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Different visuomotor processes maturation rates in children support dual visuomotor learning systems

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ABSTRACT

Different processes are involved during visuomotor learning, including an error-based procedural and a strategy based cognitive mechanism. Our objective was to analyze if the changes in the adaptation or the aftereffect components of visuomotor learning measured across development, reflected different maturation rates of the aforementioned mechanisms. Ninety-five healthy children aged 4–12 years and a group of young adults participated in a wedge prism and a dove prism throwing task, which laterally displace or horizontally reverse the visual field respectively. The results show that despite the age-related differences in motor control, all children groups adapted in the error-based wedge prisms condition. However, when removing the prism, small children showed a slower aftereffects extinction rate. On the strategy-based visual reversing task only the older children group reached adult-like levels. These results are consistent with the idea of different mechanisms with asynchronous maturation rates participating during visuomotor learning.

1. Introduction

Visuomotor learning, the capacity to improve visually guided movements, is a fundamental ability that can be found from infancy on (McDonnell & Abraham, 1979, 1981). A number of conditions affecting the motor system have been analyzed to understand its underlying mechanisms. For example, it has been shown that specific cerebellar lesions result in a profound visuomotor learning disruption in a number of tasks including adaptation to wedge prisms, force perturbations and visuomotor rotations (Block & Bastian, 2012; Fernandez-Ruiz et al., 2007; Martin, Keating, Goodkin, Bastian, & Thach, 1996; Smith & Shadmehr, 2005; Vaca-Palomares et al., 2013; Velazquez-Perez et al., 2009; Weiner, Hallett, & Funkenstein, 1983). In contrast, basal ganglia degeneration does not affect visuomotor learning in those tasks despite having a profound impact on motor behavior (Fernandez-Ruiz et al., 2003; Gutierrez-Garralda et al., 2013; Smith & Shadmehr, 2005). The effect of aging on visuomotor learning has yielded more variable results, with some studies reporting no changes, while others show significant effects (Bock & Schneider, 2002; Fernandez-Ruiz, Hall, Vergara, & Diiaz, 2000; Roller, Cohen, Kimball, & Bloomberg, 2002). This variation has been explained by the differential effect that aging could have in different processes participating during visuomotor learning (Anguera, Reuter-Lorenz, Willingham, & Seidler, 2011; Baugh & Marotta, 2009; Cressman,

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Salomonczyk, & Henriques, 2010; Fernandez-Ruiz et al., 2003; Hegele & Heuer, 2010, 2013; Langan & Seidler, 2011; Lawrence-Dewar, Baugh, & Marotta, 2012).

Recent studies designed to explore the processes involved in visuomotor learning suggest that it could be the result of the interaction of at least two mechanisms with unique properties (Shadmehr, Smith, & Krakauer, 2010; Taylor, Krakauer, & Ivry, 2014; Wolpert, Diedrichsen, & Flanagan, 2011). The first one is an explicit strategic system that shows fast learning, requires long reaction times, and is unstable and vulnerable to interruptions (Fernandez-Ruiz, Wong, Armstrong, & Flanagan, 2011; Huberdeau, Krakauer, & Haith, 2015; Lillicrap et al., 2013; Michel, Pisella, Prablanc, Rode, & Rossetti, 2007). The second one is an implicit slow learning procedural mechanism that requires low reaction times and is error-driven (Fernandez-Ruiz & Diaz, 1999; Michel et al., 2007). It has been postulated that the simultaneous expression of these mechanisms result in the characteristic visuomotor learning time-course pattern observed after the introduction of a perturbation. It consists of substantial error reduction in the initial trials, a phase sometimes denominated the initial fast learning phase, followed by decreasingly small reductions in error called the slow learning phase (Fernandez-Ruiz et al., 2011; Huberdeau et al., 2015; Shadmehr et al., 2010). The interaction of these processes also results in differential aftereffects observed after the perturbation withdrawal. The first mechanism has been related to null or smaller aftereffects that tend to decrease rapidly, while the second mechanism has been related to more robust long-lasting aftereffects (Fernandez-Ruiz & Diaz, 1999; Fernandez-Ruiz, Diaz, Aguilar, & Hall-Haro, 2004; Michel et al., 2007).

Developmental studies have shown that different abilities fully develop at different postnatal ages (Liu, Luo, Mayer-Kress, & Newell, 2012; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Luna et al., 2001). For example, it has been shown that gross motor skills are in place before the first two years of age, while processing speed, response inhibition, and working memory reach mature adult-level performance at late adolescence (WHO Multicentre Growth Reference Study Group, 2006; Luciana & Nelson, 1998; Luna et al., 2004). Then, it could be possible that the maturation asynchrony of different processes involved in visuomotor learning, like working memory or procedural processes, could result in different behavioral patterns evident during the performance of a learning task (Luna et al., 2004; Meulemans, Van der Linden, & Perruchet, 1998). To test this hypothesis, here we set to evaluate if there are different visuomotor learning and forgetting rates across development. For this purpose we tested four groups of children from the ages of 4–12 years old, and a group of young adults, in two visuomotor tasks known to differentially exploit the strategic control and the procedural mechanisms, i.e. adaptation to reversing dove prisms and adaptation to wedge prisms (Fernandez-Ruiz & Diaz, 1999; Lawrence-Dewar et al., 2012; Lillicrap et al., 2013).

2. Method

2.1. Participants

95 children (46 girls and 49 boys) right-handed, with an age range of 4–12 years from public schools in Mexico City were divided into four groups.

Group 1 included 25 children aged 4 and 5 years who attend preschool. Group 2 included 25 children aged 6 and 7 year olds in first and second grade. Group 3 included 25 children aged 8 and 9 years who attend third and fourth grade. Group 4 included 20 children 11 and 12 years old who attend fifth and sixth grade and a group of 20 right-handed adults of 20–28 years.

The participants' selection was conducted with a non-probability method using convenience sampling. Parents or tutors signed a letter of informed consent approved by the Ethics Committee of the Faculty of Medicine, UNAM, according to the Declaration of Helsinki and later revisions (World Medical Association, 2001).

2.2. Apparatus and procedure

Parents were asked to fill out a questionnaire to rule out neurological or psychiatric diagnosis. Our inclusion criteria were an average intellectual performance in the Wechsler Intelligence Scale for preschool and primary-III levels and Wechsler Intelligence for Children-WISC-IV Scale. All children were screened with the Movement Assessment Battery for Children (MABC) (Henderson & Sugden, 2007); a score at or above the 20th percentile was necessary for inclusion.

2.3. General design of experiments

The experimental procedure comprised two experiments with a different prism lens each; one used an 18-diopter displacing wedge prism and the other one used a reversing dove prism. Each experiment followed the following three phases (Fernandez-Ruiz & Diaz, 1999):

First: A baseline throwing performance was obtained by having the participants throw 26 balls (weight: 10 g) to the target before the prisms were mounted on the window (condition PRE). The position at which the balls made an impact on or around the target was marked immediately after each throw.

Second: After donning the prisms (condition PRI), the subjects were instructed to throw 26 more balls with the same arm and in the same way. For the displacement PRI condition participants saw through 18 diopter wedge prisms that produce a deviation of light to the right. For the reversing PRI condition participants saw through right-left reversing prisms (dove