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Determination of normative values of executive functions of young people aged 12 to 16 years using Virtual Reality

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Determination of normative values of executive functions of young people aged 12 to 16 years using Virtual Reality

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Abstract

Objective: The present study aims to determine the normative values of executive functions, more specifically cognitive flexibility and inhibitory control, in young people aged 12 to 16 years in the performance of Virtual Reality (VR) games. **Methods:** The sample, obtained by convenience, consists of 164 adolescents between 12 and 16 years old. For this study, a session with VR games was conducted and the Wisconsin Card Sorting Test (WCST) was performed on a computer. **Results:** Significant differences (p=.002) were found for age, with a cut-off point between 13 and 14 years old. Regarding sex, no significant differences were found. Furthermore, although the VR game and the WCST focus on the same executive functions there was a positive but not significant correlation between them. **Conclusion:** This study has shown that age has an influence on the performance of tasks that involve cognitive flexibility and inhibitory control since these skills are still under development during adolescence. It should also be noted that the use of VR is an added value due to the motivation it triggers in those who play.

Keywords: virtual reality, gaming, cognitive flexibility, inhibitory control, normative values

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1. Introduction

Executive functions refer to the cognitive processes involved in the control and coordination of information required to perform actions focussed on a goal and which facilitate new forms of behaviour, as well as to optimise a person's performance in unfamiliar circumstances (Diamond, 2013; Fourneret & des Portes, 2017; Gilbert & Burgess, 2008). These cognitive processes, further explored below, include inhibitory control, cognitive flexibility and working memory which are essential for effective, creative and socially adapted behaviour (Bryck & Fisher, 2012; Cristofori et al., 2019; Diamond, 2013).

The region of the brain most often associated with executive functions is the prefrontal cortex which has several areas and each is responsible for different functions (Blair, 2017; Cristofori et al., 2019). The dorsal lateral prefrontal cortex plays a role in working memory, object-directed attention, task switching, planning and problem-solving. The medial prefrontal cortex is related to self-awareness, emotional regulation, motivation and behaviour. The ventral lateral prefrontal cortex is responsible for inhibition, response selection and monitoring. The orbitofrontal cortex relates to inhibition, personality, and emotional and social reasoning (Jones & Graff-Radford, 2021). As the prefrontal cortex matures slowly, executive functions are amongst the last mental functions to reach maturity with gradual improvements throughout childhood and adolescence (Baum et al., 2017; Cristofori et al., 2019; Goddings et al., 2021).

According to Diamond (2013), there are three main executive functions: cognitive flexibility, inhibitory control, and working memory, from which higher-order executive functions are built, such as reasoning, problem-solving, decision making and planning. Cognitive flexibility and inhibitory control will be developed next as they are the focus of the present study.

Cognitive flexibility is the ability to adapt to the environment in the face of environmental changes, thus allowing the disengagement of a previous task efficiently, and arranging a new set of responses to the new situation (Dajani & Uddin, 2015; Fourneret & des Portes, 2017). This starts to develop in early childhood, progressing steadily from 3 years of age so that preschool children (3-5 years old) are able to handle changes between relatively simple tasks (Fourneret & des Portes, 2017). Between 7 and 9 years of age there is a marked increase in this capacity, and with learning and the maturing of neural networks throughout development, children are able to cope with unexpected changes and solve increasingly complex tasks, reaching between 15 and

17 years of age a level of cognitive flexibility equivalent to that of adults (Best & Miller, 2010; Davidson et al., 2006; Dick, 2014).

Inhibitory control influences cognitive flexibility since, when faced with a new situation, new strategies must be presented because the previous ones are no longer appropriate and must therefore be inhibited (Dajani & Uddin, 2015). Thus, inhibitory control represents the ability to control behaviour, attention, thoughts, and emotions when facing stimuli (Diamond, 2013). This allows for an automatic response to be interrupted during the execution of a task (Miyake et al., 2000). In turn, self-control concerns control over one's behaviour and emotions (Diamond, 2013). Concerning the development of inhibitory control, this shows a remarkable improvement during the first three years, and after 5-7 years the evolution occurs at a slower pace until the age of 17 when an adult-equivalent level is reached (Fourneret & des Portes, 2017).

Working memory refers to the ability to store and manipulate information temporarily and is fundamental for reasoning, for relating things that may seemingly be unrelated and is also important for creativity as it helps in recombining elements in new ways (Diamond, 2013; Goddings et al., 2021). The development of working memory occurs linearly during development from 4 years of age through adolescence and involves a bilateral fronto-parietal network that includes lateral prefrontal and posterior parietal cortical regions (Fourneret & des Portes, 2017; Goddings et al., 2021).

Executive functions are essential for mental health, physical health, quality of life, school performance and success, success at work, family and marital relationships, and public safety (Diamond, 2013). For example, changes in executive functions are related to overweight or obesity, as individuals have difficulty regulating their behaviour and making appropriate decisions, resulting in sedentary and unhealthy eating behaviours (Cappelli et al., 2019). At the school level, Borella et al. (2010), showed that working memory and inhibitory control changes were related to reading comprehension difficulties. In a cohort study by Moffitt et al. (2011), 1000 people born in the same city and year were followed for 32 years. They found that children aged 3 to 11 who had better inhibitory control were less likely to commit mistakes, take risky choices, smoke, or use drugs in adolescence and, consequently, had better physical and mental health as adults (Moffitt et al., 2011). In adolescents, when there is a delay or disturbance in the development of executive functions, this puts at risk the control of their actions and thoughts and may lead to inappropriate behaviour and deficits in social skills (Lalonde et al., 2013).

Taking into account the importance of executive functions in daily life, an accurate assessment is essential. As a means of assessing cognitive flexibility and inhibitory control, there are two most commonly used tests, the WCST to assess cognitive flexibility and the Stroop Test to assess inhibitory control.

The WCST is a neurocognitive test consisting of four stimulus cards and two decks with sixty-four cards, whose objective is to classify the cards that differ in three categories: the colour, the number and the shape of the drawings. The test rule is unknown and it should be the participant who determines it according to the feedback from the evaluator who only says whether it is right or wrong, and during the test the classification rule changes without the participant being informed (Grant & Berg, 1948; Miles et al., 2021).

