p<.01$). Comparison with the Parkinson patients does not achieve significance ($t(34)=-2.03$, $p<.06$). Admittedly, the number of cortical patients who have been tested on the perception tasks is quite small and more work must be conducted to establish this finding. Nonetheless, the present results present an interesting double dissociation: one form of auditory processing, the perception of loudness, involves cortical structures whereas another auditory task is dependent on a subcortical region, the cerebellum. More relevant to the present study is the finding that one of the groups was impaired in the loudness task. This serves to demonstrate that each perceptual task was sensitive to potential group differences.

Table 3 is of interest because of other evidence suggesting that the temporal lobes play an important role in timing functions (Carmon & Nachshon, 1971; Effron, 1963; MacKay, 1985; Tallal & Newcombe, 1978). Some of these

Table 2

PERCEPTION TASK MEANS AND STANDARD DEVIATIONS FOR DURATION AND LOUDNESS JUDGMENTS			
GROUP	N	DURATION (ms.)	LOUDNESS (dB.)
Controls			
Elderly	21	28.8 (13.9)	1.02 (0.54)
College Aged	24	26.1 (16.3)	0.97 (0.35)
Parkinsons	28	31.5 (18.3)	1.13 (0.55)
Cerebellars	27	45.7 (31.1)	1.05 (0.36)
Corticals	8	31.5 (18.7)	1.63 (0.82)

Note: Scores are in terms of the estimate of one standard deviation determined by calculating the step difference between lower and upper thresholds and making appropriate transformations.

hypotheses have attributed an explicit timing role to the temporal lobes whereas other ideas have emphasized the sequential nature of left hemispheric function. Sequencing processes may only require the ability to maintain temporal order rather than control some form of real-time metric as is assumed to be required in the present tasks. The results of testing severe temporal lobe epileptics show that these patients do not have any deficit in making duration judgments. This result holds for patients in which the seizure focus is in the left or the right temporal lobe. This finding is somewhat surprising given that some of these patients are intellectually impaired and have some memory disorders (John Walker, Good Samaritan Hospital, personal communication). Unexpectedly, the epileptics did appear to be impaired in the perception of frequency task. These differences, however, were not reliable due to the large variability in both the epileptic and control groups.

Decomposition of Tapping Variability

Two transformations were applied to the raw data in determining the clock and motor delay estimates using the Wing and Kristofferson (1973) model. First, variability was calculated in terms of deviation from a regression line fitted through the 30 intervals for each trial. The motor delay estimate is increased by this transformation since any positive correlation between successive responses due to drift in the subject's subjective base interval will be negated. However, the actual effect turned out to be minimal. Second, the decomposition procedure yielded some estimates which appeared to indicate that certain assumptions of the Wing and Kristofferson (1973) model had been violated. Generally, this involved a Lag 1 covariance estimate which was positive. Alternative models (Wing, 1977) did not appear to be more valid, and thus the violations may best be attributed to the relatively small data set of six trials per block. To minimize the effect of these violations, a motor delay estimate of zero was recorded whenever the Lag 1 covariance estimate was greater than zero and all of the variability was assumed to be due to the timekeeper process. Note that without this substitution, the estimate of the timekeeper variability would be greater than the total variability. As reported in Ivry and Keele (1986), using negative motor delays and clock variances greater than the total variance did not change the tenor of the conclusions.

In the control groups, the percentage of tapping blocks which showed violations of the basic Wing and Kristofferson model was 12.8% (12.5% for the college aged subjects and 13.2% for the elderly control group). Most of these involved Lag 1 covariance estimates which were minimally above zero and can probably be attributed to the fact that each subject only completed two blocks of trials. The patients, however, tended to show a different pattern of results. The peripheral neuropathy patients rarely demonstrated any violations (2% of all blocks) whereas the data of the other patients indicated violations

Table 3

PERCEPTION TASK MEANS AND STANDARD DEVIATIONS FOR DURATION AND FREQUENCY JUDGMENTS			
GROUP	N	DURATION (ms.)	Frequency (Hz.)
Controls			
College Aged	24	26.1 (16.3)	4.96 (4.25)
Temporal Epilepsy			
Left Focus	16	28.0 (16.0)	6.84 (4.91)
Right Focus	13	24.8 (12.5)	7.23 (4.76)

Note: Scores are as in Table 4.

of the model on 21.0% of the blocks. The respective figures were 18.0%, 14.3%, and 26.0% for the Parkinson, cortical, and cerebellar groups. The high percentage of violations, especially for the cerebellar group dictates that these clock and motor delay estimates be considered cautiously.

The fourth and fifth columns of Table 1 show the partitioning of this overall variability score into separable estimates of the variability associated with the timekeeper and motor delay processes, respectively. The age effect observed for the control subjects in terms of increased variability for the elderly subjects appears to be entirely attributable to increased variability in the timekeeper process ($t(43)=3.43, p<.01$). A similar comparison of these groups motor delay estimates revealed no differences ($t(43)=0.79$). (But see Keele et al., 1985a for a similar study in which a different pattern of results emerged.)

The results of the peripheral neuropathy group provide a critical test of the validity of employing the Wing and Kristofferson method in neuropsychological testing. A strong prediction of the model is that any deficit that these patients have should appear as inflated motor delay estimates since the neurological damage, being peripheral, is clearly in the implementation system. The results for the four peripheral patients are supportive. The clock estimate for this group is slightly lower than the elderly control group whereas the motor delay estimate is over 50% higher. This latter difference only approaches statistical significance ($t(23)=-1.75, p<.05$) probably because the number of peripheral neuropathy subjects is so small. (An alternative comparison involving these patients will be presented in the next section.)

