# THE ROLE OF ATTENTION IN THE REGULATION OF ASSOCIATED MOVEMENT IN CHILDREN

*Jo-Anne C. Lazarus*
*John I. Todor*

Skilled hand movement, in particular bimanual co-ordination, involves not only activation of appropriate motor sequences, but also inhibition of unintended, extraneous movements. Early in development the young child finds it easier to perform symmetrical than assymmetrical movements (Elliott and Connolly 1973), presumably because primitive neuromotor synergies link the two hands (Bernstein 1967). Asymmetrical movements require the additional involvement of inhibitory control mechanisms to override these neuromotor synergies, *i.e.* to 'uncouple' the two limbs (Preilowski 1975).

Previous investigators have referred to extraneous movements as associated movement (Fog and Fog 1963, Abercrombie *et al.* 1964, Zulch and Muller 1969), motor overflow (Stern *et al.* 1976, Szatmari and Taylor 1984) or synkinetic movement (Cambier and Dehen 1977). The frequency of associated movement has been reported to decrease with age (Abercrombie *et al.* 1964, Cohen *et al.* 1967, Connolly and Stratton 1968), but can be observed even in adults under conditions of extreme force, fatigue or stress (Gregg *et al.* 1957, Fog and Fog 1963, Podivinsky 1964, Wolff *et al.* 1983). However, these studies measured either the frequency of associated movement or used a subjective scale of its intensity. Using a quantitative measure, Lazarus and Todor (1987) tested children aged six to 16 years and found that associated movement (measured as peak force output) decreased significantly between six and eight years, with little change thereafter.

As a group, children with clearly diagnosed central nervous system (CNS) dysfunction show greater associated movement than their normal age-peers (Abercrombie *et al.* 1964, Cohen *et al.* 1967). In fact, in the study by Cohen and colleagues, a sample of children with 'soft signs' of neurological damage performed similarly to younger children with respect to associated movement. If the absence of associated movement reflects neural maturity and refinement of movement patterns, the ability to demonstrate conscious inhibition of associated movement could have a direct impact on therapeutic techniques used in the rehabilitation of neurological patients, as well as providing a means of evaluating the potential for training or learning motor skills in a number of disabled populations (*i.e.* those with learning disabilities, behavior disorders, attentional deficits, hyperkinesis, mental retardation).

The fact that some authors have subjectively observed a reduction but not extinction of associated movement when children were asked to inhibit it (Cohen *et al.* 1967) raises the possibility that


*Developmental Medicine and Child Neurology*, 1991, 33, 32–39

inattention is involved, a factor which may also change with age. However, since associated movement was measured as overt movement, rated on a four-point scale, the occurrence of low-level muscle activity that does not lead to visible movement cannot be ruled out. A systematic look at the extent to which children of different ages can alter or reorganize the pattern of associated movement by engaging attentional processes may shed some light on the mechanisms by which this motor overflow phenomenon decreases with increasing age, particularly between six and eight years. While it is recognised that the regulation of neuromuscular mechanisms may be a subconscious, involuntary dynamic process, there is some evidence of systematic adaptation through voluntary means (Cohen *et al.* 1967).

In the index finger/thumb flexion task used by Lazarus and Todor (1987), the child is required to squeeze two parallel, immovable steel bars with the index finger and thumb to various percentages of his or her own maximal volitional force. In order to perform this task, the child has to monitor active hand force in order to reach the target level. If the child were to be made aware of associated movement in the contralateral limb and asked to inhibit it, the task would not only involve conscious monitoring of the active hand squeeze to produce a designated force, but also involve attending to the contralateral limb. Wolff and Cohen (1980) have suggested that co-operation between the hemispheres may involve inhibition of collateral discharges or unintended mirror movements. Thus this type of 'bimanual performance' would require control of each limb, as well as co-ordination between the two hemispheres. The intent of the movement in the above task requires different signals for each limb, *i.e.* excitatory to the flexor muscles in one hand and inhibitory and/or no activation to the flexor muscles in the contralateral hand. As such, it would be in direct opposition to the neuromotor synergy for symmetrical hand movements (Elliott and Connolly 1973), particularly in young children. In the task described above, active hand contraction and the accompanying visual display of intensity is likely to be the focus of the child's attention. Inhibiting the automatic bimanual synergy is likely to be of secondary importance. By increasing the focus on the 'passive hand' (*i.e.* enhancing the feedback produced by unwanted movements), one may be able to assist the child in directing attention to inhibiting associated movement.

