Physiology & Behavior 291 (2025) 114815

Contents lists available at ScienceDirect

Physiology & Behavior

journal homepage: www.elsevier.com/locate/physbeh

Effects of maturity status, training background and stereopsis on perceptual-cognitive skills from childhood into adolescence

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ARTICLE INFO

Keywords:
Perceptual-cognitive skills
Maturity status
Stereopsis
Training background
Adolescence

ABSTRACT

Perceptual-cognitive skills are determinant for sports performance in young athletes. The present study aimed to clarify how maturity status influences perceptual-cognitive skills with consideration of training background and stereopsis. One hundred and sixty-six 10- to 16-year-old male participants were divided into eight groups based on their training background (moderately-trained: 1–2 weekly sessions; well-trained: 4–5 weekly sessions) and maturity status (Pre-Pubertal$_1$ < -2 years from APHV, Pre-Pubertal$_2$ = -2 to -0.5 years from APHV, Pubertal = -0.49 to +0.5 years from APHV, Post-Pubertal > +0.5 year from APHV). Perceptual-cognitive skills were evaluated using a previously validated 3D-MOT task (i.e., the NeuroTracker^{MT}) with (3D) and without (2D) stereoscopic conditions. Pre-Pubertal$_1$ before ~13 years had significantly lower scores than their older counterparts ($p < 0.05$ at least), while no significant differences were observed between Pre-Pubertal$_2$, Pubertal, and Post-Pubertal children. In addition, significantly higher scores were found under the 3D condition regardless of maturity status and training background ($p < 0.001$). Finally, no significant effects of training background or interaction between training background, stereopsis, and maturity status were found on NeuroTracker^{MT} performance scores. In conclusion, the present results show that maturity status positively impacts perceptual-cognitive skill development until the age of ~13 years but that stereopsis-related advantage is not dependent on maturity status between 10 and 16 years. While no significant differences were observed between well- and moderately-trained children, high inter-individual variability regardless of stereopsis indicates that perceptual-cognitive skill evaluation during childhood and early adolescence may be useful for talent identification and long-term athlete development purposes.

1. Introduction

Perceptual-cognitive skills, defined as “the human brain’s ability to extract contextual information from dynamic visual scenes” [1], represent a major component of performance in most sports. Such skills generally manifest in athletes through their predictive and decision-making abilities, reflecting the athlete’s vision and game intelligence [2]. To further characterize and train perceptual-cognitive skills, some researchers have developed tools such as the NeuroTracker^{MT} (NT^{MT}), which includes software coupled with a 3D screen that allows users to track multiple moving target balls in an immersive space. The game task, called the three-dimensional multiple-object tracking (3D-MOT) task [3,4], is a high-level cognitive exercise stimulating neural networks involved in visuospatial processing, including the prefrontal cortex, parietal lobes, and cerebellum [5].

Several factors have been found to promote perceptual-cognitive skill, including stereopsis and training background. Stereopsis, defined as the ability to perceive depth and three-dimensional structure from binocular vision, facilitates performance in dynamic environments, particularly when athletes need to track multiple moving objects in 3D space [6,7]. Of particular note, Plourde et al. [4] showed that perceptual-cognitive performance is better under 3D (stereoscopic) than

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https://doi.org/10.1016/j.physbeh.2025.114815
Received 26 December 2024; Received in revised form 17 January 2025; Accepted 18 January 2025
Available online 19 January 2025

2D (non-stereoscopic) conditions in 7–12-year-old children and 18–40-year-old adults but not in older people aged over 65 years. Regarding training background, Gabbett et al. [8] showed that video-based perceptual training could be used effectively to enhance decision-making ability during small-sided games in adult female soccer players. Similarly, Romeas et al. [9] reported that perceptual-cognitive 3D-MOT training could improve ball passing decision-making ability in adult male soccer players, thus positively translating to on-field performance.

