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Contribution of the propriomuscular channel to movement coding in children:

A study involving the use of vibration-induced kinaesthetic illusion

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Abstract

The specific contribution of the propriomuscular afferent channel to the coding of movement was investigated in children aged 5, 7 and 9 years by applying vibration to muscle tendons, which is known to elicit kinaesthetic illusions in adults in a motionless limb. Vibrations at various frequencies ranging from 20 to 130 Hz were applied to the distal tendon of the right triceps brachii. The subject had to simultaneously copy with the left forearm the kinaesthetic sensation thus induced. The ability of the children to discriminate between various real movement speeds (2, 5 and 100/s) was established using the same method. In all the children, the vibratory stimulation evoked an illusory sensation of elbow flexion, the velocity of which depended on the subject's age and the vibration frequency. At 5 years of age, the perceived velocity was highest and did not depend on the vibration frequency; it was lower at 7 and 9. It began to depend on the vibration frequency at the age of 9, when higher values were obtained with the median than with the extreme frequencies, as in adults. The results indicate that propriomuscular information contributes to conscious movement perception at each of the ages considered here, but that the processing of this information varies with age as children become aware of the quantitative (movement speed) content of the proprioceptive messages.

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1. Introduction

Various sensory channels are interacting during children's development. The role of the proprioceptive channel, which bas been pointed out by Wallon (1949), has been investigated much less than that of the visual channel. It probably pertains to the fact that, unlike vision, proprioception is a composite system, intricately linked to motor efferences (Sugden, 1990), and, therefore, it cannot be easily isolated from the skill process and measured distinctly. Several developmental studies have been carried out in which proprioception bas been related to intersensory integration (e.g. Connolly and Jones, 1970; Von Hofsten and Rösblad, 1988; Manyam, 1986; Millar, 1972; Orliaguet, 1985, 1986), or to mnemonic strategies (Sugden, 1978, 1980). The studies in which proprioceptive sensitivity bas been investigated per se, have generally involved discrimination tasks and have yielded perceptual threshold assessments.

Laszlo and Bairstow (1980) showed that the ability of children to discriminate the position of their two arms, after they had been passively moved up two inclined runways set at different angles, improved considerably between the ages of 5 and 8 years, and levelled between 8 and 12. Elliott et al. (1988), repeating this study with a revised stimulation method, observed a linear decrease in the perceptual threshold between 4 and 11 years of age. In matching tasks involving proprioceptive judgements of distance, a considerable improvement in the subjects' performance has also been observed during this developmental period (Connolly and Jones, 1970; Corlett, 1981; Hulme et al., 1983; Millar, 1972).

Paradoxically, such a developmental trend in proprioceptive accuracy is opposite to the age-related changes between the visual and proprioceptive dominance observed in situations involving a perceptual conflict (discordant information about limb positions -Orliaguet, 1985, 1986). Younger children (aged 5, 6 and in some cases 7) tended to rely more on the proprioceptive information, whereas the reverse trend, that is to say the dominance of a visual strategy, emerged as the children grew older. Orliaguet explained this trend by a change in the spatial frame of reference. It therefore seemed interesting to test in children the perceptual effects of purely proprioceptive stimuli, especially muscular ones, while simultaneously analysing the intensive and parametric features of the kinaesthetic responses.

Muscular afferents have been widely recognized as the main source of movement perception (Burgess et al., 1982; Goodwin, 1976; Matthews, 1982; McCloskey, 1978), and the afferent pattern bas been found to originate in the muscles stretched during the movement (Roll and Vedel, 1982). Kinaesthetic sensations can be elicited in a motionless human limb by a vibration applied to the tendon of a muscle (Goodwin et al., 1972; McCloskey 1973; Roll et al. 1980), thus giving rise to an afferent pattern originating in the primary muscle spindle activities (Burke et al., 1976; Roll et al., 1989). During a vibration-induced kinaesthetic illusion the subject perceives a limb movement in the direction that would normally have stretched the vibrated muscle. Since these spindle messages are quite similar to those generated by a real movement, as shown by microneurographic data (Burke et al., 1976; Roll and Vedel. 1982; Roll et al., 1989), the tendon vibration technique can be used to analyse the development of muscular proprioception without any interference from other components. Moreover, Roll and Vedel (1982) have shown the existence in adults of a U-shaped function between the vibration frequency (ranging from 10 to 120 Hz) and the perceived velocity of the illusory movement, with the perceived velocity reaching its peak around 70-80 Hz. This U-shaped function was tested in children to assess their capacity to perceive the quantitative characteristics of the afferent pattern, in addition to the vividness of their kinaesthetic sensations. The kinaesthetic sensations were quantified by means of a procedure previously used in adults (Gilhodes et al., 1986), which consisted of analysing actual movements performed by the subject mimicking with the one limb the illusory movement induced in the other limb by vibration. To validate the movement imitation as a discriminative response, a control experiment was conducted to test the children's ability to copy with one limb real passive movements imposed on the other limb, while respecting their velocities.