The purpose of this experiment was to examine the role of attentional processes in the regulation of associated movement in children, using a quantifiable measurement technique. Children of various ages performed a unimanual force production task, with and without enhanced sensory feedback to reflect the force of associated movement in an effort to suppress irrelevant muscle activity in the contralateral limb.

## Method

### *Subjects*

To control for possible gender differences, 10 boys in each of five age-groups were studied: their mean ages were 6·7, 8·9, 10·6, 12·5 and 16·8 years. Males were chosen since previous experience with this task suggested that males generally were more willing and motivated to exert maximal force than were their female counterparts. This sample was a subsample from a previous study by Lazarus and Todor (1987), consisting of those children who exhibited the most intense associated movement in their age-group. This criterion was used because a demonstration of conscious inhibition by children who have difficulty in suppressing overflow spontaneously would be more convincing, both theoretically and clinically. All the children were in regular classrooms and had a right-hand preference for writing. One child in the 12-year age-group was eliminated from the study because of a history of neurological problems, resulting in a final sample of 49 children (Table I).

### *Apparatus*

The apparatus used was the version of the clip-pinching task of Fog and Fog (1963) developed by Todor and Lazarus (1986), with the following modification. Subsequent to being amplified by the Beckman R511A polygraph, the output

TABLE I
**Age distribution of sample**

| *Group* | *Mean ages* Years | Months | *(SD)* | *N* |
|---|---|---|---|---|
| A | 6·7 | 80·9 | (2·01) | 10 |
| B | 8·9 | 106·7 | (2·32) | 10 |
| C | 10·6 | 127·6 | (3·47) | 10 |
| D | 12·5 | 150·3 | (3·29) | 9 |
| E | 16·8 | 201·4 | (6·24) | 10 |

signal from the left ('passive hand') squeeze bars was routed through an audio amplifier, an oscillator and a four-inch speaker positioned to the left of the child. Thus the left-hand signal was audible to the child while it was being routed to the computer.

*Procedures*
The right hand served as the active hand, with left-hand overflow as the dependent measure. This was done in order to obtain the dependent measure in conditions in which experience would have optimized biological potential. The child was positioned as described by Lazarus and Todor (1987), with the thumbs, index fingers and arms secured by Velcro straps in a standardized location. Each child's maximal volitional force (MVF) was re-established. For the remaining trials in this training procedure, the 75 per cent MVF level was used as the criterion force-level, as it had previously produced associated movement in all age-groups, without fatigue becoming a major factor.

In the pre-training condition, each child was given a minimum of two and a maximum of six trials at 75 per cent MVF, in order to establish a baseline level of associated movement at this particular exertion level. The criterion for determining the number of pre-trials for a given individual was as follows: as soon as the child produced a level of force in the 'passive limb' that exceeded a predetermined baseline measure on either two consecutive or two non-consecutive trials, the pre-training trials were terminated. Since fatigue increases associated movement, those who demonstrated low levels of 'passive hand' activity were given up to six trials in an attempt to elicit associated movement.

At this point the auditory amplifier was turned on and the child was made familiar with the sound of the feedback so that he would not be startled by it. The child was encouraged to squeeze the left bars to produce an auditory signal, which varied in pitch (ranging from 0Hz to 5kHz) as a function of the force exerted by the left hand. Extension of the left thumb and/or index finger produced an auditory signal that changed abruptly in pitch as a function of the force exerted. This enabled the two forms of associated movement, homologous flexion (contralateral agonist) and heterologous extension (contralateral antagonist), to be detected and measured.