However, other factors such as age and maturity status could also influence perceptual cognitive skill; yet, these factors remain under explored. This is surprising since the central nervous system (CNS) mainly matures before 12–14 years of age [10], and prepubertal children could have a more significant advantage in terms of cognitive improvement induced by exercise than adolescents, young adults or elderly people [11,12]. Interestingly, Plourde et al. [4] showed in a small sample of 60 untrained individuals that 7–12-year-old children and older people (> 65 years) have lower perceptual-cognitive scores measured with the NT^{MT} than 18–40-year-old adults, although the differences were statistically different only between young adults and older people. Ehmann et al. [13] also reported that soccer players of the youngest age group (U12) exhibited significantly lower scores in a 360°-multiple object tracking task than youth players in the age groups U16, U17, U19, and U23, and that elite players in the oldest groups U19 and U23 had better perceptual-cognitive performances than their sub-elite counterparts in the same age group, meaning that training at a high level may play a significant role in increasing perceptual-cognitive skills during the post-pubertal period.

However, while these results are of interest, the above-mentioned studies did not assess maturity status, although it may represent a more discriminant confounding variable than chronological age in perceptual-cognitive changes from childhood into adolescence. Furthermore, these studies did not measure the role of stereopsis with respect to maturity status and training background, despite evidence that stereoacuity might continue to develop until the ages of 9–14 years, depending on studies and tests used [4]. In addition, during childhood and early adolescence, exercise training could significantly promote binocular stereoacuity since the CNS is highly stimulated in 3D dynamic visual scenes throughout training sessions. However, this remains to be further clarified. This may prove central to talent identification and the training strategies to adopt for succeeding in a sport requiring perceptual-cognitive skill, as in team sports (i.e., soccer, rugby, handball, etc.).

Given the gaps in existing research, the aim of the present study was to investigate the respective influences of maturity status, training background, and stereopsis as well as their interaction on perceptual-cognitive skills using the NT^{MT} task. We hypothesized that, between 10 and 16 years of age, (i) perceptual-cognitive performance may be lower before puberty regardless of stereopsis, (ii) youth athletes may show superior perceptual-cognitive performances to their non-athlete counterparts, notably in more mature individuals, and (iii) children and adolescents may have better perceptual-cognitive performance under stereoscopic (3D) than non-stereoscopic (2D) conditions, mainly in trained individuals since their CNS could be more stimulated in 3D dynamic visual scenes because of their regular training regimens.

2. Materials and methods

2.1. Participants

One hundred and sixty-six 10- to 16-year-old male volunteers volunteered and were divided into eight groups depending on their maturity status and training background. Sixty-two were considered well trained (4–5 weekly sessions) while 104 were considered moderately trained (1–2 weekly sessions). Participants were also divided into four groups according to maturity status, as described below (Pre-Pubertal$_1$, Pre-Pubertal$_2$, Pubertal and Post-Pubertal). All were members of the Montferrand Sports Association (ASM) from Clermont-Ferrand, France, and practiced rugby or soccer. They were healthy and had normal binocular stereoacuity as measured by the TNO and Lang I tests [14]. The present study was approved by an Institutional Ethics Review Board (CERSTAPS; IRB 00,012,476–2022–31–10–203) and was conducted in conformity with the policy statement regarding the use of human subjects as outlined in the sixth *Declaration of Helsinki*. Participants were informed of the experimental procedures and gave their written assent before any testing was conducted. In addition, the written informed consent was obtained from the parents or guardians.

2.2. Experimental design

Participants were tested in a single experimental session lasting ~30 min. The session was dedicated to gathering participants' physical characteristics (anthropometric measurements, visual acuity evaluation, maturity status assessment), explaining the test procedure, and finally assessing perceptual-cognitive skills using a 3D-MOT task (described below). Participants were tested on the 3D-MOT task both with and without stereopsis, i.e., 3D and 2D, respectively. The order of conditions was randomly assigned with a minimum rest of 10 min between. Only one attempt was allowed for each test to avoid training effects [15]. All participants were tested under identical conditions to ensure consistency and minimize variability due to external factors. These controlled conditions included the same screen size (65 inches), viewing angle (30°) and testing distance (2.6 m). In addition, participants were tested in a standing position. This choice was deliberate, as standing position is more representative of the postural demands in sports activities than sitting position [3]. None had been trained with the 3D-MOT task before the study, so all participants were naïve to the test. Data collection was led by a trained experimenter. All data were verified by an independent research assistant unrelated to the data collection. The measurements were taken between October 2022 and March 2024.

