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## ABSTRACT

**Aim:** The aim of this study was to understand the role played by visual information on the development of verticality and postural stability in healthy children.

**Methods:** The study comprised 66 healthy children from 4.0 to 15.7 years of age. Postural performances were recorded with a TechnoConcept platform. At the same time, the children's perception of subjective visual vertical (SVV) was recorded while they adjusted a vertical fluorescent line, either in the dark or in the presence of perturbing visual stimuli. Two testing control conditions without an SVV task were also performed by all of the children: static posturographic recording with open eyes and closed eyes.

**Results:** Postural measurements provided evidence of a correlation between the children's age and the tasks performed. Postural stability improved with age until eight to nine years, and SVV performance improved after 10–11 years. After these ages, postural and SVV capabilities did not change until at least 15 years of age.

**Conclusion:** Our findings suggest that the maturation of cortical and central processes involved in both the perception of verticality and in postural stability took place during childhood. However, maturation occurred later for vertical perception, which could imply delayed maturation of sensory integration processes.

## INTRODUCTION

Postural control involves the processing of three sensorial inputs by the cerebellar and central nervous system to have a posture of reference: visual, vestibular and somesthesic (1). In 1974 Lee and Aronson reported the important role that vision plays in standing and postural control (2). Their study was carried out with optic flow pattern stimuli and revealed that the infants demonstrated forward or backward body sways, depending on the direction of visual stimuli and that compensatory adjustments were made to their posture in response to the visual proprioceptive information. These authors suggested that infants used visual proprioception more intensively than mechanical proprioception information to maintain good postural control.

As shown by several researchers, postural stability can depend on many factors, including the type of tasks performed, the availability of sensory information and the age of the participants (3). In particular, if an individual has to perform dual task – two demanding tasks – simultaneously, a competition for processing resources can occur, causing performance degradation of one or both tasks (4). Several studies have explored this dual task in children and have reported a significant interaction between cognitive processes and balance capabilities (5–7). All of these studies were in line with the U-shaped nonlinear interaction model described by Huxhold et al. (8), which showed that performing a secondary task during a postural task could prevent attention from being focused on postural stability, leading to a reduction of postural sway, namely automatic attentional system. In other words, such improvement might be due to the fact that postural control could become more automatic.

**Abbreviations**
OKN, Optokinetic visual stimulation; SVV, Subjective visual vertical.

**Key notes**
- This study evaluated the impact of vision on the postural stability and the perception of verticality in 66 healthy children from 4.0 to 15.7 years of age.
- Our findings suggest that the maturation of cortical and central processes involved in both the perception of verticality and in postural stability took place during childhood.
- However, maturation occurred later for vertical perception, which could imply delayed maturation of sensory integration processes.

Postural activity and verticality are closely related, and it is essential to have an internal model of verticality as a reference in order to allow the development of postural stability and body control in the environment (9). Lopez et al. (10) showed that both perception and integration of verticality are essential for humans and responsible for various motor behaviours organised around the vertical axes, such as spatial navigation and locomotion, body orientation in space and stabilisation. Thus, an internal model of verticality is imperative in healthy development, to build mental representation of the body (11). The perception of verticality requires normal activity of the neural circuits located on the superior parietal cortex (1,18), the insula (11,12) and the thalamus (13). To our knowledge, there have been very few studies to date that have explored children's vertical perception together with postural capability. A study from our group (14) compared vertical perception during a postural task in young children aged from six to eight years and adults. We not only found poorer postural stability in young children than adults, but also reported larger variability and a lower accuracy in vertical perception.

The aim of this study was to further explore the perception of verticality while measuring postural sway – to define the role of visual information on the development of verticality and postural stability – in a group of 66 children aged from four to sixteen years. Our working hypothesis was that perception of verticality and stability in children would improve with age, as both are controlled by cortical and central processes that are developed during childhood, until adolescence. This was consistent with a study where diffusion tensor imaging was used to explore brain development and showed that there was a continuous maturation of glial populations until adolescence (15).

