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Impaired Capacity of Cerebellar Patients to Perceive and Learn Two-Dimensional Shapes Based on Kinesthetic Cues

Yuri Shimansky, Marian Saling, David A. Wunderlich, Vlastislav Bracha, George E. Stelmach, and James R. Bloedel¹

Division of Neurobiology
Barrow Neurological Institute
Phoenix, Arizona
The Motor Control Laboratory
Arizona State University
Tempe, Arizona

Abstract

This study addresses the issue of the role of the cerebellum in the processing of sensory information by determining the capability of cerebellar patients to acquire and use kinesthetic cues received via the active or passive tracing of an irregular shape while blindfolded. Patients with cerebellar lesions and age-matched healthy controls were tested on four tasks: (1) learning to discriminate a *reference* shape from three others through the repeated tracing of the *reference* template; (2) reproducing the *reference* shape from memory by drawing blindfolded; (3) performing the same task with vision; and (4) visually recognizing the *reference* shape. The cues used to acquire and then to recognize the *reference* shape were generated under four conditions: (1) “active kinesthesia,” in which cues were acquired by the blindfolded subject while actively tracing a *reference* template; (2) “passive kinesthesia,” in which the tracing was performed while the hand was guided passively through the template; (3) “sequential vision,” in which the shape was visualized by the serial exposure of small segments of its outline; and (4) “full vision,” in which the entire shape was visualized. The sequential vision condition was

employed to emulate the sequential way in which kinesthetic information is acquired while tracing the *reference* shape. The results demonstrate a substantial impairment of cerebellar patients in their capability to perceive two-dimensional irregular shapes based only on kinesthetic cues. There also is evidence that this deficit in part relates to a reduced capacity to integrate temporal sequences of sensory cues into a complete image useful for shape discrimination tasks or for reproducing the shape through drawing. Consequently, the cerebellum has an important role in this type of sensory information processing even when it is not directly associated with the execution of movements.

Introduction

A century of investigations examining the characteristics of cerebellar systems and the deficits produced by cerebellar lesions has provided many insights into cerebellar function (Dow and Moruzzi 1958; Gilman et al. 1981), including the fact that this structure is involved in processing information derived from representing a wide variety of sensory modalities via an involvement of many central projections (Bloedel and Courville 1981). These inputs include projections arising from muscle spindles, tendon organs, and joint receptors, as well as from a wide variety of cutaneous mechanoreceptors (Bloedel and Courville 1981; Granit 1970). Most discussions regarding the pro-

¹Corresponding author.

cessing of these inputs have emphasized their role in the regulation of movements (Gilman et al. 1976, 1981; Granit 1970; MacKay and Murphy 1979; Kawato and Gomi 1992; Stein and Glickstein 1992).

The importance of the sensory processing produced by the cerebellum was emphasized recently by Paulin (1993), who suggested that this cerebellar-dependent integration could contribute substantially to the ongoing control of movement. Perhaps because the processing of sensory information by components of the motor system is so tightly coupled to the generation and control of movements, few investigations have been undertaken to examine the contributions of these central structures to the perceptual phenomena resulting from the activation of these same afferent inputs. However, the divergent, parallel organization of cerebellar efferent systems to many central sites that are not related directly to movement generation (see Haines 1997) suggests that the processing of sensory information by this structure does not necessarily have to be associated with a motor action. Recently, Gao et al. (1996) published a provocative study in which they provided evidence that the cerebellum could contribute to the perception of cutaneous stimuli even if movement or the intent or need to move was excluded as a factor. This result suggests that, independent of the capacity of a central nervous system component to employ this sensory processing in motor control, it also may contribute to sensory perception. In addition, there is progressively mounting evidence that the cerebellum may have a role in the recognition and/or perception of different stimuli even when these stimuli are dissociated from the need to generate movements. For example, Canavan et al. (1994) demonstrated that cerebellar patients had a decreased capacity to recognize abstract visual cues when compared with normal subjects. The experiment reported here examines whether the cerebellum contributes to the perception of kinesthetic cues.

It is well known that kinesthetic cues are employed during the execution of normal movements (Cordo and Flanders 1989; Lovelace 1989; Tillery et al. 1991; Soechting and Flanders 1992). These cues are processed rapidly enough to provide highly relevant information required for the on-line control of volitional limb movements (Cordo 1988, 1990; Flanders and Cordo 1989). It is also clear that coding of target and limb position can employ coordinate systems that are based

on kinesthetic information (Tillery et al. 1991; Darling and Miller 1993). Many of these applications of kinesthetic information require transformations of sensory inputs from the periphery into reference frames that are suitable not only for generating movements but also for generating visual representations of body position or the characteristics of external objects or conditions being evaluated.