2.3. Anthropometric characteristics and body composition

Body mass (BM) was measured using a digital weight scale (TANITA, BC-545 N, Japan) and standing height was assessed using a portable stadiometer with the participants barefoot (TANITA, HR001, Japan). Sitting height was measured with the stadiometer while the participants sat on the floor with their back against a wall. Body mass and height were measured with the participant in light clothing and without shoes. Body mass index (BMI) was calculated as BM (kg) divided by standing height squared (m^2). Skinfold thicknesses were measured at the triceps and subscapular sites using a Harpenden calliper (British Indicators Ltd, St Albans, UK) and the mean value from three reproducible measurements was calculated. Measurements were taken on the right side of the body. Body fat percentage (%BF) was determined using the equations developed by Slaughter et al. [16], which are specific to sex, ethnicity and age, and are recommended for assessing body fat in children aged 8 to 18 years.

2.4. Maturity status assessment

Maturity status was assessed from maturity offset (MO, i.e., years to (from) age at peak height velocity (APHV)) by using chronological age, standing height, sitting height, and body mass. Its calculation was based on sex-specific regression equations according to the method proposed by Mirwald et al. [17]. Participants were considered as Pre-Pubertal$_1$, Pre-Pubertal$_2$, Pubertal or Post-Pubertal based on their MO according to the following definitions: Pre-Pubertal$_1$ < -2 years from APHV, Pre-Pubertal$_2$ $= -2$ to -0.5 years from APHV, Pubertal $= -0.49$ to $+0.5$ years from APHV, Post-Pubertal $> +0.5$ year from APHV [18].

2.5. 3D-MOT task

The 3D-MOT task used in the present study involved the manipulation of 8 spheres within a virtual cube (Fig. 1). Initially, all 8 spheres were depicted in yellow **(presentation phase,** Fig. 1a). Subsequently, three spheres turned red for 1 s **(indexing phase,** Fig. 1b). All 8 spheres returned to their original yellow color and began to move in all directions (X, Y and Z) in a virtual 3D cube **(movement phase,** Fig. 1c). Their trajectories involved interactions such as collisions, occlusions, and rebounds against the cube's walls. After 6 s, the spheres came to a halt, prompting the participant to identify the three initially highlighted targets **(identification phase,** Fig. 1d). Subsequently, feedback was provided to the participant by highlighting the original three targets (Fig. 1e).

One speed threshold was determined for each condition (with and without stereopsis) using a one-up, one-down staircase procedure as per Levitt [19]. Each trial commenced at a standardized speed value of 1 NT^{MT} unit, representing 68 cm/s in virtual speed. Correct identification led to a speed increase of 0.05 log units, while errors resulted in an equivalent decrease, maintaining a threshold criterion of 50 %. The staircase ceased after twenty inversions, with the speed threshold computed based on the mean speed across the final four inversions. The number of targets (i.e., three balls) was chosen to make sure that all children and adolescents could perform the task without losing interest during the session [4]. Stereoscopic perception was induced using anaglyph techniques, with participants using red-blue glasses. In the stereopsis condition, the disparity range spanned from 0 to 150 s of arc, contingent upon the specific position of the spheres within the virtual cube.

2.6. Statistical analysis

Data were screened for normality of distribution and homogeneity of variances using Shapiro-Wilk and Barlett's tests, respectively. Three-way ANOVA was used to examine the effects of maturity status, training background, stereopsis and their interaction on NT^{MT} scores (speed thresholds) of participants. When ANOVA revealed significant main or interaction effects, a Fisher's LSD post-hoc test was applied to test the discrimination between means. The effect size was assessed using the partial eta-squared (η_p^2) and ranked as follows: ~0.01 = small effect, ~0.06 = moderate effect, ≥0.14 = large effect [20]. The limit for statistical significance was set at $p < 0.05$. Statistical procedures were performed using Statistica 8.0 software (Statsoft, Inc., United States). Results are presented in the text and tables as mean ± SD.