## METHODS

### SUBJECTS

This study comprised 66 healthy children, aged from 4.0 to 15.7 who were recruited from schools near the hospital. The children were divided into six groups depending on their age (Table 1): Group one comprised 17 children aged four to five years (mean age: 5.0 ± 0.1 years). Group two comprised 14 children aged six to seven years (mean age: 6.7 ± 0.1). Group three comprised 11 children aged eight to nine years (mean age: 8.9 ± 0.2). Group four comprised 12 children aged 10–11 years (mean age: 11.2 ± 0.2). Group five comprised nine children aged 12–13 years (mean age: 13.0 ± 0.5) and Group six comprised 10 children aged 14–15 years (mean age: 15.1 ± 0.1). The analysis of variance (ANOVA) for age showed a significant difference between all these groups ($F_{(5,67)} = 372.12$, $p < 0.001$).

**Table 1** Composition of the age-related groups of children with the means ± standard errors, the total number of children and the number of boys and girls in each group

| Groups | Age range (years) | Mean age (years) | Number of children | Number of girls | Number of boys |
|---|---|---|---|---|---|
| 1 | 4–5 | 5.0 ± 0.1 | 17 | 9 | 8 |
| 2 | 6–7 | 6.7 ± 0.1 | 14 | 6 | 8 |
| 3 | 8–9 | 8.9 ± 0.2 | 11 | 4 | 7 |
| 4 | 10–11 | 11.2 ± 0.2 | 12 | 5 | 7 |
| 5 | 12–13 | 13.0 ± 0.5 | 9 | 6 | 3 |
| 6 | 14–15 | 15.1 ± 0.3 | 10 | 4 | 6 |

We included all children who had normal or corrected vision during the test. All the children had normal vestibular, neurological and audiological evaluation, and none of the children did presented with any vestibular, ocular or any neurological pathology.

The investigation adhered to the principles of the Declaration of Helsinki and was approved by our institutional Human Experimentation Committee, the Comité de Protection des Personnes CPP Ile de France V, Hôpital Saint-Antoine. Written, informed consent was obtained from children's parents after an accurate explanation of the experimental procedure.

### Experimental setup

Experiments were carried out in a dark room, one child at a time and with each child standing upright on the force plate. Postural measurements were performed in the standard Romberg condition: the child was positioned on the platform, with their heels placed 4 cm apart, their feet placed parallel on the footprints at an angle of 30° and their arms along their body.

A specially constructed subjective visual vertical (SVV) system was used to assess the visual vertical perception, which looked like an elongated clown, and was made from a phosphorescent tube and fluorescent cardboard (14). The clown was placed two metres away from the child, at eye level, and it could be moved to the left or to the right by the child using a remote control. A monitor screen showed how far the clown was adjusted by the child, giving the final value of tilt in degrees.

### EXPERIMENTAL PROCEDURE

Children were asked to stand upright on the force plate in the dark room, breathing normally, arms side by their side, not speaking and not clenching their teeth. They held the remote control with their hands in front of their belly button. The movement required by the remote control was just a contraction of the thumbs. The keyboard only weighed 40 g, and it consisted of two buttons: the right and left buttons allowed the child to turn the clown to the right and left, respectively.

Five experimental postural conditions were recorded for each subject: in three of them, SVV measurements were also recorded and two control conditions with eyes open and with eyes closed were run to assess their postural stability without SVV measurement. In the eyes open condition, the subject fixed the clown that was vertically aligned at 0°, and in the eyes closed condition, their eyes were covered by a patch.

In the case of SVV, two conditions were performed with two different optokinetic stimulations (OKN) presented randomly (OKN + SVV condition). For this stimulation, a moving pseudorandom dots visual pattern was projected in front of the child: 360 dots of 0.34 cm (0.235°) of diameter subtending 12° (around 41.69 cm) of the visual field with a density of 2637 dots/m². The dots rotated clockwise or anticlockwise with a constant angular velocity of 80°/second (right and left, respectively). In the third condition, the subject was in the dark without any OKN stimulation and subjective visual vertical was assessed (no OKN + SVV condition).

Before each trial with the three SVV conditions, the experimenter randomly tilted the clown to the right or left side at different angles. Then, the child was asked to straighten the clown up until it reached what he or she estimated to be the perfect verticality. At the same time, postural stability was recorded.