The importance of the cerebellum for the transformation of sensory cues into a representation within a coordinate system appropriate for controlling movements has been emphasized extensively by Pellionisz (1985), Pellionisz and Llinas (1985), and Paulin (1993). Roll and Gilhodes (1995) showed recently that important transformations may occur specifically related to the processing of kinesthetic information. They demonstrated that transformations of proprioceptive cues may be responsible for representing spatial features of limb trajectories in joint space coordinates. Furthermore, kinesthetic information is likely required for deriving optimally an internal representation of the position of visualized targets in extrapersonal space (Tillery et al. 1991). Given the substantial amount of kinesthetic information received by the cerebellum and its capacity to affect interactions in motor pathways, this structure could contribute to these functionally critical transformations. If so, and if the premise of our experiment is correct, this cerebellar-dependent processing also could contribute to the perception of kinesthetic cues.

One of the few previous studies addressing the issue of the participation of the cerebellum in kinesthesia was performed by Grill et al. (1994). These investigators examined the perceived duration, amplitude, and velocity of passively imposed finger movements. Statistically significant deficits in the capacity to differentiate between joint displacements of different durations and between different velocities of ramp displacements were reported. Although these deficits were not profound, they suggested the possibility that the cerebellum may in fact contribute to the perception of kinesthetic cues. The present study pursued the role of the cerebellum in kinesthesia from a somewhat different perspective. Rather than examining the perception of relatively simple cues, our paradigm requires that a higher order of information processing be performed—the formation of an internal representation of the shape by integrating temporal sequences of kinesthetic cues re-

ceived through the active or passive tracing of an irregular shape while blindfolded. We hypothesized that the optimal on-line processing of temporal and spatial kinesthetic cues required for the execution of this task involves integration performed by the cerebellum. The experiment employed a learning paradigm to determine whether repeated exposure to the same shape improved the capacity of the subjects to recognize it among other dissimilar shapes, a process likely to depend on the establishment of an internal representation of the original image.

In the first task of the experiment, we compared the capacity of normal subjects and cerebellar patients to improve their discrimination of a *reference* template from three others using one of four different ways to assess its shape and compare it with the test templates: active tracing of the *reference* template with their eyes closed; passive tracing of the *reference* with their eyes closed; sequential visualization of successive segments of the template; and complete visualization of the *reference* template. This design made it possible to compare the acquisition and evaluation of cues using kinesthetic information with those observed when visual information was employed. Second, to determine whether subjects could draw an outline of the *reference* shape once acquired under each of the above conditions and to test whether visualization of the hand during drawing made a difference in the performance of the subjects, we compared their capacity to reproduce the *reference* shape by drawing, first while blindfolded and then with vision. In the last task, the capacity to recognize the *reference* shape visually was tested. This part of the experiment evaluated whether the subject could recognize the *reference* shape when no kinesthetic cues were required. The present study is the first to assess the performance of these types of complex tasks requiring kinesthetic cues in patients with cerebellar disorders.

The data will demonstrate that unlike normal subjects, cerebellar patients are substantially impaired in their capability to perceive two-dimensional irregular shapes based only on kinesthetic cues. This impairment is manifested in all the above tasks. Evidence also will be presented indicating that this deficit in part relates to a reduced capacity to integrate temporal sequences of sensory cues into a complete image useful for performing recognition tasks or for representing the shape through drawing. Preliminary data from this

study has been presented previously (Shimansky et al. 1996).

Materials and Methods

Experiments were performed with seven patients having chronic, isolated cerebellar lesions and seven age-matched healthy controls, all of whom participated after providing full consent on the basis of all guidelines specified by the Institutional Review Board for Human Research. A brief summary of their clinical characteristics is given in Table 1. As outlined in Figure 1, the experiment was performed in two phases, the shape acquisition/discrimination phase and the drawing and visual recognition phase. Throughout both phases of the experiment, the subject was seated comfortably in front of a table on which the experimental manipulations were performed.

SHAPE ACQUISITION/DISCRIMINATION PHASE

In the first phase of the experiment, subjects were tested on their capacity to recognize an irregularly shaped object based on information regarding its shape acquired under four different conditions. In the first two conditions, blindfolded subjects acquired information about the shape of an object either by moving a pen actively through a grooved template three times [active kinesthesia (AK)] or by holding a pen-shaped manipulandum that was moved passively through the grooved template while the elbow was suspended above the surface of the table [passive kinesthesia (PK)]. In the third condition, the subject was exposed to the object's shape using a sequential vision (SV) paradigm. For sequential presentation of the object's shape, the template was covered by a non-transparent disk with a 10-mm gap exposing only ~3% of the outline of the template at any one time. The disk was then rotated at a speed of 4 rpm. (one full turn in 15 sec), a speed that matched that of the active or passive movements performed during the first two conditions. In the fourth condition, the shape of the object was visualized in its entirety [full vision (FV)].