The Stroop test is used to assess inhibitory control and is composed of two tasks, a reading task and a colour naming task in which colour names are presented and printed in incongruent colour. In both tasks, the participant should inhibit a response, for example, reading, while naming the colour of the word (Scarpina & Tagini, 2017; Stroop, 1935).

Other tests allow the assessment of executive functions directly and accurately, such as the Behavior Rating Inventory of Executive Function (BRIEF), Trail Making Test (TMT) and Delis-Kaplan Executive Functions System (D-KEFS) (Llinàs-Reglà et al., 2017; McFarland, 2020; Roth et al., 2015). Although they provide valid and standardised information, they rely on subjective third-party information such as parents or teachers questionnaires, or paper-pencil tests that are mostly performed in controlled environments which eliminate factors that usually influence cognitive functioning, such as environmental everyday life demands (Lalonde et al., 2013). Thus, it has become important to develop new assessment methods that come closer to real-life demands such as the use of Virtual Reality (VR) (Borgnis et al., 2022; Negu et al., 2016).

Sherman & Craig (2018) have defined VR as a medium with interactive simulations that sense the participant's position and actions and provide constant feedback, giving the sensation of being immersed or present in the simulation. The main characteristics of a VR system are immersion, interaction and presence (Radianti et al., 2020). Immersion represents the feeling of being inside the environment giving an illusion of inclusive and immersive reality (Maggio et al., 2019; Radianti et al., 2020). Interaction happens once the user controls the situations in the virtual environment according to his/her will (Maggio et al., 2019; Radianti et al., 2020). Presence is the subjective experience of being in a place or environment, even when the user is physically located elsewhere (Radianti et al., 2020).

Lalonde et al. (2013) showed that VR can offer a direct assessment of cognitive functioning with the possibility of including demands that require functional abilities necessary for everyday situations and that it increased motivation, with a positive impact on the ecological validity of test result interpretations. In addition to assessment, VR has been increasingly used in the rehabilitation of executive functions promoting the maintenance or gain of these functions as reviewed by Borgnis et al. (2022).

One of the great advantages of VR is the possibility of modulating and adapting the exercises according to the user's skills. Furthermore, the user can monitor their performance through visual and auditory feedback (Borgnis et al., 2022; Maggio et al., 2019; Radianti et al., 2020). For example, in study of Shochat et al. (2017), a VR game platform called "Active Brain Trainer" was used to train specific cognitive functions, where these games progressively adapted in real-time to the user's performance, allowing the user to progress at his own pace. Moreover, as the users received immediate audio-visual feedback after a correct answer and a reward (virtual medals) at the end, it increased their motivation and performance. As another example, in study of Shen et al. (2020) a set of three games to train the core executive functions (inhibitory control, working memory and cognitive flexibility) was developed, providing feedback, but also allowing to tailor the level of difficulty of the exercises according to the users.

Considering the advantages of using VR to assess executive functions, and the substantial improvements in executive functions during adolescence establishing normative values on the performance of tasks that require executive functions could prove important as these will have a relevant impact on participation in occupations and on the analysis of participation behaviour (Goddings et al., 2021; Hartung et al., 2020; Lalonde et al., 2013). Therefore, this study aims to determine the normative values of executive functions, more specifically cognitive flexibility and inhibitory control in young people aged 12 to 16 years in the performance of VR games.

2. Methods

This is a quantitative study of a descriptive observational type since the data collected can be measured and the assessments were carried out at a single moment in time. In addition, it aims to describe the behaviour of a representative sample of a population (Cohen et al., 2011; Mann, 2003).

2.1. Participants

The sample of this study was composed of 164 participants. The recruitment method was not probabilistic by convenience since it depended on the researchers' subjective criteria, as well as on the ease of access and availability. To obtain this sample, the researchers contacted the heads of schools in the districts of Porto and Viseu.

For the selection of participants, the inclusion criteria were defined as being aged 12 years old or over, due to the complexity of VR games, and having a command of the Portuguese language to understand the rules and instructions of each game. As for the exclusion criteria, individuals who had a health condition that interfered with participation in the game and/or the safety of the player himself were excluded.

Although 205 informed consents/sociodemographic questionnaires were given, only 165 participants replied, of which one participant was excluded because he had a motor condition in one of the upper limbs and, therefore, could not hold the two controllers. Thus, 164 participants were included in the sample. From this initial sample, 30 participants were chosen non-probabilistically by convenience to perform a computer-based test (WCST) to assess the same executive functions trained in the VR game.

2.2. Data Collection

To characterise the sample, a sociodemographic questionnaire was given to each parent about his/her child, where the following data were collected: age, sex, year of schooling, district, developmental disorders, experience with VR, health problems, medication and therapeutic monitoring. Health problems and medication were questioned as they could influence performance in the VR game.

As for VR, the game React from the Enhance VR application belonging to Virtuleap was used to assess the performance of young people in terms of cognitive flexibility and inhibitory control. In this game, the player needs to categorise the objects that are approaching, by their colour and shape, and throw them into one of the portals, placing one on the left and one on the right, taking into account the characteristics determined by each of these portals. During the game, the characteristics accepted by each of the portals will change and distracting shapes will appear that do not go to any portal and which the player must ignore (Virtuleap, 2022). As for the results, this game generated scores (means of the points of each game) and levels.

The equipment used for VR data collection was the Head-Mounted Display (HMD) glasses, model "Quest", manufactured by the company Meta with a Qualcomm snapdragon 835 processor, 4Gb RAM, 64Gb internal memory, resolution per eye in pixels: 1400 x 1600, a refresh rate of 72Hz, with a battery capacity of two to three hours, with a mass of 571 grams and motion controllers (Touch controllers).