Table 4

TAPPING TASK: WITHIN SUBJECT COMPARISONS					
GROUP	N	INT	SD	CL	MD
Parkinsons					
Unaffected Hand	4	528.7	29.3	25.6	9.4
Impaired Hand		540.7	50.1	46.5	11.5
On Medication	7	524.0	33.6	28.4	10.7
Off Medication		521.7	33.6	27.7	11.8
Cerebellars	8	536.4	33.4	25.0	13.5
		537.7	49.1	37.0	20.5
Corticals	7	537.8	33.0	23.8	13.9
		543.9	41.5	30.1	18.3
Peripherals	4	530.2	28.5	22.8	12.1
		529.2	34.0	23.2	17.2

Note: Top line within each pair refers to performance with good effector, bottom line is for impaired effector. On-Off comparison refers to chronic Parkinsonians who were tested in both a normal medicated condition and while foregoing their morning medication periods.

The data from the functionally deafferented patients are supportive of the open-loop assumption of the Wing and Kristofferson model. Specifically, the model states that feedback from a given response interval should have no effect on subsequent intervals. This prediction is supported by the finding that the functionally deafferented subjects' performances were nearly identical to the elderly control subjects. Furthermore, the patients' performance was unchanged following the elimination of visual information. A striking example of the effects of deafferentation with one patient was demonstrated by grabbing her tapping finger part way through a trial to temporarily prevent movement, and then releasing it. The patient was unaware of the perturbation and expressed great surprise at her "poor" score for these trials, scores which were greatly inflated by the long gap during the perturbation. The motor delay estimates of 13.2 and 14.0 are lower than the scores for six of the 21 control subjects, but may still reflect some slight disruption in the implementation pathways. Nonetheless, the more impressive finding is that performance is quite good.

The mean clock and motor delay estimates for both the cortical and cerebellar groups are increased in comparison to the Parkinson patients and elderly control subjects. The statistical analyses of these results, however, are somewhat problematic. In terms of the clock estimate, the cerebellar group performed significantly worse than both the elderly control group ($t(46)=-4.11$, $p<.001$) and the Parkinson group ($t(54)=-3.50$, $p<.01$). The clock estimate for the cortical group only approached the

significance value when compared to the elderly control group ($t(26)=-1.63$, $p<.10$). On the other hand, the cortical group had a significantly higher motor delay estimate than the elderly control subjects ($t(26)=-2.50$, $p<.01$) and the Parkinson subjects ($t(34)=-3.47$, $p<.01$). The cerebellar patients do not show a reliable difference in terms of the motor delay estimate from either comparison group. However, this null result is tempered by the fact that there were a disproportionate number of cerebellar patients who had a positive Lag 1 covariance score and thus received a motor delay estimate of 0.

It is unreasonable, of course, to expect that the subjects with positive Lag 1 covariance had no variability in their implementation process. In other publications, we provide a more detailed analysis of individual subjects and certain forms of violations (Ivry & Keele, 1986; Ivry et al., in press). An alternative which retains the group methodology, is to examine only the data of those subjects for whom the assumptions of the model appear valid. When this analysis is performed, there is only one deviation from the preceding analyses: the adjusted scores yield a reliable difference between the motor delay estimates for the cerebellar patients in comparison to the elderly control group and the Parkinson subjects ($t(32)=-3.04$, $p<.01$ for the elderly control group and $t(36)=-3.46$, $p<.01$ for the Parkinson group).

In summary, the group results of the tapping task indicate that both the cortical and cerebellar patients are more variable in making periodic responses. Although the decomposition results are a bit unclear, the results are in

general agreement with the analysis of the overall variability scores and the perception results. The cerebellar patients were the only group to consistently demonstrate increased variability in the clock estimate. In addition, the motor delay estimate also appears to be increased for this group. More convincingly, the motor delay estimate for the cortical patients was found to be elevated.

Within Subject Comparisons

In addition to the group data, some of the subjects from each of the four neurological groups presented the opportunity for making within subject comparisons. These subsets were mostly composed of patients who showed large clinical differences between two effectors. The benefit of this type of comparison is that the patients can serve as their own control.

The usual procedure employed with these subjects was to alternate testing on the tapping task between the index fingers of the affected and unaffected hand. We have never found any differences as a function of handedness in this task nor have we found any differences between performance with the hand in comparison to the foot (Keele et al., 1985b). Therefore, any differences which appear in these neurological subjects can be attributed to their lesions. Affected-unaffected tapping comparisons were made with seven cortical patients, eight cerebellar patients, three peripheral neuropathy patients, and three Parkinson patients.

There were four other types of within-subject comparisons which will be included in this section. First, we performed a within-hand comparison for the peripheral neuropathy subject with median nerve damage. The efferent innervation pattern for the median nerve is limited to the radial aspect of the hand allowing us to compare thumb and index finger performance with control data obtained from the little finger. Second, a newly-diagnosed Parkinsonian patient provided the opportunity to compare pre- and post-medication performance. Third, one cerebellar subject, who had incurred a hematoma in the posterior, vermal region, demonstrated no clinical signs when using his upper limbs whereas he was affected in movements involving the lower limbs. For this subject the within-subject comparison involves tapping with the left foot and the left hand. Lastly, in this section we will report the performance of the On-Off Parkinson group under both testing conditions.

The results of these single subject mini-experiments are pooled by subject group in Table 4. The top row for each group indicates their performance in the unaffected condition and the bottom row shows their scores when tapping in the affected condition. Almost all of the subjects included in this table completed between four and nine blocks of six tapping trials with each effector. Thus, the data are considerably more stable than in the preceding section in which most subjects only completed two blocks.

The results are in close agreement with that found in

the group comparisons. The peripheral neuropathy patients consistently show increased variability when tapping with the affected finger and this increase is solely assigned to the motor delay component. The increased implementation variability ranged from 15% to 75%. This result further bolsters the critical two-process assumption of the Wing and Kristofferson model.

The cortical and cerebellar patients show increased estimates in both the clock and motor delay estimates when tapping with their affected hand. The degree of the impairment varies from patient to patient in both groups, sometimes affecting the clock estimate and sometimes the motor delay score, but rarely both (see Ivry et al., in press). The point which needs to be made here is that these within-subject comparisons mirror the findings of the group data. Note that in both the cortical and cerebellar groups, performance with the unaffected hand tends to approximate normal performance (i.e., the elderly control group), although there may be a slight increase in the motor delay estimate. In contrast, both the clock and implementation estimates are increased when performing with the impaired effector.