A different set of template shapes was used in each of these acquisition/discrimination paradigms. The degree of template shape complexity was the same in AK, PK, and SV conditions,

Table 1: *Clinical characteristics of patients in this study*

Subject	Diagnosis	Radiological findings ^a	Deficits
1. G.M.: male, 49 years	right cerebellar arteriovenous malformation (resected in 1992)	CT: large lesion involving the right cerebellar hemispheric cortex, vermis, and the cerebellar nuclei	dysarthria, ataxia of right arm and leg, a significant intentional tremor, and a slight ptosis (1 mm) on the right side
2. C.R.: male, 58 years	left cerebellar cortex tumor (tumor and undersurface of the tentorium excised in 1988)	MRI: large tumor (40 × 30 mm) with slight involvement of the left nuclei	slight gait ataxia and mild ataxia and target oscillations with his left arm
3. R.F.: male, 44 years	left hemisphere dysplastic gangliocytoma (resected in 1991)	MRI: dysplastic gangliocytoma (30 × 70 mm) involving the left hemisphere, midline, and a small part of the right hemisphere	slightly ataxic gait and upper extremity ataxia prior to surgery; presently does not display signs of cerebellar deficits
4. T.J.: male, 53 years	right cerebellar cortical lesion (surgically excised in 1995)	MRI: 11-mm lesion in the dorsolateral aspect of the right cerebellar hemisphere	upper extremity cerebellar ataxia, as well as an intentional tremor in the right arm
5. H.J.: female, 48 years	posterior fossa pilocystic astrocytoma (at age of 13)	CT: only rudimentary parts of the cerebellum remain	severe lower and upper limb ataxia with intentional tremor in the right arm
6. E.A.: female, 45 years	left cerebellar recurrent tumor (completely excised in 1995)	MRI: large lesion involving left cerebellar hemisphere and large parts of the vermis	slight gait ataxia and mild ataxia of the upper extremities
7. D.T.: female, 53 years	right cerebellar tumor (excised in 1996)	MRI: large tumor with slight involvement of the right cerebellar nuclei	extremely mild gait ataxia and slight ataxia of the right arm; general weakness of right arm

^a(CT) Computerized tomography; (MRI) magnetic resonance imaging.

and it was slightly higher (greater number of protrusions) in the FV condition. All images used in this study were unfamiliar to the subjects before the experiment. The time interval between experiments involving the performance of the different paradigms by the same subject was never less than a week.

For each of the four conditions tested, a series of four sets of trials was performed. The design of a typical set is characterized in Figure 2. At the beginning of each set, a subject was asked to scan a *reference* profile (trace it three times in AK and

PK conditions, visually examine its shape during three full turns of the disk in SV condition, and visualize the shape for 30 sec in FV condition) and memorize its shape. Then a sequence of five *test* profiles was presented in pseudorandom order. Two of the five were the same as the *reference* profile and three were different. The subjects were required to scan each *test* profile (always in the same way as the *reference* profile) and indicate whether its shape was identical to the *reference* one. Then, the number of errors made in the discrimination procedure for the set was recorded.

Figure 1: Protocol of the experiment. The pictures denote four alternative conditions under which the first task (acquisition/discrimination) was performed (see Materials and Methods). Conditions for the other three tasks (indicated by the pictures on the left) were the same independent of the condition of the first task.

This procedure was repeated three additional times, providing a succession of four sets of trials over which any change in the number of errors was assessed.

DRAWING AND VISUAL RECOGNITION PHASE

Before the drawing tasks began, the subject was asked to scan the *reference* shape to which he/she was exposed previously at the initiation of the acquisition/discrimination phase. This was done for each of the four conditions described above (AK, PK, SV, FV). The subject then was asked to draw it from memory five consecutive times while blindfolded. The second drawing task was identical to the first with the exception that the subject drew the profile using vision. In the final test of this phase, each subject was required to recognize visually the shape of the *reference* profile without any additional exposure to it. In the first trial, pictures of the same four shapes (including the *reference*) were presented serially. If the subject identified the *reference* shape correctly in the first trial, the task was considered to be completed, and no additional trials were performed. If the answer was not correct, the incorrectly-identified shape was removed from the group, and another trial was performed. If no shape was identified as the *reference*, the last of the four shapes

presented, which was never the *reference*, was removed. In the second trial, the three remaining shapes were shown together. If again a mistake was made, the misidentified shape was removed, and a third trial was performed in which the subject chose between the remaining two shapes. The subject's score on this recognition task was the number of trials required to identify the *reference* shape. When an error was made on the third trial, the subject received the score of 4.

DATA ANALYSIS

For each of the four conditions in the discrimination task (AK, PK, SV, and FV), statistical comparison of the numbers of errors (failure to recognize the *reference* profile or identification of a non-reference profile as the *reference*) made in each successive set was performed using the standard

Figure 2: An example of a set of template shapes, this one used in the PK condition. Shape 1 was the *reference* shape, and shapes 2–4 were *test* shapes. The four sequences of shape presentations used in each of four successive sets of trials in the shape acquisition/discrimination task are shown below. Each sequence began with the subject tracing the reference shape. This was followed by a succession of five trials in which the shapes were presented in a pseudorandom order. See Materials and Methods for explanation.

t-test (CSS Statistica) to compare the performance of cerebellar patients and control subjects, with $P < 0.05$ selected as the basis for determining significance. These groups were compared based on their errors in the first set of trials, the last set, and the total errors across all sets. Also, the number of errors in the last set was compared with that in the first set within each group of subjects to estimate the effect of any learning. In addition to the inter-group comparisons, the performance of each group was assessed relative to the chance level. The latter was calculated as the mathematical expectation of the number of errors produced if the identification of the subjects of each shape (in a set of two *reference* and three *test* shapes) as “reference” or “nonreference” were totally random (the independent probability of either choice being equal to 0.5). The mathematical expectation of the number of errors in one set of trials and the total across all four sets is equal to 2.5 and 4, respectively, and the corresponding standard deviations are approximately equal to 1.12 and 2.24, respectively.