The Wisconsin Card Sorting Test (WCST) of the E-Prime 3.0 Command Reference software was also used, carried out on three laptops (HP Laptop 15s-fq5012np (15. 6" - Intel Core i5-1235U - RAM: 8GB - 256GB SSD - Intel Iris Xe Graphics); Lenovo ThinkPad X250-20CLS06D00 (12.50" - Intel Core i7-5600U - RAM: 8GB - 256GB - Intel Broadwell-U PCH-LP); HUAWEI MateBook D15 (15. 6" - Intel Core i5-1135G7 - RAM: 8GB - 512GB SSD PCIe - Intel Iris Xe Graphics)) to assess cognitive flexibility and inhibitory control. The WCST provided by E-prime is identical to the neurocognitive test with the same name, and in which five cards appear on the screen at the same time (one response card that is presented at the bottom of the screen and four stimulus cards in a row at the top) and whose objective is to categorize the presented cards based on colour, shape or number of symbols. The rule of the test is unknown and it should be up to the participant to determine it according to the feedback from the computer that only says whether it is right or wrong, and during the test, the classification rule changes without the participant being informed (Grant & Berg, 1948; Miles et al., 2021). As regards to the results, the following can be analysed: number of errors, perseverative answers, perseverative errors, nonperseverative errors, number of conceptual level answers, the total number of completed categories, attempts to form the first category, disruptions and "learning to learn" index. Although there is confusion in the literature about how to score the WCST, the most commonly used variables to assess cognitive flexibility are perseverative responses and perseverative errors (Miles et al., 2021). The WCST has good internal consistency scores with Cronbach's alpha values of 0.916 (Almeida, 2018).

2.3. Procedures

This study was submitted for assessment and approval by the Ethics Committee of the School of Health, Polytechnic of Porto School (ESS | P. Porto), under the number CE0109C/2022.

The surveys were carried out with young people aged between 12 and 16 years. To this end, each parent was given an informed consent form, according to the Declaration of Helsinki, and asked to fill it out to authorise the participation of their child in this study (Association, 2013). In addition to considering the ethical principles set out in this declaration, the rules of privacy, data protection and behaviour in the best interests of the participants were also respected. As for the collection, processing and storage of personal data, Regulation (EU) 2016/679 of the European Parliament and Council and the Portuguese Law 58/2019 were complied with. In order to guarantee the anonymity and confidentiality of the data, the principal investigator assigned a code to each participant and data regarding the questionnaires, games and tests applied. Beyond that, the study was explained in detail, the guarantee of data confidentiality and in case of dropout, the participant could be reinstated if they wished.

Together with the informed consent form, sociodemographic questionnaires were given to the participants' parents.

For data collection, a VR session – corresponding to the Benchmark session – was performed in person, lasting minutes in a school context. As this study is part of a larger project, several mental functions were assessed with five games of the Enhance VR application: Whack-a-mole to assess attention, Staker for problem-solving, Orbital for spatial orientation, Slinger for response speed and motor accuracy, and React for cognitive flexibility and inhibitory control. However, for the present study, only the results obtained in React were analysed, which lasted six minutes and was the last to be applied. This session took place in the schools within large classrooms, with no objects around, where there were only the researchers and two students who played at the same time, as two Quest glasses were used. To play the games, the participants were not allowed to leave the play area and, therefore, they played the game sitting on chairs without armrests, which did not influence the performance in the game as only the upper limbs were used.

In a later session, students who had already performed the VR game were randomly selected to perform the WCST on a computer, which like the VR session, was done in school classrooms.

2.4. Data Analysis

IBM Statistical Package for the Social Sciences (SPSS) 28 software (*IBM SPSS Statistics 28*, 2022) was used for statistical analysis, with a significance level of 0.05 being considered for all tests applied.

To characterize the sample, a descriptive analysis was made using measures of central tendency (mean) and dispersion (standard deviation) for discrete or continuous variables, and absolute values (n) and percentage values (%) for categorical variables.

Then, inferential statistics were performed by first testing the normality of the variables under study using the Kolmogorov-Smirnov test (Ghasemi & Zahediasl, 2012). Parametric tests were used, specifically the Student's t-test for independent samples and one-way repeated measures ANOVAs whenever the distribution was considered normal, using threshold criteria for skewness and kurtosis (less than |2.0| and |9.0|, respectively) (Kim, 2015). The t-student test for independent samples was used to compare means between two groups (sex, age range, district and previous VR experience). On the other hand, one-way repeated measures ANOVAs were used to compare means between different groups (age, year of schooling and frequency of VR use). For these models, Mauchly's test was used to test for sphericity. Whenever this assumption was not met and the epsilon was greater than 0.57, the Huynh-Feldt correction was used, otherwise, the Greenhouse-Geisser correction was used (Berkovits et al., 2000; Emerson, 2022; Saisana, 2014).

Virtuleap provided the raw results of a larger uncontrolled sample, that is, the number of participants and the means obtained in React taking into account the ages. With this, a visual comparison was made between these results and those obtained in the present study.

When the ages were analysed, it was noticeable that there was a pattern and that there was a cut-off point between the youngest and the oldest. Thus, the ages were grouped into two groups (from 12 to 13; and from 14 to 16 years).

Pearson's Correlation was used to perform the correlation between the VR game and the WCST performed on a computer (Akoglu, 2018).

3. Results

3.1. Sample Characterisation

The sample of this study included a total of 164 adolescents, 77 females (46.95%) and 87 males (53.05%) aged between 12 and 16 years ($\bar{x}$=13.35; σ=1.072), belonging to the districts of Porto (n=103; 62.80%) and Viseu (n=61; 37.20%), in Portugal. Regarding the year of schooling, 60 participants belonged to 7th grade (36.58%), 53 to 8th grade (32.32%) and 51 to 9th grade (31.10%). From this sample 8 adolescents (4.88%) had developmental disorders, such as Attention-Deficit/Hyperactivity Disorder (Table 1).

More than half of the participants had never used VR (n=107; 62.24%) and of those who had already used it (n=57; 37.76%) 49 (29.88%) used it sporadically, 5 (3.05%) used it once or twice a week and only 3 (1.83%) used it three or more times a week (Table 1).