In the sensory feedback condition, the child was again told to squeeze the right-hand bars to the 75 per cent MVF criterion level on the oscilloscope. They were also told to keep the left hand still: 'Don't let the sound come on; if it does come on, try to eliminate it by relaxing the left hand'. Three trials were given in this condition.

The auditory amplifier was turned off in the post-training condition, and the child was once more instructed to squeeze the right hand to the 75 per cent MVF criterion level on the oscilloscope. He was told to try to keep the left hand motionless during right-hand squeezing, even though auditory feedback would not be given. Two trials were given in this condition. Trials within a condition were separated by a 30-second interval while the data were being stored onto floppy disk. Approximately one minute elapsed between the two conditions, allowing time only for instructions.

*Analysis*
Peak positive force from the 'passive hand' represented the magnitude of homologous associated movement, while negative force represented heterologous associated movement.

For each condition, an individual's homologous associated movement score was defined as the mean of all the trials in that condition; that is the mean of from two to six pre-training trials, the mean of three sensory feedback trials, and the mean of two post-training trials. Trials with negative force (heterologous movement) were removed from the analysis of homologous associated movement, since in these trials peak positive force would be zero. Trials were only included if the active hand was able to maintain at least 80 per cent of the target force level for a period of at least three seconds.

## Results

A 5 × 3 (age-group × condition) analysis of variance with repeated measures was performed on peak positive force (associated movement) data for each qualifying trial. There was a significant main effect for condition ($F(2, 80) = 10{\cdot}71$, $p < 0{\cdot}001$). *Post hoc* analysis (Tukey's Honestly Significant Difference (HSD); 0·05) revealed a significant decrease in the magnitude of associated movement from the pre-training to the sensory feedback (SF) condition, with a subsequent significant increase during post-training trials (Fig. 1). Pre- and post-training conditions were also significantly different from each other. There was no main effect or interaction with age (Table II).

A second 5 × 3 (age-group × condition) analysis of variance with repeated measures was performed to control for the large variations in active hand-force across the five age-groups (Table III). In this case the dependent measure (associated movement) was expressed as a percentage of that individual's active hand-force value for that individual trial. As with the absolute value analysis (after logarithmic transformation of the data to account for unequal variances), there was a significant main effect for condition ($F(2, 80) = 20{\cdot}70$, $p < 0{\cdot}001$). *Post hoc* analysis (Tukey's HSD; 0·05) again revealed that the magnitude of associated movement decreased significantly from the pre-training to the sensory feedback condition and increased significantly during the post-training trials.

The main effect for age was significant ($F(4, 35) = 3{\cdot}23$, $p < 0{\cdot}02$). As shown in Figure 2, the six-year age-group exhibited greater intensity of associated movement than all other age-groups, although *post hoc* analysis (Tukey's HSD; 0·05) failed to reveal any significant difference in the means. (Note that Figure 2 depicts data before logarithmic transformation.) There was no significant age × condition interaction (Table IV).