For the drawing and visual recognition phase, the resemblance of each subject’s drawings to the corresponding *reference* shape was compared qualitatively between the group of cerebellar patients and the group of control subjects. The differences relevant to this manuscript were substantial enough so that inferences could be drawn easily from the qualitative differences in the performance between the two groups of subjects. Because no scoring of these qualitative features was performed, the evaluator was not blind relative to the nature of the subject. For the visual recognition test, the number of trials required to recognize the *reference* shape under each condition was compared between cerebellar patients and control subjects based on the standard *t*-test.

Results

SHAPE ACQUISITION/DISCRIMINATION TASK

In the first series of experiments performed in the four groups of cerebellar patients and age- and sex-matched control subjects, each individual was required to perform four sets of trials. In each trial the subjects scanned the *reference* template and then performed a discrimination task with a total of five templates with four different shapes that were presented in a pseudorandom order. This was

done for all four acquisition/discrimination conditions (see Fig. 1). As described more thoroughly in Materials and Methods, the capacity of each subject to discriminate between the *reference* shape and three other nonreference shapes was evaluated over four consecutive sets of trials to assess whether the number of errors (failure to recognize the *reference* shape or identification of a nonreference shape as the *reference*) decreased as this task was practiced. The results of this part of the experiment are shown in Figure 3 and summarized in Tables 2–5.

The data obtained when shape discrimination was performed via active kinesthesia (Fig. 3A) and passive kinesthesia (Fig. 3B) were very similar. In both conditions, the numbers of errors made in the first set of trials were not significantly different ($P > 0.1$, *t*-test, also used in subsequent comparisons) between cerebellar patients and normal subjects or from the chance level. However, in contrast to control subjects, whose number of errors in the last (fourth) set of trials was significantly different from chance level and less than in the first set of trials ($P < 0.01$), the cerebellar patients were unable to significantly decrease the number of errors over the four sets of trials ($P > 0.1$). The total number of errors made by the cerebellar patients was significantly higher than that made by the control subjects ($P < 0.01$). When the subjects were

Figure 3: Learning curves for the shape discrimination task. The number of errors (failure to recognize the *reference* shape or the designation of a *test* shape as the *reference*) made by cerebellar patients (□) and control subjects (○) are plotted against the number of the set of trials. The experimental condition is shown above each graph. Error bars indicate the s.e.

Table 2: Control subjects vs. cerebellar patients

Condition	Set 1 errors	Set 2 errors	Set 3 errors	Set 4 errors	Total errors	Recognition errors
Active kinesthesia	$P \leq 0.34$	$P \leq 0.24$	$P \leq 0.24$	$P \leq 0.01$	$P \leq 0.02$	$P \leq 0.01$
Passive kinesthesia	$P \leq 1.00$	$P \leq 0.02$	$P \leq 0.01$	$P \leq 0.02$	$P \leq 0.01$	$P \leq 0.01$
Sequential vision	$P \leq 0.38$	$P \leq 1.00$	$P \leq 0.06$	$P \leq 0.34$	$P \leq 0.19$	$P \leq 0.02$
Full vision	$P \leq 0.74$	$P \leq 0.35$	$P \leq 0.35$	$P \leq 0.34$	$P \leq 0.31$	$P \leq 0.15$

asked after completion of the kinesthesia paradigms whether they had a mental visual image of the *reference* shape while performing the shape discrimination task, most control subjects and cerebellar patients gave a positive answer.

When shape acquisition/discrimination was performed in the sequential vision paradigm (Fig. 3C), neither the number of errors in the first or last set of trials, nor the total number of errors made by cerebellar patients was found to be significantly different from those made by control subjects ($P > 0.1$). The nonparametric Mann-Whitney U-test was used for these inter-group comparisons instead of the *t*-test because the standard deviation in the group of cerebellar patients was considerably larger than that for control subjects (e.g., 3.44 and 0.82, respectively, for total number of errors, $P < 0.01$, *F* test). This difference in standard deviation suggests that the group of cerebellar patients was not homogeneous with regard to their performance in the SV paradigm (see Discussion). The most important finding in this condition was that cerebellar patients, like the control subjects, improved their performance considerably over the four sets. Their number of errors was at the chance level ($P > 0.1$) in the first set of trials but was significantly different from the chance level ($P < 0.01$) in the last set

of trials. However, the difference between the number of errors in the first and the last set of trials was found to be statistically significant for control subjects ($P < 0.01$) but only close to significant for cerebellar patients ($P = 0.07$), apparently attributable to the above-mentioned high variability of their results.

When shape acquisition was performed using full vision (Fig. 3D), both cerebellar patients and normal subjects had comparably low error rates from the very first set of trials. The performance of both groups was significantly different from chance (Tables 3 and 4). Because of this, rates of improvement were difficult to substantiate in this paradigm. Nevertheless, both groups showed a trend toward a decreased number of errors. The differences between the scores of cerebellar patients and control subjects were not significant and were noticeably smaller than in all other paradigms.