Table 1

Descriptive Information of the Sample

Sample characterisation	Sample (n=164)	
	n (%)	*M (SD)*
Age		
12	45 (27.44)	
13	42 (25.61)	
14	57 (34.76)	13.35 (1.072)
15	15 (9.14)	
16	5 (3.05)	
Age range		
12-13 years	87 (53.00)	13.35 (1.07)
14-16 years	77 (47.00)	
	n (%)	
Sex		
Female	77 (46.95)	
Male	87 (53.05)	
Year of schooling		
7th grade	60 (36.58)	
8th grade	53 (32.32)	
9th grade	51 (31.10)	
District		
Porto	103 (62.80)	
Viseu	61 (37.20)	
Developmental disorders		
Yes	8 (4.88)	
No	156 (95.12)	
Previous VR experience		

Yes	57 (34.76)
No	107 (65.24)
Frequency of VR use	
Never	107 (65.24)
Sometimes	49 (29.88)
1 or 2 times per week	5 (3.05)
3 or more times per week	3 (1.83)

Note. M=mean; SD=standard deviation; n=absolute frequency; %=relative frequency

3.2. React VR Game Results

When analysing the scores and levels obtained in the React VR Game it is possible to verify that there are significant differences when comparing the means of age, age range, year of schooling and district (p=.035; p=.002; p=.003; p=.001, respectively; Table 2)., Regarding age and age range, it can be seen that older participants obtained higher scores ($\bar{x}$=37.03) and levels ($\bar{x}$=6.55) than younger participants ($\bar{x}_{score}$=30.16; $\bar{x}_{levels}$=5.45) and, therefore, as the year of schooling increased, so did the obtained values. As for the district, participants from Porto schools obtained lower scores ($\bar{x}$=29.24) and levels ($\bar{x}$=5.31) than those from Viseu ($\bar{x}_{score}$=40.38; $\bar{x}_{levels}$=7.07). Although the differences between the means by sex are not significant, it can be seen that male participants obtained better results ($\bar{x}_{score}$=34.77; $\bar{x}_{levels}$=6.16) than female participants ($\bar{x}_{score}$=31.82; $\bar{x}_{levels}$=5.74). As for previous VR use, the means of those who had already used it are higher ($\bar{x}_{score}$ e=34.82; $\bar{x}_{levels}$=6.21) compared to those who had never tried it ($\bar{x}_{score}$ =32.62; $\bar{x}_{levels}$=5.83), though these differences are not significant. Regarding how frequently VR is used, no significant differences were found, although the scores and levels were higher in those who use it three or more times per week ($\bar{x}_{score}$=46.34; $\bar{x}_{levels}$=8.00) compared to those who use it once or twice per week ($\bar{x}_{score}$=24.86; $\bar{x}_{levels}$=4.60) or sporadically ($\bar{x}_{score}$=35.13; $\bar{x}_{levels}$=6.27).

Table 2

Results Obtained in the VR Game React

	Sample (n=164)			
	Scores		Levels	
	M (SD)	*p*	*M (SD)*	*p*
Sex				
Female	31.82 (15.56)	.114[a]	5.74 (2.54)	.147[a]
Male	34.77 (15.62)		6.16 (2.57)	
Age				
12	27.86 (15.69)	.035[b]	5.07 (2.57)	.037[b]
13	32.62 (14.39)		5.86 (2.37)	

14	37.45 (15.35)		6.65 (2.50)	
15	35.08 (17.87)		6.13 (2.92)	
16	38.03 (7.95)		6.60 (1.34)	
Age range				
12-13 years	30.16 (15.18)	.002[a]	5.45 (2.50)	.003[a]
14-16 years	37.03 (15.39)		6.55 (2.52)	
Year of schooling				
7th grade	28.30 (15.45)		5.12 (2.51)	
8th grade	34.61 (14.55)	.003[b]	6.17 (2.41)	.003[b]
9th grade	38.09 (15.42)		6.75 (2.51)	
District				
Porto	29.24 (14.03)	.001[a]	5.31 (2.31)	.001[a]
Viseu	40.38 (15.76)		7.07 (2.59)	
Previous VR experience				
Yes	34.82 (15.73)	.195[a]	6.21 (2.57)	.184[a]
No	32.62 (15.57)		5.83 (2.55)	
Frequency of VR use				
Never	32.62 (15.57)		5.83 (2.55)	
Sometimes	35.13 (15.27)		6.27 (2.53)	
1 or 2 times per week	24.86 (17.08)	.223[b]	4.60 (2.51)	.235[b]
3 or more times per week	46.34 (17.32)		8.00 (2.65)	

Note. [a]T-test for independent samples; [b]ANOVA test

Interestingly, the results in this study are consistent with the overall data in the players database collected by Virtuleap, where a cut-off point is observed in the averages of the scores by age. That is, participants from 11 to 13 years old had lower means ($\bar{x}$=38.08) than participants from 14 to 16 years old ($\bar{x}$=48.74). Is worth noting that the scores are higher than those obtained in this study at all ages (Table 3).

Table 3

Gross Results Obtained by Virtuleap

	React score	
	n	*M*
Age		
11	50	33.17
12	109	39.32
13	115	40.75
14	129	45.44
15	199	48.07
16	284	50.71
Age range		
11-13 years	274	38.08
14-16 years	612	48.74

3.3. Characterisation of the Sample That Took the WCST

The sample that performed the WCST included 30 adolescents, 15 females (50.00%) and 15 males (50.00%) aged between 12 and 15 years ($\bar{x}$=13.33; SD=1.028), belonging to the districts of Porto (n=14; 46.67%) and Viseu (n=16; 53.33%). Regarding the year of schooling, 11 participants belonged to 7th grade (36.67%), 11 belonged to 8th grade (36.67%) and 8th to 9th grade (26.66%). From this sample, 2 adolescents (6.67%) had developmental disorders (Table 4).

Table 4

Descriptive Information of the Sample That Took the WCST

Characteristics	Sample (n=164)	
	n (%)	*M (SD)*
Age		
12	8 (26.67)	
13	8 (25.67)	13.33 (1.028)
14	10 (33.33)	
15	4 (13.33)	
	n (%)	
Sex		
Female	15 (50.00)	
Male	15 (50.00)	
Year of schooling		
7th grade	11 (36.67)	
8th grade	11 (36.67)	
9th grade	8 (26.66)	
District		
Porto	14 (46.67)	
Viseu	16 (53.33)	
Developmental disorders		
Yes	2 (6.67)	
No	28 (93.33)	

3.4. WCST Results

There are significant differences in the WCST results (Table 5) in the mean time to perform the test by age range, (*p*=.017), with the youngest taking less time ($\bar{x}$=1889.50) than the oldest ($\bar{x}$=2233.55). There are also significant differences when comparing the means of the right answers by year of schooling (*p*=.002), with 8th graders obtaining significantly lower values ($\bar{x}$=20.82) when compared with 7th graders ($\bar{x}$=23.73; *p*=.023) and 9th graders ($\bar{x}$=24.97; *p*=.003; Table 5 and 6).