The results for the Parkinson subjects are more problematic. The On-Off comparison shows minimal difference as a function of medication extending the earlier observation that basal ganglia deficits do not affect performance on this task. This result was obtained despite the obvious symptomological changes created by the alteration in the medication cycle. The patients were generally unable to walk and showed extreme bradykinesia in arm movements. Nonetheless, the patients were unimpaired in finger tapping. This result, however, stands in contrast to the within-subject results for the four other Parkinson subjects (bad hand or pre-medication). The Wing and Kristofferson decomposition indicates that there is little difference between the motor delay estimates. The problem for these Parkinson patients stems from increased variability in the timekeeper process. The percentage increase ranged from 55%-114%. It is difficult to reconcile the divergent results observed with the Parkinson patients. We have not been able to account for these findings by classifying patients into the subcategories (e.g., those who are rigid, or have tremor, or are bradykinetic) of Parkinson's Disease cited in the literature (DeLong & Georgopoulos, 1981).

Discussion

Previous work in our laboratory (Keele et al., 1985b; Keele et al., 1987) has led us to postulate that the control of voluntary movement may involve the use of a cognitive operation which controls timing functions. Furthermore, the ability to produce regularly timed intervals was found to correlate with the ability to accurately perceive intervals of a comparable duration. These findings have been interpreted as favoring the existence of an internal time-keeping process. One of the main purposes of the present

research was to identify those neural structures which are part of this timekeeping process. Damage to these neural systems would be expected to lead to difficulty in tasks which involve the timing mechanism. On the other hand, there are no a priori reasons to expect the timing processes to be strictly localized. Thus, the use of neurological patients is useful, not only as a means of further investigating the existence of timing processes, but also as a way of uncovering the nature of those processes.

The results of the patient work are extremely promising. Only the group of cerebellar patients was found to have a deficit in both the tapping and the time perception tasks. These results offer strong support for the hypothesis that the integrity of the cerebellum is critical for the operation of an internal timing process. Most interesting, the domain of this timekeeper is not limited to the motor system, but appears to be employed whenever time-related computations are needed. In the Introduction, we reviewed clinical, experimental, and theoretical work which we believe are suggestive of a timing function of the cerebellum. We believe the results of the perception of time task provide the strongest and most direct evidence in support of this idea. While theoretically supported, the results were quite surprising since the literature does not appear to contain any evidence showing purely perceptual deficits associated with cerebellar lesions, despite the massive input to the cerebellum from sensory pathways (Goldberg, 1985; Ito, 1984; Kemp & Powell, 1971). It is important to reemphasize that the perception of loudness task demonstrates that the cerebellar deficit can not be considered a general deficit in auditory perception, but rather, that the perceptual deficit is specific to timing. Without the conceptual framework of separable operations, such a specific deficit would tend to be overlooked.

Taken together with the tapping results, the results from the time perception task support our earlier hypothesis (Keele et al., 1985b) regarding the existence of a common timing mechanism which is involved in both the production and perception of time. These results represent an important step in developing the concept of the motor program. The motor program is defined at a global level in terms of an abstract representation. However, it is composed of a number of distributed procedures which can be employed in the performance of a wide range of coordinated behaviors. The finding that lesions in the cerebellum affect both the perception and production of time also demonstrate that these distributed procedures can not simply be labelled "motor" or "sensory". A more functionally defined division of cognitive operations may be more appropriate. If the timing process is typical of cognitive operations, the criterion for identifying these operations can be twofold: first, is the procedure specialized for performing a particular function and, second, can the procedure be used regardless of the application for which that function is needed.

The results of the Wing and Kristofferson (1973) model may at first glance appear quite problematic. First,

a consistent percentage of the patients demonstrate violations of the assumptions of the Wing and Kristofferson model. The violations appear to become more evident as tapping performance deteriorates. Second, not only were the cerebellar patients found to have increased clock estimates, but the clock estimate tended (although not significantly so) to be higher for the cortical patients and was considerably elevated in a small subset of Parkinson patients. We believe that these results can be accommodated within the present understanding of the neuroanatomical connections between the various motor systems of the brain. A simplified wiring diagram is provided in Figure 1. The focus in this diagram is on the position of the basal ganglia and cerebellum in relation to the motor cortex and spinal systems.

The first point to be made is that the primary motor cortex and the cerebellum are critical components of the two primary pathways down the spinal cord. The pyramidal tract provides the most direct cortical influence,