For each of these five conditions, four trials were run and they were randomly recorded. Before starting the experiment, children were trained in the dark without any OKN stimulation to perform subjective visual vertical (no OKN + SVV condition), without recording it, until we were sure that they had understood the task and performed it properly.

### Data acquisition and processing

To measure postural stability, we have used a principle of stain gauge platform y (TechnoConcept, Céreste, France). The excursions of the center of pressure (CoP) were measured for 12.8 seconds, and the surface of the CoP was calculated following the standards proposed by Gagey and Weber (16). The equipment contained an analogue to digital converter of 16 bits, and the sampling frequency of the CoP was 40 Hz.

We analysed three postural parameters: (i) the surface of the CoP, corresponding to an ellipse with 90% of CoP excursions, which allows to efficiently measure CoP spatial variability; (ii) the length of the CoP in the medio-lateral direction, which is the path of the CoP in this direction; and (iii) the mean speed of the CoP, which represents a good index of the amount of neuromuscular activity required to regulate postural control.

We expressed the SVV value, in degrees, as the error from the absolute visual vertical at zero degrees. For each child, we calculated the mean of the four responses, in absolute values, that were performed for the three conditions: (i) with OKN stimuli velocity at 80°/seconds to the left and to the right, (ii) OKN + SVV at 80°/seconds left and 80°/seconds right, respectively and (iii) without any OKN stimulation (no OKN + SVV).

### Statistical analysis

Data were analysed using the linear regression models with postural parameters for all conditions tested: OKN + SVV: 80° left and 80° right, respectively, no OKN + SVV and eyes open and eyes closed. The predictor variables for each test were the children's age in years.

Statistical analyses of variance were also performed using the ANOVA test, with the different groups of children as the between-subject factors and the individual means of postural parameters and the absolute mean SVV value as the within-subject factors.

The post hoc analysis was carried out with Fisher's least significant difference. The effect of a factor was considered as significant when the p value was below 0.05.

## RESULTS

### Postural parameters

We measured the correlation coefficient $R^2$ for the three postural parameters in each of the five conditions: OKN + SVV: 80° left and 80° right, respectively, no OKN + SVV and eyes open and eyes closed There was a significant effect with age, as the surface of the CoP decreased significantly as the age of the children increased. The $R^2$ value reached significance for the surface of CoP measured in all conditions tested: OKN + SVV at 80° left ($R^2 = 0.26$, $p < 0.001$), OKN + SVV at 80° right ($R^2 = 0.34$, $p < 0.001$), no OKN + SVV ($R^2 = 0.19$, $p < 0.001$), eyes open ($R^2 = 0.24$, $p < 0.001$) and eyes closed ($R^2 = 0.10$; $p < 0.001$).

The length of CoP in the medio-lateral direction decreased significantly as the age of children increased. The $R^2$ value reached significance for the length of CoP in the medio-lateral direction measured in all conditions tested: OKN + SVV at 80° left ($R^2 = 0.35$, $p < 0.001$), OKN + SVV at 80° right ($R^2 = 0.36$, $p < 0.001$), no OKN + SVV ($R^2 = 0.41$, $p < 0.001$), eyes open ($R^2 = 0.41$, $p < 0.001$) and eyes closed ($R^2 = 0.41$, $p < 0.001$).

The mean speed of CoP decreased significantly while the age of children increased. The $R^2$ value reached significance for the mean speed of CoP measured in all conditions tested: OKN + SVV at 80° left ($R^2 = 0.37$, $p < 0.001$), OKN = SVV at 80° right ($R^2 = 0.43$, $p < 0.001$), no OKN + SVV ($R^2 = 0.35$, $p < 0.001$), eyes open ($R^2 = 0.34$, $p < 0.001$) and eyes closed ($R^2 = 0.13$, $p < 0.001$).