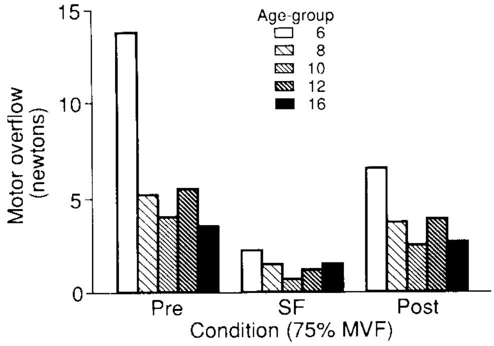


*Fig. 1. Associated movement by age and condition (expressed in newtons).*

TABLE II

**Magnitude of associated movements by age-group and condition (expressed in newtons)**

| *Condition* | *Age-group (yrs)* 6·7 | 8·9 | 10·6 | 12·5 | 16·8 |
|---|---|---|---|---|---|
| Cell means | | | | | |
| PRE | 13·72 | 5·08 | 4·13 | 5·47 | 3·43 |
| SF | 2·30 | 1·47 | 0·72 | 1·00 | 1·46 |
| POST | 6·49 | 3·73 | 2·44 | 3·93 | 2·67 |
| Standard deviations | | | | | |
| PRE | 14·22 | 5·83 | 4·22 | 6·88 | 2·61 |
| SF | 2·58 | 2·05 | 0·68 | 1·41 | 1·09 |
| POST | 8·88 | 3·62 | 2·68 | 6·59 | 1·24 |
| Anova F values | | | | | |
| Age 2·41, NS | | | | | |
| Condition 10·71* | | Age × condition 1·38, NS | | | |

*p < 0·001.

TABLE III

**Range of active hand-force by age-group (75 per cent MVF)**

| *Age-group (yrs)* | *Mean force (newtons)* | *Minimum* | *Maximum* |
|---|---|---|---|
| 6·7 | 16·436 | 7·764 | 20·313 |
| 8·9 | 20·572 | 10·467 | 30·187 |
| 10·6 | 22·236 | 12·710 | 36·293 |
| 12·5 | 31·451 | 15·508 | 45·733 |
| 16·8 | 43·379 | 20·328 | 73·001 |

## Discussion

The results of this quantitative analysis confirm earlier observations that associated movement can be inhibited voluntarily if attention is drawn to the contralateral limb (Cohen *et al.* 1967, Cambier and Dehen 1977). The effect is greater when feedback from the limb is enhanced by an auditory signal. However, just being

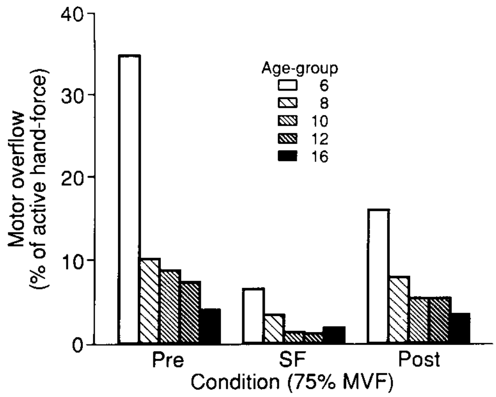


*Fig. 2. Associated movement by age and condition (expressed as percentage of active hand-force).*

TABLE IV

**Magnitude of associated movements by age-group and condition (expressed as natural logarithm of percentage of active hand-force)**

| *Condition* | *Age-group (yrs)* 6·7 | 8·9 | 10·6 | 12·5 | 16·8 |
|---|---|---|---|---|---|
| Cell means | | | | | |
| PRE | 2·64 | 1·38 | 1·61 | 1·59 | 0·67 |
| SF | 1·14 | 0·13 | 0·18 | 0·36 | 0·00 |
| POST | 1·96 | 1·20 | 1·05 | 1·16 | 0·79 |
| Standard deviations | | | | | |
| PRE | 1·22 | 1·17 | 0·86 | 1·32 | 1·22 |
| SF | 1·09 | 1·33 | 0·60 | 0·57 | 1·23 |
| POST | 0·95 | 1·16 | 1·34 | 1·06 | 0·92 |
| Anova F values | | | | | |
| Age 3·23* | | | | | |
| Condition 20·70** | Age × condition 0·36, NS | | | | |

*P<0·02, **p<0·001.

aware that an auditory tone would come on when movement occurred in the contralateral limb seemed to be sufficient for most children to effectively inhibit overflow to that limb, since the number of trials during which the sound actually came on (*i.e.* motor activity in the passive limb surpassed a designated baseline level) was minimal.

The fact that children of all ages in this study were substantially able to inhibit associated movement with enhanced sensory feedback suggests that the neural substrate for inhibiting bimanual motor outflow is functional to some degree at 6½ years of age. In addition, there appears to be a reliably documented attentional component to the motor overflow phenomenon which is amenable to voluntary control and which presumably engages the inhibitory processes in some way.