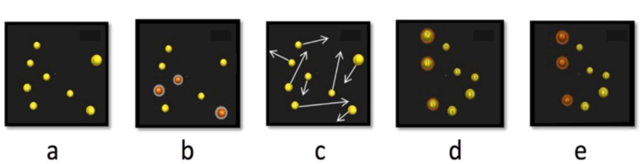

Fig. 1. Five steps of the 3D-MOT task. (a) presentation phase where 8 spheres are shown in a 3D volume space, (b) indexing phase where 3 spheres (targets) change color (red) and are highlighted (hallo) for 1 second, (c) movement phase where the targets indexed in stage b return to their original form and color and all spheres move for 6 s crisscrossing and bouncing off of each other and the virtual 3D volume cube walls that are not otherwise visible, (d) identification phase where the spheres come to a halt and the observer has to identify the 3 spheres originally indexed in phase (b). The spheres are individually tagged with a number so the observer can give the number corresponding to the original targets and (e) feedback phase where the subject is given information on the correct targets. **Figure reprinted from Plourde et al. [4] with permission.**

3. Results

Physical characteristics and the NT^{MT} performance scores of the eight groups are shown in Table 1. No significant maturity status × training background × stereopsis interaction effects were found for chronological age, body mass, standing height, % body fat, or body mass index.

ANOVA revealed main effects of maturity status ($F_{(3316)} = 2.871$, $p = 0.037$, $\eta_p^2 = 0.026$) and stereopsis ($F_{(1316)} = 25.243$, $p < 0.001$, $\eta_p^2 = 0.074$) on NT^{MT} performance scores. More specifically, Pre-Pubertal$_1$ before ~13 years exhibited significantly lower NT^{MT} scores than Pre-Pubertal$_2$ ($p < 0.01$), Pubertal ($p = 0.021$) and Post-Pubertal ($p = 0.012$) groups, with no significant differences between the latter groups regardless of training background or stereopsis (Fig. 2).

In addition, significantly higher NT^{MT} performance scores were found under the 3D condition (with stereopsis) independent of maturity status and training background (Table 1;Fig. 2). However, no significant maturity status × stereopsis interaction effect on NT^{MT} performance scores was detected ($F_{(3316)} = 0.219$, $p = 0.88$, $\eta_p^2 = 0.002$), meaning that stereopsis-related differences did not differ according to maturity status.

Finally, no effects of training background ($F_{(1316)} = 0.862$, $p = 0.354$, $\eta_p^2 = 0.003$), training background × maturity status interaction ($F_{(3316)} = 0.291$, $p = 0.83$, $\eta_p^2 = 0.003$), training background × stereopsis interaction ($F_{(1316)} = 0.656$, $p = 0.42$, $\eta_p^2 = 0.002$), or training background × stereopsis × maturity status interaction ($F_{(1316)} = 0.684$, $p = 0.56$, $\eta_p^2 = 0.006$) were found on NT^{MT} performance scores.

4. Discussion

The aim of the present study was to investigate the influences of maturity status, training background, stereopsis and their interaction on perceptual-cognitive skills using a previously validated three-dimensional multiple-object tracking task (NT^{MT}). The results partially confirm our hypotheses since there were significant effects of maturity status and stereopsis but no significant effect of training background or interaction effects between training background, maturity status, and stereopsis on NT^{MT} performance scores. Thus, only maturity status and stereopsis positively influenced visual and attentional abilities to process information effectively between the ages of 10 and 16 years.

The present results highlighted for the first time, by using the NT^{MT} task, that maturity status positively impacts the development of perceptual-cognitive skills, at least until the age of ~13 years, since no significant differences were observed between the Pre-Pubertal$_2$, Pubertal, and Post-Pubertal groups. This data indicates that childhood and early adolescence (until the age of ~13 years) are determinant periods in the development of perceptual-cognitive skills, possibly as a result of substantial maturation of the central nervous system (CNS) before puberty [21–23]. During this period, the cerebellum notably undergoes significant maturation, enabling more refined internal models for motor and cognitive tasks. This maturation supports pre-planning and fine-tuning of motor functions by leveraging available sensory information and coordinating with prefrontal areas for higher-order task processing [24]. Lenroot and Giedd [25] provided magnetic resonance imaging-based evidence that brain development is substantial during childhood and early adolescence, correlating structural changes in the prefrontal cortex with cognitive and behavioral advances. Furthermore, Diamond [26] emphasized the role of the prefrontal cortex in developing executive functions, with significant maturation occurring before the age of 11 years. Gogtay et al. [27] also mapped cortical development, showing that the different brain regions mature at different rates, with childhood being a peak period for developing perceptual-cognitive abilities. Collectively, these findings support the present results, showing that maturation of the CNS is a fundamental driver for improvements of perceptual-cognitive skills observed in children, particularly up to the age of ~13 years (Table 1).