Figure 1A shows the surface area of CoP ($mm^2$) for the five conditions for the six groups of children tested. The ANOVA showed a significant effect of group ($F_{(5,67)} = 10.86$, $p < 0.001$) as well as a significant effect of the condition ($F_{(4,268)} = 8.75$, $p < 0.001$). The post hoc test showed several differences among the groups (G): the surface of G1 was significantly different to the other groups, except G3 (all $p < 0.01$); the surface of the G2 was significantly larger than all other groups (all $p < 0.008$); the surface of the G3 was significantly different to G2 and G5 (both $p < 0.01$); the surface of G4 was significantly smaller than those of G1 and G2 (both $p < 0.01$); the surface of the G5 was significantly smaller than those of G1, G2 and G3 (all $p < 0.01$) and the surface of the G6 was significantly smaller than those of G1 and G2 (both $p < 0.001$).

The post hoc test showed that the surface of CoP was similar in the three conditions – OKN + SVV at

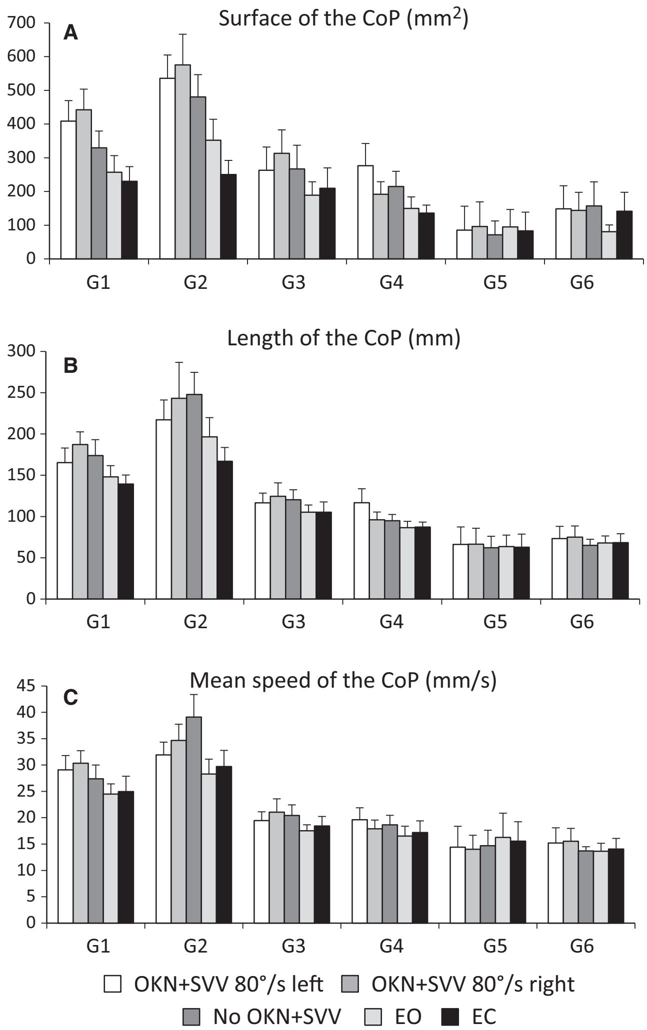


**Figure 1** Postural parameters for different conditions and age groups. Mean of CoP surface (A), CoP length in the medial–lateral axis (B) and CoP speed (C) for five different conditions (OKN + SVV: 80° left and 80° right, respectively, no OKN + SVV, eyes open and eyes closed) and all the six groups of children tested. Vertical bars indicate the standard deviation.

80°/seconds left and 80°/seconds right, respectively, and no OKN + SVV – while its values were significantly smaller with respect to the fixation (eyes open) and eyes closed conditions (both $p > 0.001$). The surface of CoP during fixation was not different to that recorded in the eyes closed conditions.

To summarise, the surface area of the CoP changed significantly until eight to nine years old and after this age, the surface of CoP did not change anymore until 15 years of age. Furthermore, during the dual task while the child was performing SVV, the surface of the CoP was significantly larger with respect to the conditions of the simple tasks with eyes open and eyes closed.