The importance of interhemispheric connections to motor overflow and/or bimanual linkage has been demonstrated in humans with lesions (Geschwind 1965) or section (Preilowski 1975, Goldberg 1985) of the corpus callosum. Goldberg's model of bimanual co-ordination is based on mutual interactions between contralateral and ipsilateral motor outflow at the cortical level. The ipsilateral innervation is thought to occur parallel to the predominant contralateral innervation. From studies of children with and without agenesis of the corpus callosum, Dennis (1976) suggests that in the course of development, uncrossed ipsilateral pathways must be inhibited, leading to a decrease in associated movement with age. She speculates that maturation (myelination in particular) of the corpus callosum is important in inhibiting the involvement of uncrossed pathways. Presumably the corpus callosum is involved in inhibiting the flow of activation to the ipsilateral motor area. In relation to mirror movements of the distal musculature of the hands, models such as this which assume that overflow is mediated via transcallosal fibres are problematic, since it has been demonstrated in monkeys, at least, that the fingers are not interconnected by these fibres (Karol and Pandya 1971, Jenny 1979). However, since motor overflow in the contralateral limb only crudely mirrors the voluntary action, one might speculate that it does not rely on the most differentiated representation of the fingers. Since the corpus callosum is still undergoing myelination through the second decade of life (Yakovlev and Lecours 1967), the reduction in overflow with increasing age may be, in part, a result of this increasing callosal maturation.

It seems plausible that the inability to inhibit associated movement spontaneously may be due to this bisymmetrical outflow system, which requires regulation at some level. As mentioned previously, behavioral data reveal that younger children tend to use the two limbs in a symmetrical fashion more often than older children (Elliott and Connolly 1973). With increasing age, it is postulated that the development of a neural inhibitory mechanism allows unconscious regulation of ipsilateral motor outflow, while the development of cognitive mediational processes (such as selective attention) allows conscious regulation of this inhibitory mechanism in situations in which spontaneous inhibition of overflow may break down, *i.e.* submaximal levels of force in young children, maximal levels of force in older children, or almost any level of muscular exertion in individuals with a variety of neurological disorders (*e.g.* cerebral palsy, head injury). It appears that the greatest contributor to lack of inhibition of motor overflow within the age-range studied here is not simply the presence or absence of an independent, lower level, neuromotor inhibitory mechanism, but a lack of integration of higher-order attentional processes with lower-level mechanisms, resulting in decreased differentiation of the behavioral repertoire. The decline in associated movement observed across ages during the sensory feedback and post-training conditions suggests that this integrative ability is progressive. Other studies relating attentional processes with motor overflow have been reported (Waber and Merola 1985, Waber *et al.* 1985).

Recently, Szatmari and Taylor (1984) and Taylor *et al.* (1988) have demonstrated a relationship between motor overflow and behavior problems, motor incoordination and adverse perinatal events, using a modified version of Fog's foot-to-hands test. Those authors have demonstrated that the overflow phenomenon is potentially a useful marker for identifying children with 'soft' signs of neurological dysfunction. With the quantification of Fog's clip-pinching task and the demonstration of conscious inhibitory control, even in young children, in the present study, the potential also exists for incorporation of inhibitory control techniques for suppression of extraneous movement/mirror movement in a variety of clinical groups. Since the current study has demonstrated that mirror movements can be inhibited by attentional effort in normal children and may reappear when cues are removed, future clinical trials should give neurologically impaired patients extended practice at consciously inhibiting extraneous movements during motor performance in an attempt to develop a 'mature' response. The prediction is that the amount of attentional effort will decrease with increased practice, just as activation of appropriate muscle sequences in learning new skills becomes less of an effort with practice.

It is interesting that for all age-groups the greatest reduction in intensity of associated movement occurred during sensory feedback. The addition of an auditory tone to coincide with the force produced in the contralateral limb helped the child to direct attention to that component of the task. Recent studies in rehabilitation medicine advocate sensory feedback techniques that make physiological and behavioral processes more apparent to the patient (Wolf and Binder-Macleod 1983, Balliet *et al.* 1986, De Weerdt and Harrison 1986). Before these studies, the primary focus of treatment for neurologically impaired patients had been on facilitating muscle activation, with little reference to compensatory or irrelevant movements. The results of the present study lend support for recent trends in therapy that emphasize inhibition and/or relaxation of uninvolved muscle groups (*e.g.* to prevent co-contraction when reciprocal inhibition would be desirable).