The results of the present study also clearly show a stereopsis

Table 1
Participants' physical characteristics and perceptual-cognitive skill scores.

	Pre-Pubertal$_1$ (n = 44)		Pre-Pubertal$_2$ (n = 63)		Pubertal (n = 36)		Post-Pubertal (n = 23)	
	WT (n = 12)	MT (n = 32)	WT (n = 29)	MT (n = 34)	WT (n = 14)	MT (n = 22)	WT (n = 7)	MT (n = 16)
Age (years)	11.4 ± 0.6	11.5 ± 0.9	13.0 ± 0.8	13.2 ± 0.6	13.7 ± 0.4	14.3 ± 0.6	14.6 ± 0.3	15.2 ± 0.3
Height (cm)	143.6 ± 5.8	146.5 ± 5.3	158.1 ± 6.0	158.9 ± 5.6	169.4 ± 4.9	169.5 ± 5.8	178.4 ± 3.8	173.4 ± 5.4
BM (kg)	36.4 ± 6.2	38.4 ± 6.0	52.4 ± 8.4	46.0 ± 6.1	62.5 ± 12.7	56.7 ± 9.7	77.5 ± 8.6	61.8 ± 6.8
BMI (kg/m^2)	17.6 ± 2.3	17.9 ± 2.7	20.9 ± 3.1	18.2 ± 1.7	21.8 ± 4.6	19.7 ± 2.6	24.3 ± 2.3	20.5 ± 1.8
BF (%)	18.7 ± 4.6	19.5 ± 4.8	21.5 ± 4.9	16.9 ± 3.2	19.0 ± 10.4	16.3 ± 3.8	22.2 ± 3.8	16.3 ± 2.1
MO (years)	−2.67 ± 0.52	−2.70 ± 0.50	−1.22 ± 0.40	−1.27 ± 0.48	0.03 ± 0.23	−0.07 ± 0.28	1.39 ± 0.38	1.38 ± 1.10
APHV (years)	14.1 ± 0.5	14.2 ± 0.5	14.2 ± 0.7	14.4 ± 0.4	13.7 ± 0.5	14.4 ± 0.6	13.2 ± 0.5	13.8 ± 1.1
NT^{MT} 2D score	0.85 ± 0.29	0.91 ± 0.34	1.02 ± 0.29	1.03 ± 0.32	1.00 ± 0.35	0.97 ± 0.32	0.85 ± 0.30	1.08 ± 0.30
NT^{MT} 3D score	1.09 ± 0.27	1.03 ± 0.37	1.17 ± 0.26	1.20 ± 0.31	1.16 ± 0.37	1.22 ± 0.37	1.22 ± 0.22	1.22 ± 0.35

Data are presented as mean ± standard deviation. Abbreviations: WT: well-trained (4–5 weekly training sessions); MT: moderately-trained (1–2 weekly training sessions); BM: body mass; BMI: body mass index; BF: body fat; MO: maturity offset; APHV: age at peak height velocity; NT^{MT} 2D score: perceptual-cognitive skill score (without stereopsis); NT^{MT} 3D score: perceptual-cognitive skill score (with stereopsis).

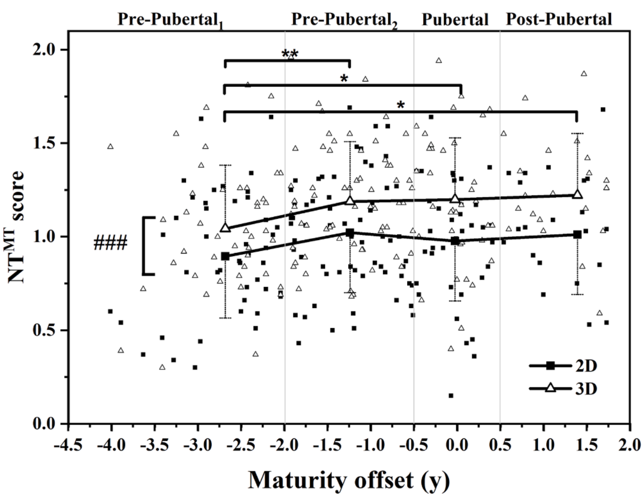

Fig. 2. Mean (SD) and individual NT^{MT} scores according to maturity status and stereopsis. NT^{MT} 2D score: perceptual-cognitive skill score (without stereopsis), NT^{MT} 3D score: perceptual-cognitive skill score (with stereopsis). * and ** indicate significant differences between maturity status groups at $p < 0.05$ and $p < 0.01$, respectively. $^{###}$ indicates a significant difference between stereopsis conditions (2D vs 3D) at $p < 0.001$.