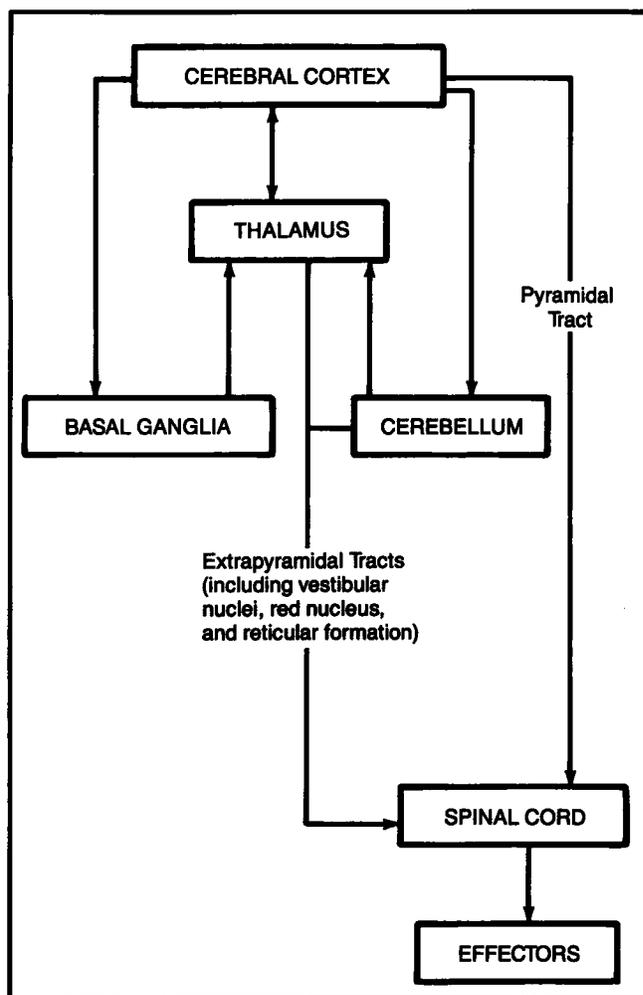


Figure 1. Simplified wiring diagram of the neural structures examined in this study which are involved in tapping. Variability in the loops which return to the cerebral cortex is hypothesized to constitute clock variance. Implementation variance is the result of variability in the descending pathways to the spinal cord.

consisting of neurons which typically originate in the motor cortex and terminate on motoneurons or spinal interneurons. The other pathway is actually composed of a number of different extrapyramidal tracts. Most of these traverse the cerebellum at some point in their circuitry (i.e., cerebello-rubro-spinal, cerebello-reticulo-spinal, cerebello-vestibulo-spinal). Thus, both the motor cortex and the cerebellum have easy access to the spinal neurons. On the other hand, there appears to be little output from the basal ganglia which can have such relatively direct influence on the spinal neurons (e.g. DeLong & Georgopoulos, 1981). This arrangement meshes nicely with the finding that both the cerebellar and cortical patients may produce inflated motor delay estimates. At least part of the lesioned tissue in these patients is presumably outside of the timing system and part of the implementation pathways. More interesting, there have never been any increases in the motor delay scores in either the Parkinson groups or the few Parkinson patients who had difficulty in the tapping task.

To account for the clock estimates, it is necessary to propose that the three neural systems are either part of a timing loop or nested within a circuit in which the cerebellum plays a primary role in timing. A loop- or circuit-based hypothesis is necessary to account for the fact that damage in either the cerebellum, cerebral cortex, or the basal ganglia can increase the variability of the timing process. The independence assumption of the Wing and Kristofferson model implies that any system which was not contained within the timing process could only affect the motor delay estimate.

There are at least two different types of timing circuits, each of which is sketched in Figure 2. The first type (Figure 2A) would implicate all of the different structures within the circuit in the control of timing. For example, the timing of 400 ms. would involve setting up a path through the loop which takes 400 ms. to circuit. 500 ms. paths would presumably involve more synapses or slower conducting neurons in order to increase the amount of time it takes to complete each circuit. Damage at any point along the circuit would disrupt the normal functioning of this type of clock.

There are a number of problems with this type of mechanism. For one thing, the pathways involving the basal ganglia and the cerebellum presumably do more than just provide long delay lines. Yet this notion of loop timing seems to presume that the actual circuits traversed throughout the entire motor pathways are determined on how much delay they contribute to the overall transmission time. Secondly, there is little overlap between the cortical-basal ganglia and the cortico-cerebellar loop despite the common relay of both subcortical structures in the ventral portion of the thalamus, and thus the circuit can not really be continuous (Goldberg, 1985; Schell & Strick, 1984; Yamamoto, Hassler, Huber, Wagner, & Sasaki, 1983). Furthermore, it is difficult to construct such a mechanism without postulating some sort of control

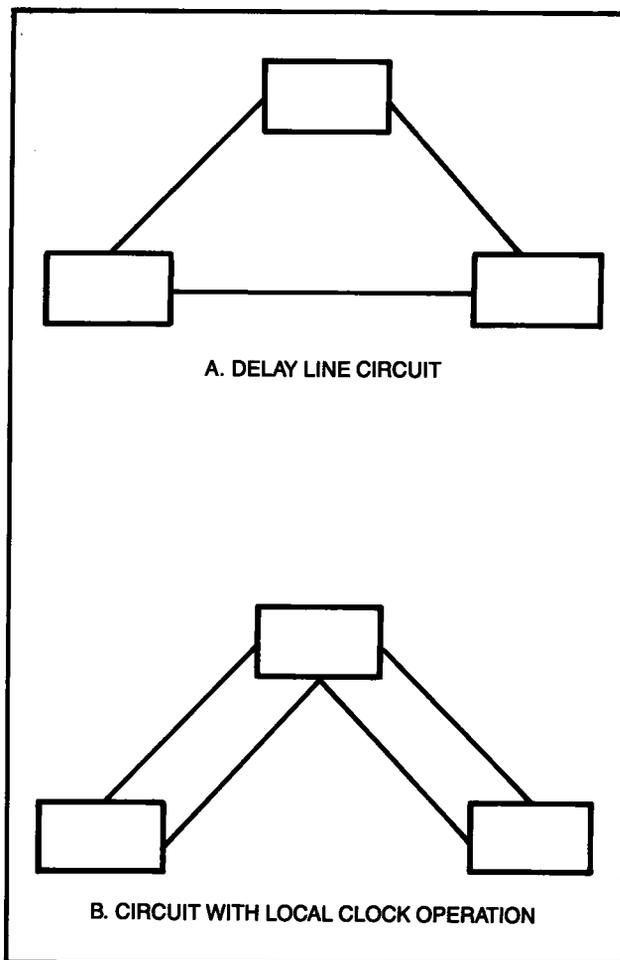


Figure 2. Two forms of a timing circuit.

system which determines the circuit of the loop. A loop traversing such diverse structures needs to be controlled by a system operating at a very global level. On the grounds of plausibility it seems reasonable to argue for local operations whenever possible. (5)

The second form of a timing circuit (Figure 2B) captures this last property quite well. The proposal is that the cerebellum plays a primary role in timing in the spirit of the millisecond timer proposed over 20 years ago by Braitenberg (1967). Cerebellar subjects demonstrate substantial increases in that portion of the variability attributed to the timing process in the tapping task. More surprising, they are the only group which showed any deficit in the perception of time task. This timing function of the cerebellum, though, is still contained within the circuit which in its entirety constitutes the motor program. We believe that the cerebellum performs the operation of computing the timing requirements for a motor program. This hypothesis is not only in accord with the anatomical data sketched in Figure 1, but is also supported by physiological recordings which have indicated that cerebellar output precedes activity in the motor cortex (Sasaki & Gemba, 1984; Thach, 1975). We propose that the cerebello-cortical signal contains explicit timing information.