There is little doubt that factors such as experience in fine motor tasks with the dominant hand may improve skill. Experience probably contributes to the progressive integration of higher-order processes with lower-level ones, leading to increased differentiation of motor performance. Although such processes may be involuntary and dynamic throughout development, the data presented here suggest that they can be aided and even driven by voluntary behavior, thus highlighting the importance of incorporating inhibitory control techniques in therapy, including enhanced sensory feedback.

*Accepted for publication 19th June 1990.*

*Acknowledgements*
This article is part of a doctoral dissertation submitted by the first author in partial fulfillment of the requirements for the Ph.D. degree at The University of Michigan, under the supervision of the second author. The research was supported by a dissertation grant from the Horace H. Rackham School of Graduate Studies of The University of

Michigan to the first author. Portions of the data were presented at the NATO Advance Study Institute on Motor Development in Children, Maastricht, The Netherlands, in June 1985, and a condensed version of the experiment was presented at the annual conference of the North American Society for the Psychology of Sport and Physical Activity, Scottsdale, Arizona, in June 1986. The help of Professors John W. Hagen, Joan E. Farrell and David E. Meyer during the dissertation process is gratefully acknowledged. The authors thank Dr. Ruth Moorman, Carol Cross, and the staff and students of the Willow Run School District, Ypsilanti, Michigan, for their co-operation.

*Authors' Appointments*
*Jo-Anne C. Lazarus, Ph.D., Department of Physical Education and Dance, University of Wisconsin-Madison, 2000 Observatory Drive, Madison, WI 53706.
John I. Todor, Ph.D., Department of Kinesiology, The University of Michigan, 401 Washtenaw Avenue, Ann Arbor, MI 48109-2214.

**Correspondence to first author.*

SUMMARY
The effect of attentional processes in regulating associated movement was studied in 10 male children in each of five age-groups from six to 16 years. They were asked to squeeze their index finger and thumb to 75 per cent of their own maximal volitional force under three conditions: a spontaneous baseline condition, a sensory feedback condition and a post-training condition without sensory feedback. Children of all ages were able to reduce the magnitude of associated movements during the sensory feedback condition. In the post-training condition some of the ability to inhibit was lost, particularly for the six-year-olds. This supports the view that the integration of higher order processes, such as attention, with lower-level neuromotor inhibitory mechanism, plays a role in the reduction of associated movement with increasing age. Implications for therapy with clinical populations are discussed.

RÉSUMÉ
*Le rôle de l'attention dans la régulation des mouvements associés chez l'enfant*
L'effet des procédures d'attention dans la régulation des mouvements associés a été étudie chez 10 garçons dans cinq groupes d'âge (de six à 16 ans). On leur demanda d'appuyer leur index sur leur pouce, à 75 pour cent de la force maxima, dans trois situations: une situation spontanée de référence, une situation de feed-back sensoriel et une situation en post-apprentissage sans feed-back sensoriel. Les enfants de tous âges pouvaient diminuer l'amplitude des mouvements associés durant la situation de feed-back sensoriel. Dans la situation de post-apprentissage, une partie de la capacité d'inhibition fut perdue, notamment à six ans. Cela favorise la thèse selon laquelle une intégration des fonctions de plus haut niveau, comme l'attention, joue un rôle accru avec l'âge, dans la réduction des mouvements associés, à côté des mécanismes neuro-moteur inhibiteurs de bas niveau. Les conséquences pour le traitement d'une population pathologique, sont discutées.