advantage in perceptual-cognitive performance. Specifically, participants' capacities to process information efficiently and rapidly in an immersive space were significantly better with stereopsis (3D) than without (2D). This finding is consistent with the data of Plourde et al. [4], showing that the stereopsis advantage is present in both 7–12-year-old children (~17 % vs 20 % in the present study) and 18–40-year-old adults (~21 %). This may be ascribed to the fact that stereopsis enhances depth perception and spatial awareness, allowing individuals to process and respond to visual information more quickly, and plays an important role in processing dynamic stimuli, thereby improving perceptual-cognitive skill [3,28]. However, the results of the present study add further information to the data published by Plourde et al. [4] by investigating the effects of maturity status, rather than chronological age, on perceptual-cognitive skills among a larger cohort of children and adolescents. The absence of interaction between stereopsis and maturity status is also consistent with the results of Plourde et al. [4], however our data indicate that stereopsis-related differences may not also differ beyond chronological age according to maturity status.

In contrast to our initial hypothesis, the present results did not reveal a significant main effect of training background or an interaction between training background, maturity status and stereopsis on perceptual-cognitive skill. This finding is inconsistent with previous research reporting differences in general perceptual-cognitive skills between expert and novice athletes (adolescents and adults) [29–32]. Faubert [33] also observed that 3D-MOT-based learning was higher in adult athletes (professionals and elite amateurs) than in untrained university students, but that this function was also dependent on sports performance level, i.e., professionals performing better than elite amateurs. However, the non-significant differences in perceptual-cognitive skills found in the present study between the well-trained and moderately-trained children are consistent with the findings of Verburgh et al. [34], who found no significant differences in orienting attention or visuospatial working memory between high-level soccer players (training history 6.7 years) and amateur soccer players (training history 5.1 years) aged 8 to 16 years. Similarly, Qui and colleagues [35] did not observe a difference in tracking accuracies between athletes training 6 h per week and non-athletes (no training volume). One possible explanation for this discrepancy could be the relatively short training history of participants in either well-trained and moderately-trained child and adolescent groups. According to Zhang et al. [11], athletes who engage in long term variable exercise (e.g., basketball, soccer, rugby) may enhance the neural connections and the efficiency of neural networks in the frontal associative areas, thereby increasing their activation. Longer intervention times with moderate-intensity variable exercise may induce significant adaptive changes of the brain related to executive functions, decision-making, and complex cognitive tasks, and therefore exert a more active cognitive enhancement benefit. In this condition, a more substantial training load, of longer duration, or being more specific to development of perceptual-cognitive skills, may be required for significant effects to be produced from childhood into adolescence. However, future studies should investigate the variables accounting for the training type and load to further understand how training background influences the development of perceptual-cognitive skills during the maturational process. The absence of interaction between maturity status and training background also suggests that, while maturity status drives perceptual-cognitive development up to around 13 years, training up to 5 sessions per week over a short training history may be insufficient to amplify this effect beyond that gained through natural maturation. If correct, then children would need to engage early and regularly in activities that stimulate perceptual-cognitive skills, as in team sports.

It is also worth noting that there was considerable variability in perceptual-cognitive skills within each group, indicating significant inter-individual variation (Fig. 2). This variability suggests that some children may naturally possess greater perceptual-cognitive skill, which could be crucial for talent identification. Identifying children with early high vs. low perceptual-cognitive skills could help to tailor training programs to optimize these abilities and thereby contribute to long-term athlete development [36]. Such a hypothesis might be explicitly examined in future research.