The data in this part of the study demonstrate that cerebellar patients differed from control subjects in their decreased capacity to improve their score in shape discrimination in both the AK and PK paradigms. However, cerebellar patients were able to improve in both the SV and FV paradigms. Last, in all paradigms but FV, the number of errors was consistently higher in cerebellar patients than

Table 3: Cerebellar subjects vs. chance level

Condition	Set 1 errors	Set 4 errors	Total errors
Active kinesthesia	$P \leq 0.10$	$P \leq 0.55$	$P \leq 0.08$
Passive kinesthesia	$P \leq 0.76$	$P \leq 0.48$	$P \leq 0.12$
Sequential vision	$P \leq 0.74$	$P \leq 0.01$	$P \leq 0.01$
Full vision	$P \leq 0.01$	$P \leq 0.01$	$P \leq 0.01$

Table 4: Control subjects vs. chance level

Condition	Set 1 errors	Set 4 errors	Total errors
Active kinesthesia	$P \leq 0.36$	$P \leq 0.01$	$P \leq 0.01$
Passive kinesthesia	$P \leq 0.65$	$P \leq 0.01$	$P \leq 0.01$
Sequential vision	$P \leq 0.07$	$P \leq 0.01$	$P \leq 0.01$
Full vision	$P \leq 0.01$	$P \leq 0.01$	$P \leq 0.01$

Table 5: Comparison of set 1 vs. set 4

Condition	Controls	Cerebellar patients
Active kinesthesia	$P \leq 0.01$	$P \leq 0.28$
Passive kinesthesia	$P \leq 0.01$	$P \leq 0.84$
Sequential vision	$P \leq 0.01$	$P \leq 0.07$
Full vision	$P \leq 0.35$	$P \leq 0.41$

normal subjects, even when improvement occurred.

DRAWING THE REFERENCE SHAPE

To assess further the characteristics of any internal representation of the *reference* shape developed during the acquisition/discrimination phase of the experiment, subjects in both groups were required to draw the *reference* shape first while blindfolded and then with their eyes open after acquiring it during the first part of the experiment. The most revealing observations on these qualitative data were the findings in the AK and FV groups. Figure 4 illustrates the drawings performed by control subjects and cerebellar patients when the template was acquired in the AK paradigm. Notice that control subjects were able to generate

Figure 4: Examples of shapes drawn under the AK condition. (A,B) Examples of a control subject's drawings made while blindfolded and with vision, respectively. (C,D) Comparable drawings by a cerebellar patient. The *reference* shape (reduced in relative size) is shown above. The condition related to each diagram is the same as in Fig. 1.

Figure 5: Examples of shapes drawn under the FV condition. The layout and all designations are the same as in Fig. 4.

fairly reasonable representations of the template while blindfolded (Fig. 4A) as well as with eyes open (Fig. 4B). Although most subjects were able to draw a shape with the relative positions and orientation of the protrusions on the surface of the template in a relatively correct manner, their capacity to illustrate differences in the size of the various protrusions of the template was definitely better with the eyes open. Cerebellar patients had considerably more difficulty with this task. Consistent with their relatively high error rate on the shape discrimination task presented above, these subjects were unable to draw a reasonable representation of the template either while blindfolded (Fig. 4C) or with eyes open (Fig. 4D). However, it was apparent that their drawings show a noticeable trial-to-trial consistency.

When shape acquisition was performed with FV (Fig. 5), control subjects were able to draw a reasonable representation of the template either with eyes closed or open. In general the drawings with eyes closed included the different protrusions of the pattern in a reasonably accurate fashion (Fig. 5A). Cerebellar patients still displayed deficiencies in drawing an accurate representation of the template despite the fact that shape recognition was done with full vision. The drawings of the cerebellar patients while blindfolded usually consisted of a distorted representation of the template (Fig. 5C). Interestingly, this representation was qualitatively better than the representation of the template drawn after the shape was acquired in the AK paradigm (see Fig. 4C for comparison). However, even when the shape was drawn with full vision (Fig. 5D), the drawing was not accurately represented.

In this example, the patient drew an extra protrusion on the lobulated object.

VISUAL RECOGNITION OF THE REFERENCE SHAPE

After all subjects completed the drawing tasks with eyes open and blindfolded, they were asked to visually recognize the *reference* shape, as described in Materials and Methods. It should be noted that this recognition task was performed without re-scanning the *reference* template, as was the case in the first component of these experiments. In three of the four conditions (PK, SV, and FV), all cerebellar patients as well as controls were able to recognize the template visually after three presentations of the set of templates. In the AK paradigm, four of seven cerebellar patients were unable to recognize the shape of the *reference* template even in the third trial (when they had to choose between only two pictures). In both AK and PK paradigms, some cerebellar patients stated they were very surprised when seeing pictures of the actual template shapes because they were so different from the shapes they expected. The average number of trials required for visual recognition of the *reference* template is shown in Figure 6 for both cerebellar patients and controls (for those cerebellar patients who did not recognize the *reference* shape in three trials, the number of trials