2. Method

2.1. Subjects

Three groups of six male and female children, aged 5, 7, and 9 (mean ages: 4.93, 7.18, 9.23; SD: 0.19, 0.21, 0.22, respectively) participated in the experiment. All used their right band in writing and drawing, their scholastic level was normal as shown by their school report, and no particular sensori-motor disorders were noted in their health report.

2.2. Apparatus

The subject sat on a comfortable chair, with forearms and hands lying relaxed on two horizontal supports. The level and the direction of these supports were adjustable so that the forearms lay in front of the subject's chest in a symmetrical position, slightly below the shoulder level and at an angle of 90° to the upper arms. The right forearm support could either be fixed in that position or moved in the horizontal plane by a silent electrical motor, transmitting to the forearm a smooth 20° rotating movement around the elbow axis, at various velocities. The left forearm support was free and could rotate in the same way, when voluntarily moved by the subject's limb. Both supports were fitted with a potentiometric system to record the forearm angular movements. An electromagnetic vibrator was fixed to the base of the right support with its head placed perpendicularly on the distal tendon of the right triceps brachii. Rectangular impulses (3 ms) delivered by a neurostimulator through a power amplifier drived the electromagnetic vibrator. The duration and the frequency of the vibration sequences could be varied. The amplitude of the vibration was maintained constant (0.5 mm peak to peak) whatever its frequency. A black curtain was placed in front of the subject's face, hanging down to the chest, so that the forearms were not visible.

2.3. Experimental conditions

Two separate experimental sessions were carried out. During the first session, subjects mimicked real passive movements. During the second session they mimicked the illusory movements elicited by vibration.

Mimicking real movements

The task consisted of simultaneously copying with the left forearm the passive 20° flexion of the elbow performed at 2, 5, or 10° /s and imposed on the right forearm by the motor-driven support. Subjects were required to simultaneously show with the left limb exactly what was happening to the right limb, at the same velocity. When bath flexion movements had stopped, the two forearms with their supports were moved back to their initial positions (90°).

Before testing, a short familiarization period was used to make the subjects comfortable with the task, and to draw their attention to perceiving and copying movements of various velocities. Five trials were performed at each velocity presented in a random order.

Mimicking illusory movements

To mimick illusory movements, the right forearm support was fixed. The task consisted of simultaneously copying with the left forearm the kinaesthetic sensations induced in the right forearm by the vibration applied to the tendon of the triceps brachii. As soon as the vibration began, subjects felt an illusory sensation of elbow flexion, lasting as long as the vibration was maintained. The vibration was applied for 4 s, at frequencies of either 20, 50, 80, 110, or 130 Hz. Standardized instructions were given to the children referring to the nature of the task (simultaneously mimicking with the left limb exactly what they were feeling in the right limb) and to the quantitative requirements of the task (moving at the felt velocity which could be variable, or not moving at all according to their feelings). At the end of each response, the left forearm was moved back to the initial position for the next trial.

Before testing, vibration was applied to the limb at several points to familiarize subjects with this unusual stimulation. Vibration was then applied at various frequencies to the tendon of the triceps brachii and the subjects were required to verbally express what they felt, to draw their attention on the sensations arising from the vibrated limb. As soon as they were able to concentrate strongly enough on the task, they were asked to produce a contralateral imitative response to the kinaesthetic sensations induced in the stimulated limb, with each of the five frequencies.

Five trials were performed at each vibration frequency. The five frequencies were presented in a varied order. During the experimental session, control trials were carried out from time to time in order to ensure that the children did not adopt stereotyped responses based on the tactile or auditory information from the vibrator. These control trials were of several types: (1) an identical vibratory stimulation was randomly applied anywhere else on the subject's arm, using the 80 Hz frequency; (2) a non-vibrating head was applied to the tendon while the vibrator was on; one trial with each of the five frequencies was given in a session. Such trials where the stimulation was reduced to the tactile contact and the auditory information from the vibrator, should not elicit any response in subjects merely reacting to kinaesthetic sensations. (3) Without any warning or addition al instructions to the subjects, the vibrator was applied to the tendon of the biceps instead of the triceps brachii, twice per session, which should yield response in the opposite direction (extension instead of flexion).