4.1. Strengths and limitations

One potential limitation of the present study is that weekly training volumes (1–2 vs. 4–5 sessions) were not sufficiently differentiated to highlight variations in perceptual-cognitive skills among youth soccer and rugby players. Randomized, controlled exercise training interventions should be used to further clarify the effects of training on the development of perceptual-cognitive skills during growth and maturation. Another limitation of the present study is that the relationship between NT^{MT} scores and sports performance was not investigated. While previous research has shown that athletes with high NT^{MT} performance scores may possess advanced perceptual-cognitive skills and produce better sports performances, these studies primarily involved adults [9,33,37] rather than children and adolescents. Therefore, future research should seek to better understand the link between perceptual-cognitive skills and sports performance from childhood into adolescence. Finally, only male children and adolescents were studied. Until now, few studies were done in females from childhood into adolescence using the 3D-MOT task while perceptual-cognitive skills could be better in male than female athletes during late adolescence [38, 39]. Further studies should explore the potential concurrent effects of sex and maturation on perceptual-cognitive skills and their impact on sports performance, notably in women's team sports.

However, one major strength of the present study is that, for the first time, maturity status rather than chronological age was examined to specifically investigate the development of perceptual-cognitive skills, notably among a large age range around the adolescent growth spurt (10 to 16 years old). The present study has provided significant scientific evidence as to how maturity status influences the development of perceptual-cognitive skills with respect to stereopsis and training background.

5. Conclusion

The results of the present study highlight for the first time the determinant role of maturity status in perceptual-cognitive skill development to the age of ~13 years and the significant advantage of stereopsis (3D condition) during childhood and adolescence. The absence of a discernible training background effect under the current experimental conditions suggests that a higher training volume, of longer duration, and/or more specific to the context of the test, may be required to meaningfully promote perceptual-cognitive skills in children and adolescents. In addition, high inter-individual variability within each group suggests that perceptual-cognitive skills evaluation early during the development of youngsters may play a role in optimizing long-term athlete development and further identify future young talents.

6. Practical applications

Data acquired in the present study showed that maturity status has a positive impact on the development of perceptual-cognitive skills, and that before the age of ~13 years it is crucial to stimulate the CNS to promote these skills. Furthermore, specific perceptual-cognitive profiles already exist by childhood and early adolescence. However, while no significant differences were observed between well- and moderately-trained children, high inter-individual variability regardless of stereopsis indicates that perceptual-cognitive skill evaluation during childhood and early adolescence may be useful for talent identification and long-term athlete development purposes. This may also prove central to the training strategies adopted for success in sports requiring specific perceptual-cognitive skills during adolescence (e.g., team sports), but also for sporting careers in youth athletes.

Author contribution statement

FM, BEL and SR designed and supervised the research. TP collected the data. XZ and SR analysed the data. XZ, AJB and SR wrote the manuscript. XZ, FM, BEL, GE, AJB and SR provided critical revisions important for intellectual content of the finished manuscript. All the authors approved the final version of the manuscript, and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed.

Ethics approval

The present study was approved by an Institutional Ethics Review Board (CERSTAPS; IRB 00,012,476–2022–31–10–203) and was conducted in conformity with the policy statement regarding the use of human subjects as outlined in the sixth *Declaration of Helsinki*.

Consent to participate

Written informed consent was obtained from all individuals included in the study and from their parents or legal guardians.

Consent for publication

Participants (and their parents or legal guardians) signed informed consent regarding publishing their data.

Funding

The present study was supported by Clermont Auvergne Metropole.

CRediT authorship contribution statement

Xiaoyu Zhang: Writing – review & editing, Writing – original draft, Validation. **Freddy Maso:** Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition, Conceptualization. **Brigitte Ekpe-Lordonnois:** Writing – review & editing, Writing – original draft, Validation, Funding acquisition, Conceptualization. **Tom Poncelet:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Gael Ennequin:** Writing – review & editing, Writing – original draft, Validation. **Anthony J. Blazevich:** Writing – review & editing, Writing – original draft, Validation. **Sébastien Ratel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare no competing interests. The results of the study are presented clearly, honestly and without fabrication, falsification or inappropriate data manipulation.

Acknowledgements

The authors thank the participants for their patience, time and effort.

Data availability

https://filesender.renater.fr/?s=download&token=a131d76f-0f8f-4b75-abad-cf99cca2c21d.

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