Figure 6: Comparison of the performance generated by cerebellar patients and control subjects on the visual recognition task. The bar graph illustrates the mean numbers of trials required for cerebellar patients and control subjects to recognize the *reference* shape acquired under the four different conditions (shown below the graph). The probability of the null hypothesis being correct based on the standard *t*-test is shown above the corresponding pair of bars (statistical significance is indicated by an asterisk). Error bars, 1 S.E.

required for recognition was scored as 4, as described in Materials and Methods). In each paradigm except for FV, the cerebellar patients required a significantly greater number of recognition trials than the control subjects ($P < 0.02$, *t*-test). Note that the cerebellar patients revealed an impaired capacity to recognize the *reference* shape even when the template was acquired by sequential vision, despite the fact that they were capable of improving their rate of shape discrimination with practice in the first phase of the experiment.

Discussion

SUMMARY OF RESULTS

AK AND PK PARADIGMS

First, in both of these conditions, the number of errors made by cerebellar patients in the first set of shape discrimination trials and that made by control subjects were not significantly different either from the chance level or from each other. Second, unlike control subjects, cerebellar patients did not significantly decrease the number of errors in shape discrimination as they practiced the *reference* template over four consecutive sets of trials, the number of errors in the last set still being at the chance level. Third, the capability of cerebellar patients to draw a *reference* shape or to recognize it visually when it was acquired under either of the kinesthesia paradigms was considerably worse than that of control subjects. Fourth, the capacity of cerebellar patients either to draw or to recognize visually a *kinesthetically* presented reference shape under either kinesthesia condition was considerably less than when the reference shape was presented *visually* (in the FV condition).

FV AND SV PARADIGMS

First, in the shape discrimination phase, the number of errors made by *both* groups of subjects was significantly below the chance level by the end of the four series of trials in both vision paradigms. Second, in the FV paradigm, both groups of subjects could perform almost equally well over all four sets of trials with a low number of shape discrimination errors. In contrast, in the discrimination phase of the SV paradigm, the cerebellar performance of the patients was noticeably worse

than that of the control subjects, and they also required significantly more trials to visually recognize the *reference* shape (in the fourth task). In the drawing tasks, the cerebellar patients performed notably better than they did in either of the kinesthesia paradigms. However, they remained qualitatively poorer in representing the *reference* shape than the normal subjects, particularly while blindfolded.

THE IMPAIRMENT IN THE ACQUISITION OF KINESTHETIC CUES

The results of this study, consistent with previous observations (Grill et al. 1994; Gao et al. 1996), unequivocally show that the processing of kinesthetic information is considerably impaired in cerebellar patients in this perceptual task. It should be emphasized that this deficit was present even though this information was not required for the execution of any movement or even the generation of any motor commands. An argument could be made that in the AK paradigm there may have been a relationship between the perceived kinesthetic cues and the generation of the tracing movement. However, if this occurred, it likely did not contribute to the results, as the performance of the cerebellar patients and normal subjects were comparable under both the AK and PK paradigms. Furthermore, the nature of this movement and its relation to the sensory cues is considerably different than under circumstances in which kinesthetic cues are required on-line to guide an ongoing movement. The fact that the performance of the subjects was the same under active and passive conditions also indicates that the deficit in shape discrimination was not related only to the generation of kinesthetic cues produced by the active movement required to trace the template. Interestingly, the learning rate appeared higher under the passive condition for normal subjects. This may be attributable to an interference between the generation of motor commands and the processing required for movement perception (Bairstow and Laszlo 1980). However, the overall similarity of the results obtained in both kinesthesia conditions (Fig. 3A, B) shows that the above interference was not critical for the perception of kinesthetic cues, at least in control subjects.

Although these experiments were not designed to differentiate between several possible reasons for the deficit observed in cerebellar pa-

tients, we propose that their inability to adequately reproduce the *reference* shape by drawing either blindfolded or with their eyes open after acquiring the shape via kinesthetic cues reflects an impairment in the processing of this type of information rather than an abnormality of some other higher order function. For example, this deficit could be explained by an impairment of retaining the image in memory, recalling it, and/or actually executing the drawing itself (attributable to the motor disorder). These possibilities are unlikely, however, given the fact that the patients could do reasonably well under the FV condition. Furthermore, it was shown in one of our recent experiments (Timmann, et al. 1996) that patients with cerebellar pathology not only could perform a mental rotation of an image and draw it in the rotated position after acquiring it by tracing with full vision, but they also could improve their performance of this task over successive trials.

Therefore, although other processes may be affected, we favor the view that the primary problem affecting the performance of the patients relates to an impairment in establishing a reliable internal representation of the *reference* shape. Interestingly, the deficit in these experiments is much greater than shown in the studies of Grill et al. (1994). They demonstrated a somewhat reduced capability to discriminate the duration and velocity of two successive passive finger movements. However, no significant deficit in the discrimination of movement amplitude was found. These smaller deficits in the discrimination of kinesthetic cues may be related to the difference between the complexity of the tasks in their experiment and that of our paradigms. In the studies of Grill et al. (1994), it was not necessary for the subjects to formulate the shape of an object to be used in subsequent parts of the experiment. This fact, together with the impairment observed in our study, suggests that the most significant deficit is related to a higher level of kinesthetic information processing than required only for discrimination of movement parameters. As stated above, we propose that this deficit is related to the generation of the internal representation of the image.