3. Results

3.1. Mimicking real movements

All the angular displacements of the left forearm imitating the passive movements of the right forearm were recorded. Fig. 1 presents individual traces, corresponding to the three required velocities for all three age groups, some of them showing an initial high velocity phase followed by a second lower and constant velocity phase. Mean velocities of the motor responses were calculated on the ramplike second phase of the arm rotation, which seemed representative of the subject's perception of the imposed movements at constant rate. A three-way Age (3) x Velocity (3) X Trials (5) analysis of

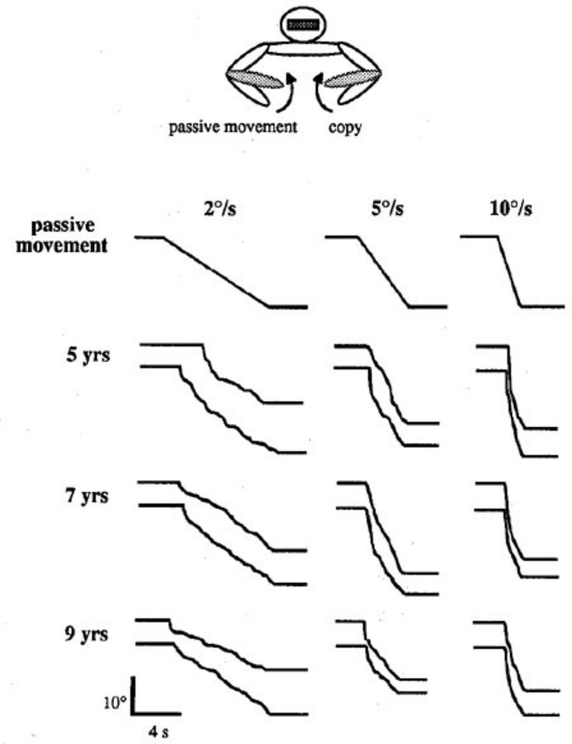

Fig. 1. Examples of individual traces (arm movement as a function of time) of subjects in three age groups requested to imitate passive movements with various velocities using their contralateral arm.

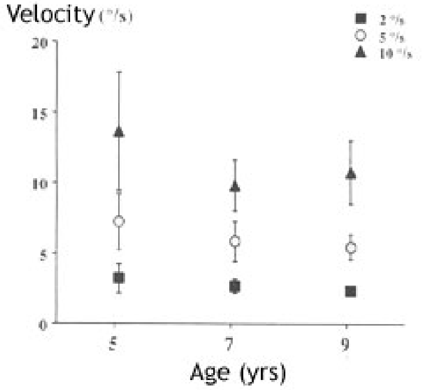

Fig. 2. Velocity of passive movement copies depending on age and real passive movement velocity (means and confidence limits at $p < 0.05$).

variance, with Age taken as a between-subject measure, and with repeated measures on the other two factors, was applied to the data.

Overall, the children's responses (fig. 2) show that they clearly distinguished between the three velocities (F(2,30) = 127.78, $p < 0.001$). The mimicked response velocity showed no significant changes with age (F(2,15) = 2.24). Repeating the trials did not result in any significant change in performance (F(4,60) = 0.79). No significant interaction was round. Children, whatever their age, clearly discriminated between velocities since significant differences were observed in all paired comparisons between velocities in each age group taken separately: with the 2°/s vs. 5°/s comparison, F(1,5) = 42.80, $p < 0.01$, F(1,5) = 45.25, $p < 0.01$, F(1,5) = 72.26, $p < 0.001$, and with the 5°/s vs. 100/s comparison, F(1,5) = 17.51, $p < 0.01$, F(1,5) = 223.28, $p < 0.001$, F(1,5) = 58.32, $p < 0.001$, for the groups aged 5, 7, and 9, respectively.

3.2. Mimicking illusory movements

In mimicking illusory movements, the response curves were not systematically bi-phasic, and a great variability was round in the velocity changes during a response. Consequently, the mean velocity of the entire movement appeared to be the best index of the children's behaviour. All angular displacements of the left forearm imitating the illusory movements induced by vibration in the right forearm were recorded. Fig. 3 presents the mean velocities of the motor responses averaged for each age-group and for each vibration frequency. A three-way Age (3) X Frequency (5) X Trials (5) analysis of variance of the same type as that used above, and a trend analysis were applied to the data.