Figure 1B shows the length of CoP in the medio-lateral axis for the five conditions for the six groups of children tested. The ANOVA showed a significant effect of group ($F_{(5,67)} = 19.33$, $p < 0.001$) as well as a significant effect of the condition ($F_{(4,268)} = 4.59$, $p < 0.001$). The post hoc test showed several differences among groups: the length of CoP in the medio-lateral axis of G1 and G2 was significantly different to the other groups (all $p < 0.001$); the length of CoP in the medio-lateral axis of G3 was significantly different to the other groups ($p < 0.03$), except G4; the length of CoP in the medio-lateral axis of G4 was significantly smaller to those of G1 and G2 (both $p < 0.001$); the length of CoP in the medio-lateral axis of G5 and G6 was significantly smaller to those of G1, G2 and G3 (all $p < 0.001$).

The post hoc test showed that the length of CoP in the medio-lateral axis was not different in the three conditions: OKN + SVV at 80°/seconds left and 80°/seconds right, respectively, and no OKN + SVV. In contrast, its value was significantly smaller with respect to the fixation (eyes open) and eyes closed conditions (both $p > 0.001$). The length of CoP in the medio-lateral axis during fixation and eyes closed conditions was similar.

To summarise, the length of CoP in the medio-lateral axis changed until the children were eight to nine years old and after this age, the length of CoP in the medio-lateral axis did not change anymore. Furthermore, during the dual task, while a child was performing SVV, the length of CoP in the medio-lateral axis was significantly larger with respect to the conditions of simple tasks, performed with eyes open and eyes closed.

Figure 1C shows the mean speed of CoP for the five different conditions for the six groups of children tested. The ANOVA showed a significant effect of group ($F_{(5,67)} = 16.41$, $p < 0.001$) as well as a significant effect of the condition ($F_{(4,268)} = 1.77$, $p < 0.13$). The post hoc test showed several differences among groups: the mean speeds of G1 and G2 were significantly different to the other groups (all $p < 0.01$); the mean speeds of G3, G4, G5 and G6 were significantly smaller to those of G1 and G2 (all $p < 0.001$).

The post hoc test showed that the mean speed of CoP in the fixation condition was significantly smaller than the other conditions (all $p < 0.01$).

To summarise, the mean speed of CoP, which was similar to the other postural parameters studied, changed until eight to nine years of age and after this age, the mean speed of CoP did not change anymore. Furthermore, the mean speed of CoP was smaller in the fixating eyes open condition with respect to the other conditions, suggesting that muscular activity is increased during a dual task and also when vision is not present.

Figure 2 shows the absolute values of subjective visual vertical measures for the three conditions tested for the six groups of children: OKN + SVV at 80°/seconds left and 80°/seconds right and the no OKN + SVV condition. ANOVA showed a significant effect of group ($F_{(5,67)} = 7.71$, $p < 0.001$) but not any significant effect of condition ($F_{(2,134)} = 0.54$, $p = 0.58$). The post hoc test showed several differences between groups: the SVV in groups G1, G2 and G3 was similar, and their values were significantly larger with respect to those of groups G4, G5 and G6 (all $p > 0.001$). The SVV in groups G4, G5 and G6 was similar.

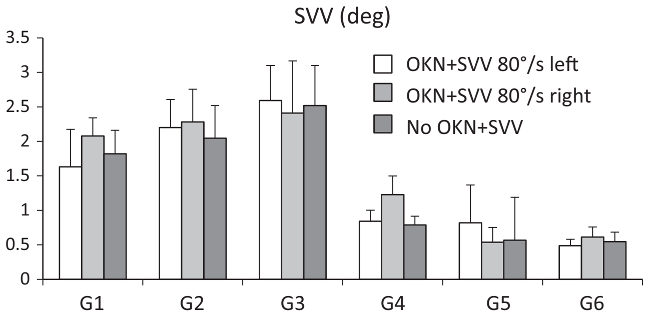


**Figure 2** Subjective visual vertical values and age groups. Mean values of the SVV are shown for three different conditions (OKN + SVV: 80° left and 80° right, respectively, and no OKN + SVV) and all the six groups of children tested. Vertical bars indicate the standard error.

To summarise, SVV improved until 10–11 years of age and after this age. the subjective visual vertical did not change significantly.