While there are no significant sex differences, male participants had more right answers ($\bar{x}$=23.27) and responded in less time ($\bar{x}$=1936.69) compared to female participants ($\bar{x}_{right\ answers}$=22.67; $\bar{x}_{time}$=2158.09). The results in the age groups show that younger ones had more correct answers ($\bar{x}$=23.13) than the older ones ($\bar{x}$=22.79), although without significant differences. With regard to time by year of schooling, no significant differences were found, but as the year increases so does mean time ($\bar{x}_{7th\ grade}$=1832.33; $\bar{x}_{8th\ grade}$ =2142.00; $\bar{x}_{9th\ grade}$ =2212.10). As for the district, the means of the right answers were very close between the two districts ($\bar{x}_{Porto}$=23.00; $\bar{x}_{Viseu}$=22.94), as well as the time ($\bar{x}_{Porto}$=2014.19; $\bar{x}_{Viseu}$=2076.44)

Table 5

Results Obtained in WCST

	Sample (n=30)			
	Right answers		Time	
	M (SD)	*p*	*M (SD)*	*p*
Sex				
Female	22.67 (2.90)	.287[a]	2158.09 (468.70)	.095[a]
Male	23.27 (2.89)		1936.69 (434.49)	
Age				
12	23.63 (2.00)	.876[b]	1892.96 (211.27)	.206[b]
13	22.63 (2.33)		1876.04 (434.83)	
14	22.60 (4.22)		2273.10 (516.10)	
15	23.25 (1.25)		2134.67 (602.02)	
Age range				
12-13 years	23.13 (2.16)	.376[a]	1884.50 (330.37)	.017[a]
14-16 years	22.79 (3.58)		2233.55 (521.78)	
Year of schooling				
7th grade	23.73 (1.74)	.002[b]	1832.33 (206.36)	.139[b]
8th grade	20.82 (3.06)		2142.00 (599.47)	
9th grade	24.97 (1.96)		2212.10 (420.89)	
District				
Porto	23.00 (2.91)	.477[a]	2014.19 (417.80)	.359[a]
Viseu	22.94 (2.91)		2076.44 (502.52)	

Note. [a]T-test for independent samples; [b]ANOVA test

Table 6

Multiple Comparisons Between Years of Schooling

Year of schooling		Right answers	
		Mean difference	*p*
7th grade	8th grade	|2.91|	.023
7th grade	9th grade	|1.15|	.915
8th grade	9th grade	|4.06|	.003

3.5. Correlations Between the React and the WCST

When correlating the scores obtained in the React and the WCST, no significant associations were found. However, it is possible to verify that the correlation is positive when comparing the scores of both tests (r=.109; r=.140), which indicates that the number of correct answers increases when the score and level obtained in React also increase. Conversely, the higher this score or level, the less time is spent by participants performing the WCST tasks (r=-.132; r=-.133; Table 7).

Table 7

Correlations Between the React and the WCST

React	WCST	
	Right Answers	**Time**
	r (*p*)	**r (*p*)**
Score	.109 (.567)	-.132 (.486)
Level	.140 (.462)	- .133 (.482)

Note. r = Pearson's correlation

4. Discussion

The present study aimed to determine the normative values of executive functions, more specifically, cognitive flexibility and inhibitory control, in young people aged 12 to 16 years old when playing VR games. In this study, significant differences were found in the scores and levels obtained in React when comparing age, age range, year of schooling and district. Although without significant differences, the mean scores and levels of those who had already used VR tended to be higher than those who had never used it. As for the WCST, younger participants were significantly quicker to respond. On both the React and WCST there were no significant differences in terms of sex. In addition, a positive but non-significant correlation was also found between React and WCST.

As mentioned above, in this study, there were significant differences when comparing the means of age, age range and year of schooling, with older participants obtaining better results in React. These results were expected as both cognitive flexibility and inhibitory control develop throughout adolescence, when the structures responsible for executive functions mature, particularly the prefrontal cortex (Durston & Casey, 2006; Jones & Graff-Radford, 2021). Puberty plays a significant role in adolescent brain plasticity, and therefore, during adolescence there is an enhancement of neural and cognitive functions (Ravindranath et al., 2022). Cognitive flexibility progresses steadily from the age of 3, with a notable increase between the ages of 7 and 9, reaching an adult equivalent level between the ages of 15 and 17 (Fourneret & des Portes, 2017). Concurrently, inhibitory control shows a remarkable development in the first three years of life, with the evolution occurring at a slower pace until the age of 17 when it reaches a level equivalent to that of adults (Fourneret & des Portes, 2017).

The age-related results that were observed are also consistent with the study of Dias et al. (2013) who found that there were significant effects of age on the performance of different tests that assess executive functions, with more performance as age increases between 6 and 17 years of age. They concluded that there were no differences in cognitive flexibility at earlier ages, with a significant gain at the age of 10, and a more gradual progression up to 14 years of age. Inhibitory control did not differ at early ages, but there were differences among older participants.

Concurrently, another study by Er-Rafiqi et al. (2021) showed significant differences in cognitive flexibility, increasing with age as they analysed the developmental trajectories of different executive functions, such as inhibition, working memory, cognitive flexibility, and planning in Moroccan children between 7 and 12 years old. In Wendelken et al. (2012) study cognitive flexibility tasks were performed in children and adults and was observed that the dorsolateral prefrontal cortex took longer to respond to update rules in children, that is, that is, when rules were changed younger ones took longer to accept them and were more likely to keep previous irrelevant rules, thus, demonstrating less cognitive flexibility.

Furthermore, the obtained results were compared with those of a larger sample, even if, uncontrolled, provided by Virtuleap, the company that created the games. It was found that the results of this study are in line with theirs, with a cut-off point between 13 and 14 years of age. However, the average scores of Virtuleap are higher than those of this study which may be related to the sample size or, since it is an uncontrolled sample, it is not possible to confirm the announced ages. In addition, the fact that several VR games were performed in the same evaluation session may influence the performance in the games, especially in the last game which in this case was React because of fatigue.

As expected, participants who had already used VR had better results in React, although these differences were not significant. As they had previously used similar equipment, they were more familiar with the equipment, procedures and the virtual environment, that is, using VR was a repeated experience and repetition leads to learning, which can lead to a change in performance over time (Henry et al., 2022; Lafontaine et al., 2020; Speelman & Shadbolt, 2018). On the other hand, since the differences were not significant, it can be considered that previous experience has little influence on gaming performance. Likewise, frequent use did not seem to influence performance significantly, despite the fact that those using a similar device three or more times a week were found to score better than those using it once or twice a week or using it sporadically. Thus, an experienced user might have an advantage, but not enough to significantly differentiate in-game performance.