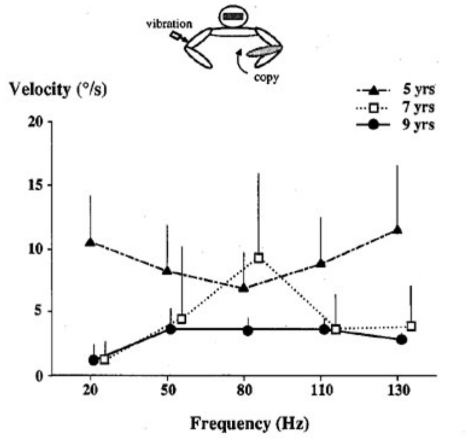

Fig. 3. Velocity of illusory movement copies depending on age and vibration frequency (mean and confidence limits at $p < 0.05$).

The velocity of the mot or responses changed with age overall ($F(2,15) =$ Il.53, $p < 0.001$): the response velocity was highest in the 5-year-old children and decreased as they grew older. Paired comparisons between the age-groups show that the velocity decreased most sharply between the age of 5 and 7 ($F(1,10) = 8.34$, $p < 0.025$), and levelled between the age of 7 and 9 ($F(1,10) = 1.69$). Repeating the trials did not change the children's responses ($F(4,60) = 1.47$), whatever their age and the vibration frequency as shown by the absence of Age x Trials ($F(8,60) = 0.86$) and Frequency x Trials ($F(16,240) = 0.93$) interaction. The response velocity was not affected on the whole by the vibration frequency ($F(4,60) = 0.84$), but the influence of the vibration frequency on the response velocity was found to be age-related, as shown by an Age x Frequency interaction ($F(8,60) = 2.12$, $p < 0.05$). As shown by all the paired comparisons carried out on the response velocities between the age-groups at each vibration frequency, the 5-year-olds' response velocity was found to be higher at the lowest and the highest frequencies than that of the two older groups (5 vs. 7 and 5 vs. 9 with 20 Hz: $F(1,10) = 22.76$ and 23.84, $p < 0.001$; with 110 Hz: $F(1,10) = 5.26$, $p < 0.05$ and $F(1,10) = 7.99$, $p < 0.025$; with 130 Hz: $F(1,10) = 6.14$, $p < 0.05$ and $F(1,10) = 10.62$, $p < 0.01$), as well as being higher at the medium frequency (80 Hz) than that of the 9-year-old group ($F(1,10) = 5.34$, $p < 0.05$). The effects of age at the extreme frequencies were due to the fact that in the 5-year-olds the response velocities were equally high at all the vibration frequencies used, as shown by the absence of any frequency-related effects in this age-group taken separately ($F(4,20) = 1.08$); whereas in the two older groups, as shown in Fig. 3, the response velocities induced by the lowest and the highest vibration frequencies were lower than those induced by the medium frequencies. This factor was found to be significant only in the older children (9 yrs.) taken separately, in whom the effects of frequency were significant (F(4,20) = 4.90, p < 0.01) and showed a quadratic trend (F(1,5) = 10.54, p < 0.025). The 7-year-olds showed a higher but extremely variable response velocity at the 80-Hz frequency, which precludes the possibility that the frequency may have significant effects at this age (F(4,20) = 1.96).

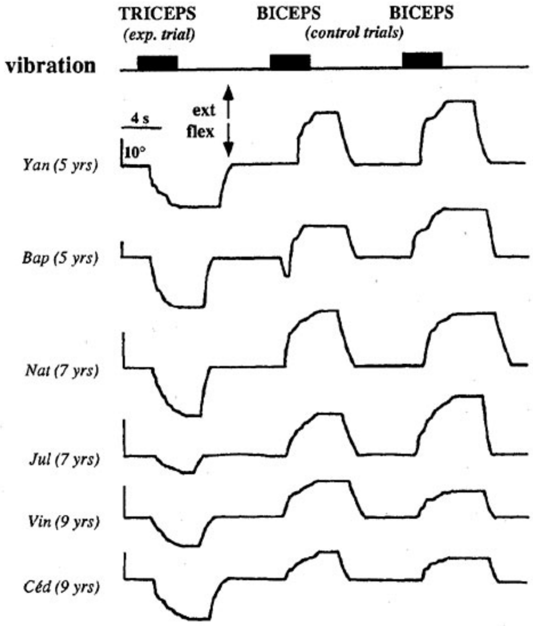

Fig. 4. Individual traces (arm movement as a function of lime) representative of the three age groups while imitating the illusory extension movements induced by biceps vibration (control trials), after a normal trial in the experimental series where triceps vibration induced illusory flexion movements.

The age-related decrease in response velocity, particularly between ages 5 and 7, was related to a decrease in amplitude (means: 14.4°, 10.77°, and 9.57°, respectively) and an increase in movement time (means: 2.10 s, 2.85 s, and 3.04 s, respectively). But the se age-related changes did not reach a significant statistical level (F(2,15) = 1.19, and F(2,15) = 2.26, respectively).