## DISCUSSION

The three main findings of this study were as follows: firstly, postural stability was poor in young children, and it improved with age until eight to nine years. Secondly, in the dual-task condition, children were more unstable and SVV values were more variable and less accurate in young children. Thirdly, after 10–11 years old, the SVV values did not change significantly. All these results will be discussed below.

### Postural stability in children improved during growth

Our results showed that postural control became more stable in children after eight to nine years of age and the new finding reported by our study is that this occurred for all simple or dual-task conditions tested. A previous study suggested an ontogenetic model for balance control strategies, stating that it was not until seven years of age that children developed head–trunk coordination, allowing them to reach better postural stability (17). Our results could be explained by this model that suggests that younger children have poor postural stability. We did note, however, that head–trunk movements were not recorded by that study and further experiments that measure head and trunk movements during the same conditions may be informative.

We suggest that improvements noted in our study could have been due to maturation of the brain structures involved in postural control, such as the parietal–temporal cortex, midbrain, superior colliculus and cerebellum (18,19).

### Children were more unstable in dual-task conditions

Our results showed that there was a significant effect of the secondary task for all postural parameters. Several studies from our group (7,20) and other groups (21,22) have reported poor postural stability in children while performing a secondary task, suggesting a shift of attention to the secondary task. All these findings are in line with the U-shaped nonlinear interaction model of Huxhold et al. (8), in which the body sway increased when children were performing a secondary task that required high levels of attention. In other words, the increase in the cognitive demand induced an increase in postural instability. In the present study, because the subjective visual vertical task required a fairly high level of attention, a deterioration of the postural performance occurred in children that was independent of their age.

### Subjective visual vertical values did not change after 10–11 years

Our study showed that the values of subjective visual vertical were rather variable and less stable until 10–11 years old, independent of the conditions tested. The absence of visual reference in the dark condition, or a perturbation of visual reference using optokinetic stimulation, can affect the allocentric reference frame used by the child to obtain a good perception of verticality. This is in line with the common conclusion that in the case of children, perception of verticality is strongly dependent on visual perception (2,9). We have suggested that the scarce subjective visual vertical performance we observed in younger children could have been due to immaturity of the cortical and central areas involved. This hypothesis is in line with the results of recent research conducted by our group (14,23), which explored the subjective visual vertical in healthy and preterm born children. More specifically, Gaertner et al. (14) showed that the accuracy of verticality at six to eight years old was scarce because children in that study were more dependent on visual information, so that the poor estimation of the SVV may have been caused by imperfect or incomplete integration of visual information. Bucci et al. (23), on the other hand, reported that preterm born children were more unstable than full-term born children and showed poor perceptions of verticality, probably due to the immaturity of the cortical processes involved in their motor control and in their treatment of perception and orientation of verticality.

Lopez et al. (24) examined the subjective visual vertical in 12 adult subjects through an electroencephalogram study and reported that the right lateral temporo-occipital cortical areas, as well as the bilateral temporo-occipital and parieto-occipital cortical areas, were activated during SVV estimation. Based on these findings, we hypothesise that all these areas may not have reached complete maturation until the age of 10–11 years. This is in line with some developmental studies (25,26) that showed that executive attention underwent significant maturation during childhood.

This study was conducted on a limited number of children, and further research on a larger number of children with different age and similar number of girls and boys between the groups would be useful to improve our understanding.

Further studies that combine postural tasks and secondary visual tasks would be useful to better evaluate the interaction between visual and motor control in children. Training that combined both visual and motor abilities could be applied for children with neurodevelopmental deficiencies.

## CONCLUSION

Our study showed that postural stability in young and healthy children improved after the age of eight to nine years, while SVV performances improved after an age of 10–11 years. These improvements could be explained by the maturation of the cortical processes involved in postural control, as well as in the perception of verticality, but also by the development of attention. On the other hand, the delay observed in SSV performances was probably due to the fact that children aged 10–11 years are, on the average, under the threshold at which the maturation of the relevant neuro-cognitive processes have been completed. On the basis of our results, we conclude that visual and motor training aimed at developing the central nervous system could contribute to the achievement of postural stability and more precise vertical evaluation.

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## CONFLICT OF INTERESTS

The authors have no conflict of interests to declare.

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