When performing the WCST, younger participants were significantly faster to respond, as was the case in Dias et al. (2013) study. This may be justified by the fact that inhibitory control is still developing at younger ages and children are more impulsive in selecting responses (Dias et al., 2013; Fourneret & des Portes, 2017; Vara et al., 2014). As for the correct answers, there were no significant differences when comparing the two age groups, with younger ones having a slightly higher mean than the older ones. This result may be related to the small sample size that performed this test.

With regard to sex, there were no significant differences in performance on the React and the WCST, nonetheless, males performed slightly better than females. In the study by Wierenga et al. (2019), no differences were observed in brain developmental trajectories, including the development of cognitive domains and executive functions. Also in the study by Shinohara & Moriguchi (2021), they compared the performance of children in cognitive flexibility tasks, specifically the Dimensional Change Card Sort –(a simplified version of the WCST), and concluded that the differences were very small and might be a result of the questionnaires and cognitive tests not being sensitive enough to detect sex differences. However, they observed that females tend to perform this type of task better than males, which were not seen in the present study.

The React and the WCST focus on the same executive functions, that is, cognitive flexibility and inhibitory control, and there is a positive but non-significant correlation between them. A positive correlation means that when the score of one increases the other also tends to increase, which would be expected since they focus on the same executive functions. The non-significant correlation may be related to the fact that they were applied with completely different devices, the first with the Oculus Quest and the second on a computer. The fact that in this study the WCST was performed on a computer has advantages over the use of the physical WCST since more variables and more accuracy are recorded on a computer (Steinke & Kopp, 2020). However, the environment surrounding the computer or VR is very different, with the latter having a possible advantage over the former. Lalonde et al. (2013) and Shochat et al. (2017), found that the use of VR games for the assessment and training of specific cognitive functions increased motivation and performance, since users receive immediate audiovisual feedback after a response and virtual rewards. Is also worth mentioning that VR provides other features such as immersion, interaction and a sense of presence (Radianti et al., 2020). Furthermore, the fact that the VR game was applied first then the WCST on a computer may have decreased motivation and therefore influenced the results.

The limitations of this study are the small sample size, which is not representative of the adolescent population in Portugal to establish normative data. Moreover, with a larger sample would probably bring closer the mean scores across ages and age groups obtained in this study with those obtained by Virtuleap. As several VR games were performed in the same session, fatigue might have influenced the results, especially as React was the last game. As sessions were conducted in the schools, uncontrolled external distractor stimuli, such as noise, may have influenced their performance.

In future research, it would be important to increase the number of participants, using a probabilistic sample, ideally from different parts of the country. It would be interesting to study whether there are differences in executive functions taking into account the environment in which they live (rural or urban). Considering the significant differences between age groups, it would be relevant to establish normative curves by age of the executive functions studied. Additionally, the age range should be increased since cognitive flexibility and inhibitory control are still maturing until the age of 17 (Durston & Casey, 2006; Jones & Graff-Radford, 2021). Response time and number of right answers in the WCST could also be studied in different age groups, with a larger population, to further understand if younger people are faster and better in the number of right answers.

5. Conclusion

The present study aimed to determine the normative values of executive functions, more specifically cognitive flexibility and inhibitory control in young people aged 12 to 16 when performing VR games. Although the number of participants in this study was not sufficient to establish normative data, it was possible to observe that age is a key aspect in the performance of cognitive flexibility and inhibitory control. Thus, the performance of young people in activities requiring these executive functions will vary according to age, improving as age increases and with a cut-off point appearing to be between 13 and 14 years old.

Executive functions are important for different areas, such as social participation or school and work performance and success, which are part of human occupations. In everyday life there may be several environmental changes in these and other occupations that require adaptation, this means having good cognitive flexibility. Since occupation is the main focus of the occupational therapist, it is important to assess and intervene in executive functions in order to enhance the participation of people, namely adolescents. That said, this study is important for occupational therapy as cognitive flexibility and inhibitory control may influence adolescent's performance and participation, but age also influences this.

In future studies, it would be important to increase the number of participants from different districts of the country in order to establish age normative curves of the executive functions studied, as well as to understand the influence of the environment in which they live.

References

Akoglu, H. (2018). User's guide to correlation coefficients. *Turkish Journal of Emergency Medicine*, *18*(3), 91. https://doi.org/10.1016/J.TJEM.2018.08.001

Almeida, V. (2018). Caracteristicas psicométricas do Wisconsin Card Sorting Test em várias amostras da população portuguesa. *Universidade Lusófona de Humanidades e Tecnologias Escola de Psicologia e Ciências Da Vida*, 1–70.

Association, W. M. (2013). World Medical Association Declaration of Helsinki: Ethical principles for medical research involving human subjects. *Jama*, *310*(20), 2191–2194. https://doi.org/10.1001/jama.2013.281053

Baum, G. L., Ciric, R., Roalf, D. R., Betzel, R. F., Moore, T. M., Shinohara, R. T., Kahn, A. E., Vandekar, S. N., Rupert, P. E., Quarmley, M., Cook, P. A., Elliott, M. A., Ruparel, K., Gur, R. E., Gur, R. C., Bassett, D. S., & Satterthwaite, T. D. (2017). Modular segregation of structural brain networks supports the development of executive function in youth. *Current Biology : CB*, *27*(11), 1561-1572.e8. https://doi.org/10.1016/J.CUB.2017.04.051

Berkovits, I., Hancock, G. R., & Nevitt, J. (2000). Bootstrap resampling approaches for repeated measure designs: relative robustness to sphericity and normality violations. *Sage PublicationsSage CA: Thousand Oaks, CA*, *60*(6), 877–892. https://doi.org/10.1177/00131640021970961

Best, J. R., & Miller, P. H. (2010). A developmental perspective on executive function. *Child Development*, *81*(6), 1641–1660. https://doi.org/10.1111/J.1467-8624.2010.01499.X

Blair, C. (2017). Educating executive function. *Wiley Interdisciplinary Reviews. Cognitive Science*, *8*(1–2). https://doi.org/10.1002/WCS.1403