In addition to the results with the cerebellar patients, timing deficits may also be observed following cortical lesions and certain basal ganglia disorders. The present model can accommodate these results. For the sake of argument, imagine that the motor cortex has just sent a signal down the pyramidal tract which triggers a key press. This signal then initiates the process needed to determine the next response. A number of different procedures or operations are then invoked. The present results indicate that at least one aspect of cerebellar function is to determine the time at which the response should be made. The basal ganglia presumably provide some other parameter input, perhaps setting the appropriate levels of force activation (Anderson & Horak, 1985; Hallett & Khoshbin, 1980). When all of the computational outputs of the various procedures are returned to the motor cortex, the next response is triggered. Once this occurs, the cycle is repeated and each procedure is again executed. The important point to note from this simplified example is that deficits which affect any of the procedures or disrupt the system at any point prior to the triggering of a response will contribute to increased timing variability. The affected structures may not play any direct role in timing control, but they can induce added noise in the timing circuit since the different subroutines can not be called until the preceding response has been initiated.

Lastly, we would like to briefly consider why the cerebellum is involved in timing control. Perhaps there is something special about the neuroanatomy of the cerebellum which makes it conducive for timing functions. As discussed in the introduction, Braitenberg's early conjecture (1967) that the cerebellum was a millisecond timer was proposed because of the unusual neural structure and neurophysiological responses of the cerebellum. An alternative approach would be to consider other functions associated with the cerebellum and examine their relationship to timing. Can they be explained in terms of a timing process? Or, perhaps the timing functions are one manifestation of a more general characteristic of cerebellar functions.

A tentative proposal intended to motivate future research is that the cerebellum can be characterized as a temporally predictive device. This proposal is based on three seemingly disparate functions associated with the cerebellum.

First, as the present research has demonstrated, one function of the cerebellum is to perform timing functions. In both production and perception tasks, accurate timing requires the ability to predict when an event should occur. In order to produce rhythmic tapping, the subject must predict when the next response should occur. Likewise, the perception task may be performed by determining if the final tone, which signalled the end of the test interval, occurred early or late. The subject had formed some sort of prediction of when the tone should have occurred and this serves as the basis of comparison.

A second example of the cerebellum as a predictive

device stems from the recent work on classical conditioning in the rabbit (Thompson et al., 1984; Yeo et al., 1985a; 1985b). These researchers have demonstrated that the engrams of classical conditioning are stored in either the cerebellar nuclei or hemispheres. These learning paradigms involve an element of prediction in that the organism must be able to anticipate the onset of the unconditioned stimulus in order to render the conditioned response adaptive. Thus, the animals in Thompson's laboratory are successful when the SOA is 250 ms. as are those in Yeo's laboratory when the SOA is 500 ms. Both sets of animals learn to produce the eyeblink shortly before the onset of the puff of air.

A third example of the cerebellum as a predictive device comes from work on the role of the cerebellum in efference copy. Efference copy refers to the process whereby a system is provided with some sort of model of an ongoing movement. Most theories (e.g., Hore & Vilis, 1984) posit that this process involves the generation of a model of the expected pattern of afferent information. The efference copy must then be compared with the actual afferent signal in order for the system to rapidly compensate for unexpected perturbations. The cerebellum is frequently assumed to be involved in this comparison process (Allen & Tsukahara, 1974; Arshavsky et al., 1983; Ito, 1984). The efference copy presumably incorporates some form of prediction or delay since the afferent signal is continuously changing over time. Furthermore, it is generally assumed that the efference copy is generated at the same time as the movement commands are issued. Thus, the cerebellum is provided with the signals for the efference copy well before the afferent signals are available.

In conclusion, these three, seemingly independent processes—timing control, classical conditioning, and efference copy—all involve an element of temporal prediction. Perhaps each of these functions involves the cerebellum because of this shared characteristic. The relationship may be indirect in that each process independently exploits special properties of the cerebellum. Alternatively, the same neural subsystems of the cerebellum may be involved in all three processes. The present study has shown that timing control is an operation performed by the cerebellum. Whether there is a more general description of the function of the cerebellum which encompasses timing, remains an open question.

Methods

Subjects

Cerebellar Patients: There were a total of 30 cerebellar patients. Nineteen of these patients were tested at a neurology clinic in Tuebingen, Germany (mean age=44.2, sd=14.8). The remaining cerebellar patients (n=11, mean age=63.2, sd=11.8) were tested at various locations in Oregon. The most likely explanation for the difference in age between the two cerebellar groups is that most of the

Oregon patients had incurred a focal cerebellar disturbance due to stroke or tumor. As with most forms of stroke, the majority of these patients are elderly. In contrast, many of the German patients were considered to suffer from a degenerative cerebellar disease, the diagnosis being based on clinical examination and radiographic data. Sixteen German subjects were in the atrophy subcategory as were two Oregon patients. The degree of atrophy varied from mild to severe and in some cases, the atrophy was suspected to have extended into nuclei that project to the cerebellum (e.g., olivopontocerebellar atrophy). The onset of these diseases varies greatly, but tends to occur in the third or fourth decade of life when there is a familial history (Konigsmark & Weiner, 1970) and slightly later in sporadic cases (Plaitakis, 1982). Eleven of the other cerebellar patients had incurred focal lesions either as the result of stroke ($n=6$) or from tumors ($n=5$). (See Ivry et al., in press, for a more thorough discussion of many of the patients with focal lesions.) In all of the latter cases, the tumors had been removed prior to testing and the surgery had necessitated the removal of at least part of the cerebellum. None of the operations had involved surgery which extended into the brain stem. The remaining patient was diagnosed as having severe cerebellar dysfunction due to an autoimmune reaction. Other patients for whom the primary diagnosis was cerebellar ischemic lesion were excluded because there was some evidence that the damage had extended into brain stem structures.

