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Relative cortico-subcortical shift in brain activity but preserved training-induced neural modulation in older adults during bimanual motor learning

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ABSTRACT

To study age-related differences in neural activation during motor learning, functional magnetic resonance imaging scans were acquired from 25 young (mean 21.5-year old) and 18 older adults (mean 68.6-year old) while performing a bimanual coordination task before (pretest) and after (posttest) a 2-week training intervention on the task. We studied whether task-related brain activity and training-induced brain activation changes differed between age groups, particularly with respect to the hyperactivation typically observed in older adults. Findings revealed that older adults showed lower performance levels than younger adults but similar learning capability. At the cerebral level, the task-related hyperactivation in parietofrontal areas and underactivation in subcortical areas observed in older adults were not differentially modulated by the training intervention. However, brain activity related to task planning and execution decreased from pretest to posttest in temporo-parieto-frontal areas and subcortical areas in both age groups, suggesting similar processes of enhanced activation efficiency with advanced skill level. Furthermore, older adults who displayed higher activity in prefrontal regions at pretest demonstrated larger training-induced performance gains. In conclusion, in spite of prominent age-related brain activation differences during movement planning and execution, the mechanisms of learning-related reduction of brain activation appear to be similar in both groups. Importantly, cerebral activity during early learning can differentially predict the amplitude of the training-induced performance benefit between young and older adults.

1. Introduction

Performance on motor tasks gradually decreases and often requires more mental effort and time as we age (e.g., Boisgontier et al., 2013; Seidler et al., 2010). Training interventions may help overcome such deficits, which can be witnessed across a large range of motor tasks. Whether or not motor learning is impaired in older relative to younger adults is still a topic of considerable debate (Seidler et al., 2010; Swinnen et al., 1998). Some studies report equivalent or even higher learning rates in older adults, and normal skill retention (Anshel, 1978; Voelcker-Rehage, 2008). Others have shown that learning rates are compromised in older adults (Anguera et al., 2010; Bo et al., 2011a; Raz et al., 2000; Rodrigue et al., 2005; Seidler, 2006; Voelcker-Rehage, 2008). The literature regarding bimanual skill learning in particular is similarly mixed, with age-related learning deficits observed for some tasks (Swinnen et al., 1998), but not for others (Voelcker-Rehage and Willimczik, 2006). Regardless of whether older adults show task-specific impairments relative to young adults, training-induced performance improvements are clearly evident and suggest lifelong plasticity potential (Seidler, 2007a,b; Swinnen et al., 1998).

To better understand the ability to learn new motor skills, studying the underlying brain mechanisms may reveal critical information about neuroplastic potential across the lifespan. With respect to motor performance in general, it has been demonstrated that older adults often show compensatory brain activity to support motor performance (e.g., Goble et al., 2010; Heuninckx et al., 2005, 2008; Swinnen et al., 2010; Van Impe et al., 2009; Ward, 2006; Ward and Frackowiak, 2003; Wu and Hallett, 2005) and higher-order cortical areas are often over-recruited during more complex (interlimb coordination) tasks (Goble et al., 2010; Heuninckx et al.,

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2005, 2008, 2010). Nevertheless, reduced activation in older versus young adults has also been observed in multilimb (Coxon et al., 2010, 2016; Van Impe et al., 2009) and unimanual (Anguera et al., 2010; Bo et al., 2011a,b) task studies. Despite those known age-related neural activity differences during motor performance, it remains unclear whether training-induced plasticity differs between young and older adults.

The present functional magnetic resonance imaging (fMRI) study therefore sought to address 2 primary research questions related to the effect of an extensive training intervention on the neural correlates of motor learning in older adults. First, we examined whether task-related brain activity as well as training-induced cerebral plasticity associated with practicing a new set of bimanual coordination skills over a 2-week period were affected by aging. We hypothesized that (1) older adults would demonstrate task-related cortical hyperactivation (Goble et al., 2010; Heuninckx et al., 2005, 2008) and basal ganglia hypoactivation (Coxon et al., 2010) not only during movement execution but also during planning and that (2) training would lead to reductions in cortical activation in both age groups, as previously observed in humans and primates (Beets et al., 2015; Picard et al., 2013), but to a lesser extent in older in comparison with young adults as a result of reduced learning potential associated with advanced age. Second, we examined the relationship between brain activation patterns during the early stage of learning and subsequent training-related behavioral outcomes. Specifically, we hypothesized that responses in brain regions showing age-related hyperactivation—that could be associated with better encoding but might also reflect higher degrees of online task monitoring that can not be overcome with training—would predict successful training outcome in older as compared to younger adults.