The possibility that the required transformations necessary for establishing this representation may occur but may be impaired is suggested from the drawing and recognition phase of the experiment. As shown in Figure 4, the patients acquiring the shape in the AK paradigm did not draw random representations of the template. Rather, certain

features of the template were drawn, and the successive drawings were consistent. This would not be expected if the subject were merely guessing. It is more likely that these drawings represent an internal image that was developed inadequately and inaccurately.

Our data do not address the important issue of functional localization in the cerebellum, because all of the patients displayed the deficits reported above. Consequently, it was impossible to make inferences by comparing observations in patient groups having different localization of their pathology. Furthermore, the variability of their performance in different components of the experiment was not substantial enough to permit any conclusions regarding localization, particularly given the size of the patient group. In this experiment the greatest emphasis was on employing patients that had substantial pathology limited to the cerebellum. Additional experiments with patients having a greater distribution of focal cerebellar pathology would be required to make any well-founded arguments regarding this issue.

TRANSLATION BETWEEN KINESTHETIC AND VISUAL INFORMATION

An important question regarding the creation of an internal representation of a template shape is whether the representation acquired in the kinesthesia paradigms necessarily should be established as a visual image. Such translation was required only for the visual recognition of a kinesthetically acquired *reference* shape. Because in the PK paradigm all cerebellar patients recognized the *reference* shape only after three trials independent of their score in the shape discrimination task, it is quite feasible that the translation from the kinesthetic to the visual modality was impaired. It is also pertinent that the ability of the patients to draw the *reference* shape without vision after having acquired it in either visual paradigm was considerably better than in the kinesthesia paradigms. Because this finding demonstrates that the transformation required to draw the shape on the basis of a visual image was not impaired substantially in cerebellar patients, their deficit in the drawing task after acquiring the shape in a kinesthesia paradigm reflected a failure to formulate a visual image, presumably attributable to the inadequacy of the transformations of kinesthetic cues required in this pro-

cess. It should be noted that shape recognition based on kinesthetic cues need not require a translation into the visual domain on theoretical grounds. However, it is possible that the nervous system selects such a translation because it is accustomed to operating in this domain when assessing or learning shapes of objects. Neither the cerebellar patients nor the control subjects were given any specific instruction pertinent to this question. When asked after the experiment whether they created a visual image of the template while kinesthetically acquiring the shape, most subjects usually gave a positive answer. Consequently, it is likely that a kinesthetic-visual transformation is performed during shape acquisition in the discrimination phase, and also that the success in the recognition task depends on the capacity to form an image in the visual domain in most subjects. This interesting question regarding the role of a kinesthetic-visual transformation in the acquisition and discrimination of spatial images requires further investigation.

INTEGRATION OF SEQUENTIALLY RECEIVED INFORMATION INTO A COMPLETE IMAGE

In contrast with visual information, kinesthetic information about a spatial shape is always received in a sequential manner. Because of the anticipated deficits in the kinesthesia paradigms, the SV paradigm was employed to obtain insights as to whether deficits in the processing of kinesthetic cues were related to the fact that the information was presented serially. The fact that cerebellar patients made significantly more errors than control subjects in the visual recognition task in the SV but not in the FV paradigm strongly suggests the existence of a deficit in their capability to integrate temporal sequences of visuo-spatial cues. Such a deficit could also account for the abnormalities in the visual perception of motion found in patients with midline cerebellar lesions (Nawrot and Rizzo 1995). Our observation, together with cerebellar impairment of the patients in the kinesthesia paradigms, suggests that the cerebellum can contribute to the development of an internal representation through the temporal integration of sensory cues. Clearly, the integrity of this functional mechanism may be important not only for the perception of shapes via kinesthetic cues but also for the control and learning of movements sequences.

THE ISSUE OF LEARNING

One of the intriguing aspects of the deficit in the perception of kinesthetic cues examined in this study is that its manifestation was clearest when patients were required to improve their capacity to perform shape discrimination over several trials. Because normal subjects improved their performance with practice dramatically on the kinesthesia paradigms, and because their performance in the initial set on the FV paradigm was substantially better than in the first set of the kinesthesia conditions, the establishment of a usable internal representation of the *reference* shape based on kinesthetic cues likely requires practice. In contrast, shape perception based on a single exposure to an object is based on the integration of a temporal sequence of kinesthetic cues. We define the improvement in the ability to recognize the shape of an object based on this type of information through practice as *kinesthetic learning*, a process in which an internal representation of the shape of the object is established by integrating sequences of data acquired over repeated exposures to the object through the acquisition of kinesthetic cues. The findings that both cerebellar patients and control subjects had similar levels of performance after the first exposure to the *reference* shape and that only the former improved after subsequent exposures to it, suggests that the cerebellum may not only be critical for establishing internal representation of objects based on kinesthetic information, but also that this structure may contribute to the process of kinesthetic learning.