The control trials randomly included in the experimental series showed that the children did not produce any response when the stimulation was applied to any other place on the arm. When the vibrator did not contact the tendon, no response was obtained with any of the five vibration frequencies. Moreover, all children gave an adequate response in the opposite direction (extension) when the vibration was applied to the tendon of the antagonist muscle (biceps), as shown in Fig 4.

4. Discussion

The results of this experiment clearly showed that vibration applied to muscle tendons induced sensations of illusory movement in children, as has previously been found to be the case in adults (Eklund, 1972; Goodwin et al., 1972; Roll and Vedel, 1982). They reveal that a kinaesthetic perceptual processing of muscle spindle afferent messages, described by an imitative motor response, is taking place even in young children. But differences are to be found in the parametric dimensions of the subjects' responses. In the younger children (5-year-olds), any muscle spindle pattern, whatever its frequency, induced practically the same high velocity motor response; whereas the responses observed in adults, and to some extent in the older children in the present study, had a lower velocity and were more frequency-dependent.

The response velocities of the younger children, which were both high and undifferentiated, call for comments. (1) This stereotypy was not induced by repetition, as shown by the control trials, otherwise they would have always responded to the mere auditory or tactile stimulation produced by the vibrator, and they would not have changed the direction of their response when the biceps instead of the triceps was stimulated. Subjects therefore actually reacted as expected to the kinaesthetic effects of the stimulation. (2) The non-discriminatory responses to various vibration frequencies in the 5-year-old children cannot be accounted for only at the response level either, since these subjects were able to produce discriminatory responses when mimicking various imposed passive movement velocities, as accurately as the older children.

These age-related changes might not occur at the sensory input level, since the muscle spindle system, probably mature at this developmental stage, emits messages similar to those generated in older subjects. It is more likely that these changes occur at the level of the central processing of the spindle afferents, so that the same stimulus may give rise to different patterns of perceptual integration depending on age. Under our stimulation conditions, the 5-year-old children were able to identify a movement in a given direction on the basis of the muscle afferent signal, without carling its velocity on the basis of the stimulation frequency. They seemed to successfully perform velocity discrimination only when some redundancy was introduced via articular information in the case of the real passive movements. Articular proprioception contributes to movement perception, as a redundant or possibly substitute information source (Clark et al., 1986, 1989; Ferrell et al., 1987; Gandevia and Burke, 1992; Matthews, 1982), and may have been responsible for the more accurate discrimination of younger children for passive movements than for illusory movements induced by vibrations with various frequencies.

The ability to distinguish between low velocity signals may be weakened in younger children because of their difficulty to voluntarily make slow and smooth movements (Costantini et al., 1973; Rey, 1968). Younger children consequently have little sensory experience of this type of movements, hence, they can hardly categorize the corresponding propriomuscular signals. This yields to an indiscriminate assimilation to the same class of often-encountered and relatively high velocity signals.

Moreover, the fact that the afferent pattern presumably originates mainly in the muscles stretched during a movement, strongly suggests that the children's discriminative capacity is dependent on the mode of operation of the antagonist muscles. It has been established by Gachoud (1983) that the activity of the antagonist muscle during lifting movements changes between 6 and 9 years of age, from a highly co-contracted type of activity to a much lower and steady activity, with an intermediate stage of modulated muscular activity patterns at age 7. Since a strong or modulated contraction of the antagonist muscle prevents it from correctly fulfilling its sensory function, this pattern of development seems to be congruent with the improvement in the sensory discrimination capacity of the antagonist muscle suggested by the results obtained between 5 and 9 years of age, and with the high variability of the responses to an optimal frequency (80 Hz) observed at age 7.

The ability to perceive the frequency of the propriomuscular signals further develops, and the velocity of the imitative responses simultaneously decreases. Therefore, as they grow up, children drop a relatively efficient strategy, which consists of extracting the general features of the stimulus (at 5-6 years of age), and gradually become sensitive to the levels of specific parameters (after 7 years of age). A similar developmental pattern has been described in children performing sinusoidal tracking movements (Mounoud et al., 1985).

In conclusion, children are open to propriomuscular messages at all ages covered by the present study, the differences between their developmental levels being mostly due to how this information, particularly its velocity parameter, is processed. The velocity of the vibration-induced illusory movements does not seem to be frequency-dependant in the younger children, although they are characterized by a particularly high tendency to use propriomuscular messages for the kinaesthetic perceptions. From age 7, this information becomes less dominant, and at the same time it turns to be more finely analysed, as is obviously the case in adults.

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