2. Materials and methods

2.1. Participants

Twenty-six younger (YA) and 25 older (OA) healthy volunteers participated in the study. All participants were naive with respect to the experimental paradigm, had normal or corrected-to-normal vision, and were right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). Laterality scores were 93.7 ± 10.0 in OA and 87.3 ± 17.1 in YA, with a $+100$ score representing an extreme right-hand preference and a -100 representing an extreme left-hand preference. None of the participants had a history of neurological or psychiatric disease. Older participants were screened for cognitive impairments using the Dutch version of the Montreal Cognitive Assessment test using the cutoff score of 26 (e.g., Nasreddine et al., 2005). The included participants scored 28.6 ± 1.5 (range 27–30). One older adult did not reach the cutoff score (i.e., score equal to 24) and was therefore excluded from the analyses. Three OA were excluded due to brain atrophy/lesions as identified by a trained neuroradiologist (one with diffuse cortical atrophy, one with atrophy in the parietal lobe, and one with a small lesion in the cerebellum). Three other OA failed to comply with task instructions (they often moved in the baseline no-move conditions). As a result, we analyzed the performance of 18 OA (68.6 ± 6.0 years; 11 females). One YA was excluded from the analysis due to technical problems with the scanner at posttest. This resulted in complete prepost data of 25 YA (21.5 ± 2.3 years; 14 females). A subset of participants who completed pre and posttest also performed a behavioral retention test 6 months after posttest (16 YA, 21.6 ± 1.9 years, 11 females; 10 OA, 67.1 ± 5.0 years, 5 females). The protocol was in accordance with the 1964 Declaration of Helsinki (World Medical Association, 2008) and was approved by the local ethical committee of KU Leuven, Belgium. Participants were financially compensated for participation and provided written informed consent before the experiment.

2.2. Experimental design and setup

MRI scanning occurred before and after 5 training sessions, distributed across 2 weeks. The scanning and training sessions each lasted 90 and 60 minutes, respectively (see Fig. 1A). Prior to the first MRI scan, participants practiced the task briefly in a dummy scanner until the task was fully understood. During MRI sessions, participants lay supine in the scanner (see illustration of dummy scanner setup in Fig. 1B), with the arms supported by pillows. Stimuli were displayed by means of an LCD projector (Barco 6300, 1280×1024 pixels), projected onto a double mirror placed in front of the eyes. Participants were instructed to produce a set of complex bimanual coordination patterns, requiring rotational movements of both hands simultaneously. A bite-bar and foam cushions were used to prevent head movements during task performance. A nonferromagnetic apparatus with 2 dials (diameter = 5 cm) for movement recording was placed over the participants' lap in a comfortable position. The dials could be adjusted to the participants' anthropometry and had an angle of approximately 45° for comfortable handling. Movements were made by turning the handle of the dials with the hands. Angular displacements were registered by means of nonferromagnetic high precision optical shaft encoders (HP, 2048 pulses per revolution, sampling frequency 100 Hz), fixed to the movement axes of both dials. This enabled registration of kinematics as well as displaying on-line visual information. During the training sessions, participants were seated in front of a PC screen (distance approximately 0.5 m). A device similar to that used during scanning was mounted on the table and included ergonomic forearm rests. Vision of the hands was occluded during all sessions.

2.3. Task

In the bimanual tracking task (BTT), a target presented on a screen has to be tracked by rotating dials with both hands simultaneously in 1 of 4 directional patterns: both hands rotated inwards (IN) or outwards (OUT) together, or in a clockwise (CW) or counterclockwise manner (CCW). The left (L) and right (R) hands controlled movements on the ordinate and abscissa, respectively. Each directional pattern was performed at 5 different relative frequency ratios: 1:1, 1:2, 1:3, 2:1, and 3:1 (L:R). For example, during the 1:2 mode, the right hand would need to move twice as fast as the left hand to match the desired movement trajectory. The combinations of rotation direction and frequency totalled 20 different coordination possibilities. Each task variant was represented by a target line with a particular slope that appeared in 1 of the 4 quadrants on the screen (Fig. 1D).

Two principal task phases were discerned. During the "planning phase", which lasted 2 seconds, the blue target line was presented together with a visual cue to indicate the upcoming condition. In this phase, participants were instructed to identify the upcoming trial, but to refrain from performing any movement. During the "execution phase", a white target dot moved over the blue target line from a start position (center of the screen) to a desired end location at a constant speed (duration = 9 seconds). The intertrial interval was 3 seconds. The tasks were trained under 2 conditions with equal number of trials: without (no feedback condition [NFB]) and with (feedback condition [FB]) augmented online visual feedback of the integrated movement patterns. In the FB condition, concurrent visual FB was provided by means of a red cursor displaying the actual tracking trajectory based on the contribution of both limbs, whereas only the blue target line was presented in the