Parkinson's Disease Patients: The Parkinson patients can be separated into three groups which will be referred to as the Oregon, German, and On-Off groups. The Oregon group ($n=12$, mean age=66.8, $sd=8.8$) and the German group ($n=11$, mean age=58.0, $sd=9.9$) were all tested with the same protocol. All of these subjects were tested without any changes in their normal medication schedule and thus were receiving some form of L-dopa at the time of testing. The On-Off group ($n=7$, mean age=65.1, $sd=7.9$) was tested in two separate sessions, once in which they were in their normal medication cycle and once in which they had skipped their morning medication periods. Four of these subjects were first tested when they were "off" medication and the other three were first tested when they were "on" medication. The two sessions were usually separated by one week.

Cortical Patients: Eight cortical patients were tested in Germany (mean age=58.4, $sd=7.9$). All had incurred lesions, confirmed by CT scans, which extended into the posterior region of the frontal lobe. These subjects presented some hemiparesis on the side contralateral to the lesion, although the degree to which they were affected varied greatly. These patients were tested at least one year after their illness, and thus their situation had stabilized to a point in which some function had returned in the hand contralateral to the lesion. Four additional cortical patients

were tested on the perception tasks only. These latter patients (mean age=65.0, $sd=9.3$) were all tested in Oregon within one month of a stroke. None of these patients were capable of moving the fingers on the contralateral hand. There was no clinical or radiological evidence that any of the cortical patients had damage in any subcortical nuclei. Six of the cortical patients had incurred left hemisphere lesions and six had right hemisphere lesions.

Peripheral Neuropathy Patients: This group included 4 subjects (mean age=55.8, $sd=18.8$) who had experienced some impairment of their hand coordination due to peripheral nerve damage. Two of these subjects had ulnar nerve damage, one median nerve damage, and one had suffered an entrapped nerve at the level of the shoulder. In some of these patients, the neuropathy had produced muscular atrophy. Our criterion for this group was not so much based on the type of peripheral neuropathy, but rather that the subject experienced some difficulty in making finger movements due to a deficit which did not involve central nervous system structures.

Sensory Loss Patients: Two subjects (ages 61 and 65), functionally deafferented below the level of the elbow on the right side, were examined. The polyneuropathy for one patient was the result of sensory polyradiculitis and had produced complete loss of all deep and surface sensation. Motor functions appeared to be normal except for some mild atrophy of the small hand muscles. The left arm of this patient had been amputated and thus we were not able to make any within-subject comparisons. The sensory deficits were bilateral for the other patient resulting from a severe chronic polyneuropathy. Sensory submodalities served by both myelinated and unmyelinated fibers were affected. Cutaneous, thermal, position, and vibration sensation were absent in the hands, gradually reappearing in the upper arms. Nerve conduction studies revealed highly abnormal sensory nerve action potentials. In contrast, motor conduction velocities were normal.

Epileptic Subjects: Twenty-nine epileptic subjects were tested on the perception tasks only. These tasks were included in an assessment procedure to determine the effects of temporal lobectomy surgery on perceptual and cognitive functioning. The patients are thus severe, chronic epileptics in which the seizure disorder has a primary focus in the temporal lobe. Sixteen of these subjects were scheduled for or had undergone a left temporal lobectomy and the disorder was right-sided for the remaining 13 subjects. The mean age of these subjects is not available, but almost all of these subjects are between the ages of 16 and 30. Some of the epileptic patients were tested both before and after surgery. No differences were observed and thus only the first score obtained from each subject will be reported. Some of the subjects were only tested post-surgery.

Control Subjects: Two groups of control subjects were tested. One group was composed of college aged students ($n=24$) who volunteered for the experiment in order to fulfill requirements for psychology courses at the University of Oregon. All of these subjects were below the age of 25. The other group was composed of subjects who were above the age of 50 ($n=21$, mean age=66.7, $sd=7.8$). All of these subjects reported a medical history which was free of any neurological problems. These subjects were paid \$5 per hour. (Any patients tested in Oregon were also paid \$5 per hour. The German subjects were not paid.)

Procedures

The tasks which were used in these experiments have all been used in previous experiments (Keele et al., 1985b; Keele et al., 1987; Pokorny, 1985). The reader is advised to consult these manuscripts for detailed descriptions of both the methodologies and the underlying logic supporting each methodology.

Tasks

1. Production of Time (tapping) Task

The subject was seated with the arm used for tapping resting on a table, palm down. The subject placed the designated effector on a microswitch mounted on a wooden block. The designated effector was usually the index finger of the subject's dominant hand unless the neurological deficit dictated otherwise. One exception was when the affected hand was the non-dominant hand for lateralized patients. A second exception was with the peripheral patients who used the finger which was the efferent target of the affected nerve. Pressing the microswitch provided a pulse to an Apple II computer which recorded all responses to the nearest millisecond.

Each trial began with a series of 50 ms tones (65 dBA) presented at regular intervals of 550 ms. This pace is sufficiently slower than the maximal tapping rate of all of the subjects, assuring that no subject had a problem maintaining the pace. (The 550 ms. pace was especially selected with the Parkinson subjects in mind given that slowness of movement is a cardinal sign of the disorder). A subject was instructed to begin tapping along with the tones once he or she had internally established the desired pace. After the subject's first response, 12 more tones were presented during which time the subject attempted to synchronize his or her responses. The subject was instructed to continue tapping at the same rate when the tones ended. After 31 self-paced taps had occurred, the computer signalled the end of the trial. Feedback was provided indicating the mean interval produced with and without the tones and the standard deviation of the inter-response-intervals (IRI).