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References

- Bairstow, P.J. and J.I. Laszlo. 1980. Motor commands and the perception of movement patterns. *J. Exp. Psychol.: Hum. Percept. & Perform.* **6**: 1–12.
- Bloedel, J.R. and J. Courville. 1981. A review of cerebellar afferent systems. In *Handbook of physiology, vol. II. Motor control* (ed. V.B. Brooks), pp. 735–830. Williams and Wilkins, Baltimore, MD.

Canavan, A.G.M., R. Sprengelmeyer, H.-C. Diener, and V. Homberg. 1994. Conditional associative learning is impaired in cerebellar disease in humans. *Behav. Neurosci.* **108**: 1–11.

Cordo, P.J. 1988. Kinesthetic coordination of a movement sequence in humans. *Neurosci. Lett.* **92**: 40–45.

———. 1990. Kinesthetic control of a multijoint movement sequence. *J. Neurophysiol.* **63**: 161–172.

Cordo, P.J. and M. Flanders. 1989. Sensory control of target acquisition. *Trends Neurosci.* **12**: 110–117.

Darling, W.G. and G.F. Miller. 1993. Transformations between visual and kinesthetic coordinate systems in reaches to remembered object locations and orientations. *Exp. Brain Res.* **93**: 534–547.

Dow, R.S. and G. Moruzzi. 1958. *The physiology and pathology of the cerebellum*. University of Minnesota Press, Minneapolis, MN.

Flanders, M. and P.J. Cordo. 1989. Kinesthetic and visual control of a bimanual task: Specification of direction and amplitude. *J. Neurosci.* **9**: 447–453.

Gao, J.H., L.M. Parsons, J.M. Bower, J. Xiong, J. Li, and P.T. Fox. 1996. Cerebellum implicated in sensory acquisition and discrimination rather than motor control. *Science* **272**: 545–547.

Gilman, S., H. Carr, and J. Hollenberg. 1976. Kinematic effects of deafferentation and cerebellar ablation. *Brain* **99**: 311–330.

Gilman, S., J.R. Bloedel, and R. Lichtenberg. 1981. *Disorders of the cerebellum*. Davis Co., Philadelphia, PA.

Grill, S.E., M. Hallett, C. Marcus, and L. McShane. 1994. Disturbances of kinaesthesia in patients with cerebellar disorders. *Brain* **117**: 1433–1447.

Granit, R. 1970. *The basis of motor control*. Academic Press, London, UK.

Haines, D.E. (ed.) 1997. *Fundamental neuroscience*. Churchill Livingstone, New York.

Kawato, M. and H. Gomi. 1992. The cerebellum and VOR/OKR learning models. *Trends Neurosci.* **15**: 445–453.

Lovelace, E.A. 1989. Vision and kinesthesia in accuracy of hand movement. *Percept. Motor Skills* **68**: 707–714.

MacKay, W.A. and J.T. Murphy. 1979. Cerebellar modulation of reflex gain. *Prog. Neurobiol.* **13**: 361–417.

Nawrot, M. and M. Rizzo. 1995. Motion perception deficits from midline cerebellar lesions in human. *Vision Res.* **35**: 723–731.

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Paulin, M.G. 1993. The role of the cerebellum in motor control and perception. *Brain Behav. & Evol.* **41**: 39–50.

Pellionisz, A.J. 1985. Tensorial brain theory in cerebellar modeling. In *Cerebellar functions* (ed. J.R. Bloedel, J. Dichgans, and W. Precht), pp. 201–229. Springer-Verlag, Berlin, Germany.

Pellionisz, A. and R. Llinas. 1985. Tensor network theory of the metaorganization of functional geometries in the central nervous system. *Neuroscience* **16**: 245–273.

Roll, J.P. and J.C. Gilhodes. 1995. Proprioceptive sensory codes mediating movement trajectory perception: human hand vibration-induced drawing illusions. *Can. J. Physiol. & Pharmacol.* **73**: 295–304.

Shimansky, Y., M. Saling, D.A. Wunderlich, V. Bracha, G.E. Stelmach, and J.R. Bloedel. 1996. Perception of kinesthetic cues required for assessing the shape of two-dimensional irregular profiles is impaired in cerebellar patients. *Neurosci. Abst.* **22**: 500.

Soechting, J.F. and M. Flanders. 1992. Moving in three-dimensional space: Frames of reference, vectors, and coordinate systems. *Annu. Rev. Neurosci.* **15**: 167–191.

Stein, J.F. and M. Glickstein. 1992. Role of the cerebellum in visual guidance of movement. *Physiol. Rev.* **72**: 967–1017.

Tillery, S.I., M. Flanders, and J.F. Soechting. 1991. A coordinate system for the synthesis of visual and kinesthetic information. *J. Neurosci.* **11**: 770–778.

Timmann, D., Y. Shimansky, P.S. Larson, D.A. Wunderlich, G.E. Stelmach, and J.R. Bloedel. 1996. Visuomotor learning in cerebellar patients. *Behav. Brain. Res.* **81**: 99–113.

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References

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