ZUSAMMENFASSUNG
*Die Bedeutung der Aufmerksamkeit für die Kontrolle von Begleitbewegungen bei Kindern*
Bei je 10 Jungen aus fünf Altersgruppen wurde die Bedeutung der Aufmerksamkeit für die Kontrolle von Begleitbewegungen untersucht. Sie mußten ihren Zeigefinger und Daumen zu 75 Prozent ihrer maximalen willkürlichen Kraft unter drei Versuchsbedingungen zusammendrücken: spontane Basiskondition, sensorische Feedback Kondition und Post-Training Kondition ohne sensorisches Feedback. Kinder aller Altersgruppen waren in der Lage, bei der sensorischen Feedback Kondition die Begleitbewegungen zu reduzieren. Bei der Post-Training Kondition war ein Teil der inhibitorischen Fähigkeit, besonders bei den Sechs-jährigen, verlorengegangen. Dies spricht für die Annahme, daß die Integration übergeordneter Prozesse, wie z.B der Aufmerksamkeit, zu untergeordneten neuromotorisch-inhibitorischen Mechanismen für die Reduzierung von Begleitbewegungen eine Rolle spielt. Die sich daraus ergebenden Rückschlüsse für die Therapie von Patienten werden diskutiert.

RESUMEN
*El papel de la atención en la regulación de los movimientos asociados en niños*
Se estudió el efecto de los procesos de atención en la regulación de movimiento asociados en 10 niños varones en cinco grupos según la edad (seis a 16 años). Se les pidió que apretaran sus dedos índice y pulgar hasta el 75 por ciento de su fuerza volicional bajo tres situaciones: una situación basal espontánea, una situación con retroalimentación sensorial y una situación post entrenamiento sin retroalimantacion sensorial. Los niños de cualquier edad eran capaces de reducir la magnitud de los movimientos asociados en la situación de retrolimentación sensorial. En la situación de postentrenamiemto se perdió cierta capacidad de inhibición, en especial en los niños de seis años de edad. Esto apoya la idea de que la integración de los procesos elevados, tales como la atención, con mecanismos inhibitorios de nivel neuromuscular más bajo juegan un papel en la reducción del movimiento asociado a medida que aumenta la edad. Se discuten las implicaciones terapeuticas y clínicas.

*References*
Abercrombie, M. L. J., Lindon, R. L., Tyson, M. C. (1964) 'Associated movements in normal and physically handicapped children.' *Developmental Medicine and Child Neurology,* **6,** 573–580.
Balliet, R., Levy, B., Blood, K. M. T. (1986) 'Upper extremity sensory feedback therapy in chronic cerebrovascular accident patients with impaired expressive aphasia and auditory comprehension.'