Each block of trials was concluded once the subject had produced either six "error-free" trials (sequence of 12 paced and 31 unpaced responses) or six "unsuccessful" trials. A trial was considered unsuccessful if any IRI was less than or greater than 50% of the base duration (less than 275 ms or greater than 825 ms). The data from the unsuccessful trials were excluded from subsequent analysis. This is a criterion which we have adopted in our previous research with normals since such deviant values could be due to either tremor or insufficient force to register a response. All subjects performed in at least two blocks of tapping trials and many (noted in the results section) participated in additional blocks. Thus, each subject produced a minimum of 12 error-free trials. The standard deviation of the inter-response-intervals serves as our primary measure of timing regularity.

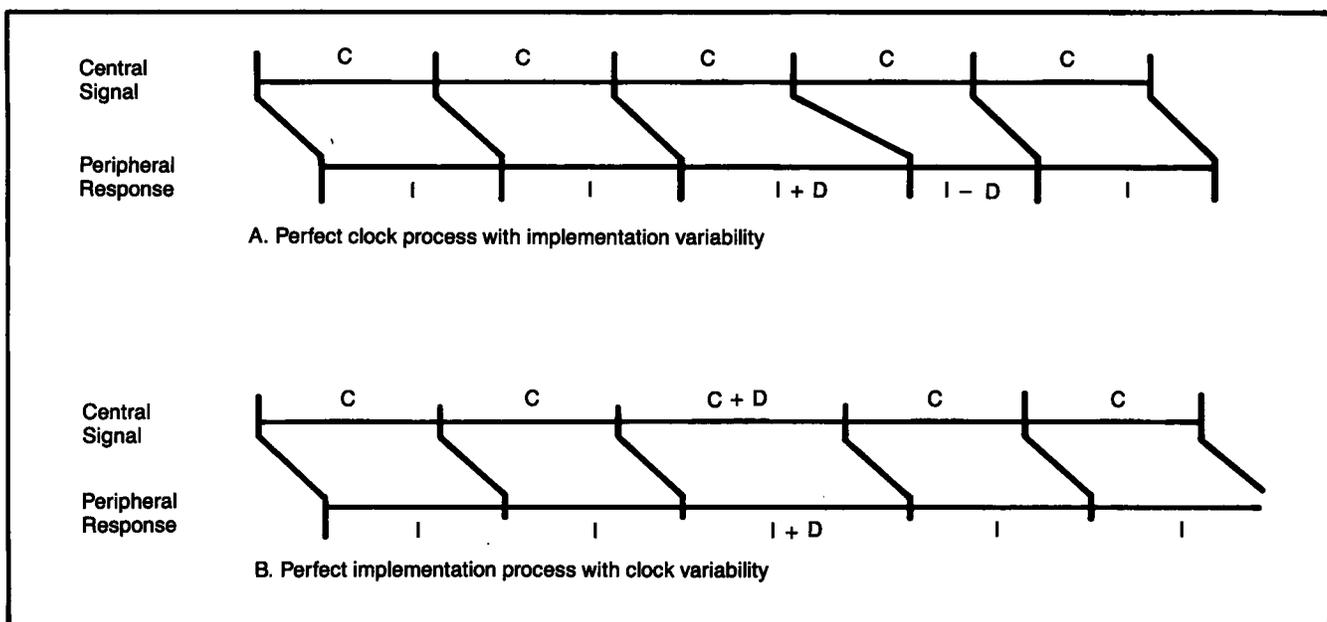


Figure 3. Hypothetical series of inter-response-intervals (IRI) resulting from the two process model of Wing and Kristofferson (1973).

An extended analysis of the tapping data is based on a theoretical model of the timing of repetitive movements developed by Wing and Kristofferson (1973). At the heart of this model is the notion that there are two processes which are involved in periodic behavior: a timekeeper system which determines when a response should be emitted and an implementation system which executes that command. The Wing and Kristofferson model postulates that the variability of the IRIs will arise from variability in these two processes. In other words, the total variability observed in the tapping task represents the independent contribution of the timekeeper and the implementation process. Each process is assumed to behave as an independent random variable with normal variance. Furthermore, the two processes are assumed to operate independently of each other. Taken together, these assumptions mandate that the system operate in an open-loop (i.e., feedback-free) mode.

Figure 3a depicts these processes in a hypothetical series of responses in which the variability of the timekeeper is zero. Each IRI is the sum of a timekeeper interval plus the difference in motor delays associated with the initiation and termination of that response. Formally, the duration of interval j can be written as

$$I_j = C_j + MD_j - MD_{j-1} \quad (\text{Eq. 1})$$

where I , C , and MD symbolize the interval, clock, and motor implementation (delay) durations, respectively. Since the two sources of variance are independent, it follows that :

$$\sigma_I^2 = \sigma_C^2 + 2\sigma_{MD}^2 \quad (\text{Eq. 2})$$

(1). σ_I^2 is directly obtained from the subject's data. It is the variance of the responses. The Wing and Kristofferson (1973) model decomposes this total variability into separable estimates of the timekeeper and the implementation variability from the covariance function of the series of responses. In short, a randomly large motor delay will produce both a long preceding response and a short following response (as shown at intervals 3 and 4 in Figure 3a). Although this may appear to be a corrective process, it is actually the result of the independence between the timekeeper and implementation system. It can be seen in Figure 3a that motor delay variation induces a negative covariance between successive intervals, and the magnitude of that variance serves to estimate motor delay variance. Figure 3b, which depicts an analogous series of taps in which σ_{MD}^2 equals zero, shows that there is no similar dependency between successive intervals as a function of imprecision in the timekeeper. Thus, an estimate of σ_{MD}^2 is obtained from the lag one autocovariance, or more specifically:

$$\sigma_{MD}^2 = -\text{autocov}(1) \quad (\text{Eq. 3})$$

σ_C^2 can now be obtained by making the appropriate substitutions in Equation 2. Note that the estimates of the

two independent processes are not obtained independently. The estimate for clock variance is obtained by subtraction of motor variance from total variance.