Borella, E., Carretti, B., & Pelegrina, S. (2010). The specific role of inhibition in reading comprehension in good and poor comprehenders. *Journal of Learning Disabilities*, *43*(6), 541–552. https://doi.org/10.1177/0022219410371676

Borgnis, F., Baglio, F., Pedroli, E., Rossetto, F., Uccellatore, L., Oliveira, J. A. G., Riva, G., & Cipresso, P. (2022). Available virtual reality-based tools for executive functions: A systematic review. *Frontiers in Psychology*, *13*, 1666. https://doi.org/10.3389/FPSYG.2022.833136/BIBTEX

Bryck, R. L., & Fisher, P. A. (2012). Training the brain: Practical applications of neural plasticity from the intersection of cognitive neuroscience, developmental psychology, and prevention science. *The American Psychologist*, *67*(2), 87–100. https://doi.org/10.1037/A0024657

Cappelli, C., Pike, J. R., Riggs, N. R., Warren, C. M., & Pentz, M. A. (2019). Executive function and probabilities of engaging in long-term sedentary and high calorie/low nutrition eating behaviors in early adolescence. *Social Science & Medicine (1982)*, *237*, 112483. https://doi.org/10.1016/J.SOCSCIMED.2019.112483

Cohen, L., Manion, L., & Morrison, K. (2011). *Research Methods in Education* (7th ed.). Routledge. https://doi.org/https://doi.org/10.4324/9780203720967

Cristofori, I., Cohen-Zimerman, S., & Grafman, J. (2019). Executive functions. *Handbook of Clinical Neurology*, *163*, 197–219. https://doi.org/10.1016/B978-0-12-804281-6.00011-2

Dajani, D. R., & Uddin, L. Q. (2015). Demystifying cognitive flexibility: Implications for clinical and developmental neuroscience. *Trends in Neurosciences*, *38*(9), 571. https://doi.org/10.1016/J.TINS.2015.07.003

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2006.02.006

Diamond, A. (2013). Executive functions. *Annual Review of Psychology*, *64*, 135–168. https://doi.org/10.1146/ANNUREV-PSYCH-113011-143750

Dias, N. M., Menezes, A., & Seabra, A. G. (2013). Age differences in executive functions within a sample of brazilian children and adolescents. *The Spanish Journal of Psychology*, *16*. https://doi.org/10.1017/SJP.2013.12

Dick, A. S. (2014). The development of cognitive flexibility beyond the preschool period: An investigation using a modified Flexible Item Selection Task. *Journal of Experimental Child Psychology*, *125*(1), 13–34. https://doi.org/10.1016/J.JECP.2014.01.021

Durston, S., & Casey, B. J. (2006). What have we learned about cognitive development from neuroimaging? *Neuropsychologia*, *44*(11), 2149–2157. https://doi.org/10.1016/J.NEUROPSYCHOLOGIA.2005.10.010

Emerson, R. W. (2022). ANOVA assumptions. *Journal of Visual Impairment & Blindness*, *116*(4), 585–586. https://doi.org/10.1177/0145482X221124187

Er-Rafiqi, M., Guerra, A., Le Gall, D., & Roy, A. (2021). *Age-related changes of cognitive flexibility and planning skills in school-age Moroccan children*. *11*(4), 669–680. https://doi.org/10.1080/21622965.2021.1934471

Fourneret, P., & des Portes, V. (2017). Approche développementale des fonctions exécutives: du bébé à l'adolescence. *Archives de Pédiatrie*, *24*(1), 66–72. https://doi.org/10.1016/J.ARCPED.2016.10.003

Ghasemi, A., & Zahediasl, S. (2012). Normality tests for statistical analysis: A guide for non-statisticians. *International Journal of Endocrinology and Metabolism*, *10*(2), 486. https://doi.org/10.5812/IJEM.3505

Gilbert, S. J., & Burgess, P. W. (2008). Executive function. *Current Biology*, *18*(3), R110–R114. https://doi.org/10.1016/J.CUB.2007.12.014

Goddings, A. L., Roalf, D., Lebel, C., & Tamnes, C. K. (2021). Development of white matter microstructure and executive functions during childhood and adolescence: A review of diffusion MRI studies. *Developmental Cognitive Neuroscience*, *51*, 101008. https://doi.org/10.1016/J.DCN.2021.101008

Grant, D. A., & Berg, E. (1948). A behavioral analysis of degree of reinforcement and ease of shifting to new responses in a Weigl-type card-sorting problem. *Journal of Experimental Psychology*, *38*(4), 404–411. https://doi.org/10.1037/H0059831

Hartung, J., Engelhardt, L. E., Thibodeaux, M. L., Harden, K. P., & Tucker-Drob, E. M. (2020). Developmental transformations in the structure of executive functions. *Journal of Experimental Child Psychology*, *189*. https://doi.org/10.1016/J.JECP.2019.104681

Henry, L. A., Poloczek, S., Messer, D. J., Dennan, R., Mattiauda, E., & Danielsson, H. (2022). Hebb repetition learning in adolescents with intellectual disabilities. *Research in Developmental Disabilities*, *125*, 104219. https://doi.org/10.1016/J.RIDD.2022.104219

IBM SPSS statistics 28. (2022). https://www.ibm.com/support/pages/downloading-ibm-spss-statistics-28

Jones, D. T., & Graff-Radford, J. (2021). Executive dysfunction and the prefrontal cortex. *Continuum (Minneapolis, Minn.)*, *27*(6), 1586–1601. https://doi.org/10.1212/CON.0000000000001009

Kim, T. K. (2015). T test as a parametric statistic. *Korean Journal of Anesthesiology*, *68*(6), 540. https://doi.org/10.4097/KJAE.2015.68.6.540

Lafontaine, M. P., Knoth, I. S., & Lippé, S. (2020). Learning abilities. *Handbook of Clinical Neurology*, *173*, 241–254. https://doi.org/10.1016/B978-0-444-64150-2.00021-6

Lalonde, G., Henry, M., Drouin-Germain, A., Nolin, P., & Beauchamp, M. H. (2013). Assessment of executive function in adolescence: A comparison of traditional and virtual reality tools. *Journal of Neuroscience Methods*, *219*(1), 76–82.