*Archives of Physical Medicine and Rehabilitation,* **67**, 304–310.
Bernstein, N. (1967) *The Co-ordination and Regulation of Movements.* New York: Pergamon.
Cambier, J., Dehen, H. (1977) 'Imitation synkinesia and sensory control of movement.' *Neurology,* **27**, 646–649.
Cohen, H. J., Taft, L. T., Mahadeviah, M. S., Birch, H. G. (1967) 'Developmental changes in overflow in normal and aberrantly functioning children.' *Journal of Pediatrics,* **71**, 39–47.
Connolly, K., Stratton, P. (1968) 'Developmental changes in associated movements.' *Developmental Medicine and Child Neurology,* **10**, 49–56.
Dennis, M. (1976) 'Impaired sensory and motor differentiation with corpus callosum agenesis: a lack of callosal inhibition during ontogeny?' *Neuropsychologia,* **144**, 455–469.
DeWeerdt, W., Harrison, M. A. (1986) 'The efficacy of electromyographic biofeedback for stroke patients: a critical review of the main literature.' *Physiotherapy,* **72**, 108–118.
Elliott, J., Connolly, K. J. (1973) 'Hierarchial structure in skill development.' *In* Connolly, K. J., Bruner, J. S. (Eds.) *The Growth of Competence.* New York: Academic Press.
Fog, E., Fog, M. (1963) 'Cerebral inhibition examined by associated movements.' *In* Bax, M., Mac Keith, R. C. (Eds.) *Minimal Cerebral Dysfunction. Clinics in Developmental Medicine, No. 10.* London: S.I.M.P. with Heinemann Medical.
Geschwind, N. (1965) 'Disconnection syndrome in animals and man. I.' *Brain,* **88**, 237–294.
Goldberg, G. (1985) 'Supplementary motor area structure and function: review and hypothesis.' *Behavioral and Brain Sciences,* **8**, 567–616.
Gregg, R. A., Mastellone, A. F., Gersten, J. W. (1957) 'Cross exercise: a review of the literature and study utilizing electromyographic techniques.' *American Journal of Physical Medicine,* **36**, 269–280.
Jenny, A. B. (1979) 'Commissural projections of the cortical hand motor area in monkeys.' *Journal of Comparative Neurology,* **188**, 137–146.
Karol, E. A., Pandya, D. N. (1971) 'The distribution of the corpus callosum in the rhesus monkey.' *Brain,* **94**, 471–486.
Lazarus, J.-A. C., Todor, J. I. (1987) 'Age differences in the magnitude of associated movement.' *Developmental Medicine and Child Neurology,* **29**, 726–733.
Podivinsky, F. (1964) 'Factors affecting the course and the intensity of crossed motor irradiation during voluntary movement in healthy human subjects.' *Physiologia Bohemoslovenica,* **13**, 172–178.
Preilowski, B. (1975) 'Bilateral motor interaction: perceptual-motor performance of partial and complete split-brain patients.' *In* Zulch, K. S., Creutzfeldt, O., Galbraith, G. C. (Eds.) *Cerebral Localization.* Berlin: Springer.
Stern, J. A., Gold, S., Hoin, H., Barocas, V. S. (1976) 'Towards a more refined analysis of the "overflow" or "associated movement" phenomenon.' *In* Sankar, D. V. S. (Ed.) *Mental Health in Children.* New York: PJB Publications.
Szatmari, P., Taylor, D. C. (1984) 'Overflow movements and behaviour problems: scoring and using a modification of Fogs' test.' *Developmental Medicine and Child Neurology,* **26**, 297–310.
Taylor, D. C., Powell, R. P., Cherland, E. E., Vaughan, C. M. (1988) 'Overflow movements and cognitive, motor and behavioural disturbance: a normative study of girls.' *Developmental Medicine and Child Neurology,* **30**, 759–768.
Todor, J. I., Lazarus, J. C. (1986) 'Exertion level and the intensity of associated movements.' *Developmental Medicine and Child Neurology,* **28**, 205–212.
Waber, D. P., Merola, J. (1985) 'Motor correlates of dichotic listening asymmetries in children.' *Neuropsychologia,* **23**, 403–410.
— Mann, M. B., Merola, J. (1985) 'Motor overflow and attentional processes in normal school-age children.' *Developmental Medicine and Child Neurology,* **27**, 491–497.
Wolf, S. L., Binder-Macleod, S. A. (1983) 'Electromyographic biofeedback applications to the hemiplegic patient.' *Physical Therapy,* **63**, 1393–1403.
Wolff, P. H., Cohen, C. (1980) 'Dual task performance during bimanual coordination.' *Cortex,* **16**, 119–133.
— Gunnoe, C. E., Cohen, C. (1983) 'Associated movements as a measure of developmental age.' *Developmental Medicine and Child Neurology,* **25**, 417–429.
Yakovlev, P. I., Lecours, A. R. (1967) 'The myelogenetic cycles of regional maturation of the brain.' *In* Minkowski, A. (Ed.) *Regional Development of the Brain in Early Life.* Oxford: Blackwell.
Zulch, K. J., Muller, N. (1969) 'Associated movements in man.' *In* Vinken, P. J., Bruyn, G. W. (Eds.) *Handbook of Clinical Neurology, Vol. 1: Disturbances of Nervous Function.* Amsterdam: North Holland. pp. 404–426.

*Developmental Medicine and Child Neurology,* 1991, 33, 32–39