Support for the model has been obtained in a number of studies. The model accounts well for the autocovariance functions produced by normal subjects (Wing & Kristofferson, 1973). The correlation between successive intervals is almost always negative whereas the covariance for lags greater than one is minimal. (2) Second, Wing (1980) reported that only the estimate of the timekeeper variability was related to the duration of the base interval. As predicted, the motor delay estimate was constant.

2. Perception Tasks

All of the perception tasks (duration, loudness, and pitch) used the threshold procedure developed by Taylor and Creelman (1967) and extended by Pentland (1980; also Lieberman & Pentland, 1982). The Parameter Estimation by Sequential Testing (PEST) procedure determines a criterion threshold or response probability for any psychophysical function whose shape can be assumed to conform to a standard symmetrical ogive. The distribution mean is arbitrarily designated and will serve as the standard stimulus. The standard deviation is fixed according to our simulation work and previous research. (3) The test stimulus for each trial is selected as the current estimate of either the upper or lower threshold point. Following the subject's response, a revised estimate of the distribution can be made. This procedure will determine the new threshold estimates and thus the next test stimulus. The advantage of the PEST method is that the amount of information gathered by each measurement is maximized since trials which use test stimuli that are not near the threshold points are avoided.

In the present experiments, the test threshold was set at 1.5 standard deviations from the point of subjective equality. This approximates points along the logit distribution at which the subject is correct on approximately 90% of the trials. The differences between the upper and lower threshold points were used as measures of perceptual acuity. These estimates were based on 25 judgments for the upper threshold and 25 judgments for the lower threshold.

2a. Time Perception: Subjects compared successive intervals generated by two pairs of tones. Each 1000 Hz tone was 50 ms in duration and played at a volume of 73 dB (A). The stimulus onset asynchrony between the first pair of tones was always 400 ms and was designated the standard interval. One second after the offset of the first pair, the second pair was presented. On half the trials the interval between the second pair of tones was chosen in order to estimate the lower threshold (i.e., the point at which the subject would respond "shorter" on 90% of the trials) and on the other half of the trials the upper threshold was sampled (i.e., the point at which the subject would correctly respond "longer" on 90% of the trials). On each

correctly respond "longer" on 90% of the trials). On each trial the subject responded by indicating whether the second interval was longer or shorter than the standard, first interval. The logit distribution was divided into 61 equal steps with 8 ms. between each step. Thus, the actual values which could be tested were limited to 8 ms. steps between 160 ms. to 640 ms.

2b. Loudness Perception: This task was included in order to serve as a control for general auditory deficits. Difficulty in the time perception task may not be the result of a specific deficit in the timing process, but rather, could reflect a general inability to process auditory stimuli. The procedure was similar to the time perception task in that each trial involved two pairs of tones separated by one second. The tones within each pair were always separated by 400 ms and the duration of each tone was 50 ms played at a frequency of 1000 Hz. The volume of the two tones in the first pair was 73 dB (A), whereas the volume of the second pair varied. The subject judged whether the volume of the second pair was louder or softer than the standard. The logit distribution was divided into 61 steps with approximately 0.27 dB (A) between each step. The actual range of test values was therefore limited to fall between 64.9 dB (A) and 81.1 dB (A).

2c. Frequency Perception: This task was included as the auditory control in our testing with one group of subjects, the temporal epilepsy group. The procedure was identical to that used in the other two perception tasks except that the second pair of tones varied in frequency as opposed to either duration or loudness. Each of the 61 steps were separated by 1.16 Hz creating in effect a test range spanning from 965.2 Hz to 1034.8 Hz.

Order of Tasks

In general, a standard protocol was used with both the Oregon and German groups, the only difference being that an interpreter was employed for instructing the German patients. The testing began with a block of tapping and then alternated between the perception tasks and more tapping blocks. Subjects were always given some practice on the tapping task prior to the first block. However, with certain patients, the protocol was varied. For instance, patients with unilateral lesions were generally tested extensively on the tapping task since both the affected and unaffected hand could be tested in order to obtain within-subject control data. For these subjects, one block of data per hand was obtained successively. The hand order was counterbalanced. Except for the epileptic patients, the time perception task always preceded the loudness perception task. The epileptic patients were only tested on the perception of time and frequency tasks, the order being counterbalanced across subject.

Notes

1. This follows since, if x and y are independent random variables,

$$\sigma_{x+y}^2 = \sigma_x^2 + \sigma_y^2$$

2. The model predicts that the covariance of all lags greater than 1 should be zero. Timekeeper variability does not contribute to the covariance estimate at any of the lags greater than zero. Implementation variability will also not produce any non-zero covariance estimates at lags greater than 1 since its effect is limited to the intervals bordered by a single response.

3. Simulation studies (Pokorny, in preparation) show that the method is robust over a wide range of initialization values. Initial selection of a mean value which deviates from the value used for the standard stimulus does not increase the variability of the threshold estimates if a sufficient number of trials are used to obtain the estimates. Similarly, discrepancies between the standard deviation value used to establish the initial function and the actual standard deviations do not create errors as long as the initialization values create a sufficiently large range of possible test values.

4. In a preliminary report of this research (Ivry and Keele, 1986), the Parkinson and elderly control subjects were pooled and tested against the cerebellar patients. This may be appropriate since there are no differences between the Parkinson subjects and the control subjects on any of the tasks and their ages are comparable. If a similar t-test were made with the present data, a highly significant perception of duration deficit is found for the cerebellar patients ($t(74) = -2.66$, $p < .01$) with a two-tailed test.

5. The argument that the timekeeper should be considered a local operation should not necessarily be taken as a more general statement. The framework which we are developing in our laboratory is that the process of movement control can best be understood with a distributed model. Coordination involves a number of independent computational procedures which are distributed across a number of neural systems. Within a given neural system, however, the computation may be quite specific and thus that operation is locally controlled. See Rummelhart and McClelland (1986) for a similar argument.

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