https://doi.org/10.1016/J.JNEUMETH.2013.07.005

Llinàs-Reglà, J., Vilalta-Franch, J., López-Pousa, S., Calvó-Perxas, L., Torrents Rodas, D., & Garre-Olmo, J. (2017). The Trail Making Test. *Assessment*, *24*(2), 183–196. https://doi.org/10.1177/1073191115602552

Maggio, M. G., Maresca, G., De Luca, R., Stagnitti, M. C., Porcari, B., Ferrera, M. C., Galletti, F., Casella, C., Manuli, A., & Calabrò, R. S. (2019). The growing use of virtual reality in cognitive rehabilitation: fact, fake or vision? A scoping review. *Journal of the National Medical Association*, *111*(4), 457–463. https://doi.org/10.1016/J.JNMA.2019.01.003

Mann, C. J. (2003). Observational research methods. Research design II: Cohort, cross sectional, and case-control studies. *Emergency Medicine Journal : EMJ*, *20*(1), 54–60. https://doi.org/10.1136/EMJ.20.1.54

McFarland, D. J. (2020). Factor-analytic evidence for the complexity of the Delis-Kaplan Executive Function System (D-KEFS). *Assessment*, *27*(7), 1645–1656. https://doi.org/10.1177/1073191119843584

Miles, S., Howlett, C. A., Berryman, C., Nedeljkovic, M., Moseley, G. L., & Phillipou, A. (2021). Considerations for using the Wisconsin Card Sorting Test to assess cognitive flexibility. *Behavior Research Methods*, *53*(5), 2083–2091. https://doi.org/10.3758/S13428-021-01551-3

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/COGP.1999.0734

Moffitt, T. E., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H. L., Houts, R., Poulton, R., Roberts, B. W., Ross, S., Sears, M. R., Thomson, W. M., & Caspi, A. (2011). A gradient of childhood self-control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(7), 2693–2698. https://doi.org/10.1073/PNAS.1010076108/SUPPL_FILE/SAPP.PDF

Negu, A., Matu, S. A., Sava, F. A., & David, D. (2016). Virtual reality measures in neuropsychological assessment: A meta-analytic review. *Http://Dx.Doi.Org/10.1080/13854046.2016.1144793*, *30*(2), 165–184. https://doi.org/10.1080/13854046.2016.1144793

Radianti, J., Majchrzak, T. A., Fromm, J., & Wohlgenannt, I. (2020). A systematic review of immersive virtual reality applications for higher education: design elements, lessons learned, and research agenda. *Computers & Education*, *147*, 103778. https://doi.org/10.1016/J.COMPEDU.2019.103778

Ravindranath, O., Calabro, F. J., Foran, W., & Luna, B. (2022). Pubertal development underlies optimization of inhibitory control through specialization of ventrolateral prefrontal cortex. *Developmental Cognitive Neuroscience*, *58*, 101162. https://doi.org/10.1016/J.DCN.2022.101162

Roth, R. M., Erdodi, L. A., McCulloch, L. J., & Isquith, P. K. (2015). Much ado about norming: The behavior rating inventory of executive function. *Child Neuropsychology : A Journal on Normal and Abnormal Development in Childhood and Adolescence*, *21*(2), 225–233. https://doi.org/10.1080/09297049.2014.897318

Saisana, M. (2014). Analysis of variance. *Encyclopedia of Quality of Life and Well-Being Research*, 162–165. https://doi.org/10.1007/978-94-007-0753-5_83

Scarpina, F., & Tagini, S. (2017). The Stroop Color and Word Test. *Frontiers in Psychology*, *8*(APR). https://doi.org/10.3389/FPSYG.2017.00557

Shen, J., Xiang, H., Luna, J., Grishchenko, A., Patterson, J., Strouse, R. V., Roland, M., Lundine, J. P., Koterba, C. H., Lever, K., Groner, J. I., Huang, Y., & Lin, E. J. D. (2020). Virtual reality-based executive function rehabilitation system for children with traumatic brain injury: design and usability study. *JMIR Serious Games*, *8*(3). https://doi.org/10.2196/16947

Sherman, W. R., & Craig, A. B. (2018). Understanding virtual reality. In *Elservier*. ELSEVIER SCIENCE & TECHNOLOGY.

Shinohara, I., & Moriguchi, Y. (2021). Are there sex differences in the development of prefrontal function during early childhood? *Developmental Psychobiology*, *63*(4), 641–649. https://doi.org/10.1002/DEV.22039

Shochat, G., Maoz, S., Stark-Inbar, A., Blumenfeld, B., Rand, D., Preminger, S., & Sacher, Y. (2017). Motion-based virtual reality cognitive training targeting executive functions in acquired brain injury community-dwelling individuals: A feasibility and initial efficacy pilot. *International Conference on Virtual Rehabilitation, ICVR*, *2017-June*. https://doi.org/10.1109/ICVR.2017.8007530

Speelman, C. P., & Shadbolt, E. (2018). The role of awareness of repetition during the development of automaticity in a dot-counting task. *PeerJ*, *2018*(1). https://doi.org/10.7717/PEERJ.4329/SUPP-1

Steinke, A., & Kopp, B. (2020). Toward a computational neuropsychology of cognitive flexibility. *Brain Sciences*, *10*(12), 1–24. https://doi.org/10.3390/BRAINSCI10121000

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643–662. https://doi.org/10.1037/H0054651

Vara, A. S., Pang, E. W., Vidal, J., Anagnostou, E., & Taylor, M. J. (2014). Neural mechanisms of inhibitory control continue to mature in adolescence. *Developmental Cognitive Neuroscience*, *10*, 129–139. https://doi.org/10.1016/J.DCN.2014.08.009

Virtuleap. (2022). *Enhance games overview*. *April*.

Wendelken, C., Munakata, Y., Baym, C., Souza, M., & Bunge, S. A. (2012). Flexible rule use: Common neural substrates in children and adults. *Developmental Cognitive Neuroscience*, *2*(3), 329–339. https://doi.org/10.1016/J.DCN.2012.02.001

Wierenga, L. M., Bos, M. G. N., van Rossenberg, F., & Crone, E. A. (2019). Sex effects on development of brain structure and executive functions: Greater variance than mean effects. *Journal of Cognitive Neuroscience*, *31*(5), 730–753. https://doi.org/10.1162/JOCN_A_01375