OXFORD

Cerebral Cortex, 2023, **33**, 6420–6434
https://doi.org/10.1093/cercor/bhac514
Advance access publication date 30 December 2022
Original Article

Interactions between the aging brain and motor task complexity across the lifespan: balancing brain activity resource demand and supply

P. Van Ruitenbeek[1,2,*], T. Santos Monteiro[1], S. Chalavi[1], B.R. King[1,3], K. Cuypers[1,4], S. Sunaert[5,6], R. Peeters[5,6], S.P. Swinnen[1,6]

[1]KU Leuven, Movement Control and Neuroplasticity Research Group, Biomedical Sciences,Tervuursevest 101, box 1501, 3001, Leuven, Belgium,
[2]Department of Neuropsychology and Psychopharmacology, Faculty of Psychology and Neuroscience, Maastricht University, Universiteitssingel 40, 6229 ER, Maastricht, the Netherlands,
[3]Department of Health & Kinesiology; University of Utah, 250 South 1850 East, Salt Lake City, Utah 84112,
[4]Neuroplasticity and Movement Control Research Group, Rehabilitation Research Institute (REVAL), Hasselt University, Agoralaan Gebouw A, 3590,Diepenbeek, Belgium,
[5]KU Leuven, Department of Imaging and Pathology, Biomedical Sciences, UZ Herestraat 49, box 7003, 3000, Leuven, Belgium,
[6]KU Leuven, Leuven Brain Institute (LBI), ON V Herestraat 49, box 1020, 3000, Leuven, Belgium

*Corresponding author: Faculty of Psychology and Neuroscience, Maastricht University, Universiteitssingel 40, 6229 ER Maastricht, the Netherlands. Email: p.vanruitenbeek@maastrichtuniversity.nl

The Compensation Related Utilization of Neural Circuits Hypothesis (CRUNCH) proposes a framework for understanding task-related brain activity changes as a function of healthy aging and task complexity. Specifically, it affords the following predictions: (i) all adult age groups display more brain activation with increases in task complexity, (ii) older adults show more brain activation compared with younger adults at low task complexity levels, and (iii) disproportionately increase brain activation with increased task complexity, but (iv) show smaller (or no) increases in brain activation at the highest complexity levels. To test these hypotheses, performance on a bimanual tracking task at 4 complexity levels and associated brain activation were assessed in 3 age groups (20–40, 40–60, and 60–80 years, $n = 99$). All age groups showed decreased tracking accuracy and increased brain activation with increased task complexity, with larger performance decrements and activation increases in the older age groups. Older adults exhibited increased brain activation at a lower complexity level, but not the predicted failure to further increase brain activity at the highest complexity level. We conclude that older adults show more brain activation than younger adults and preserve the capacity to deploy increased neural resources as a function of task demand.

Key words: aging; brain activation; CRUNCH; sensori-motor control.

Introduction

The world population is becoming increasingly aged; in Europe, the share of adults over 65 years of age will rise from 26.3% in 2019 to 43.5% in 2070 (European Commission 2019). Aging has been associated with behavioral deficits, and in particular motor deficits, which have a significant impact on functional independence and well-being (Wiesmann et al. 2004) whereby older adults require additional care (Nilsson 2003; Seidler et al. 2010). Understanding the aging brain may ultimately contribute to designing effective strategies to optimize motor control function in older adults, aimed at increasing quality of life (Scherder et al. 2008). Within this context, understanding how the aging brain copes with increased demands is of high societal interest. As demands can be considered relative to the brain's capacity to perform, increased demands may be due to both the anticipated technological evolution of society and/or age-related decline of the brain's capacity. We focussed on differences in brain activation across the adult lifespan in response to increased demands during execution of a sensori-motor task with varying complexity levels.

A commonly held view of normal aging is that the widely reported decreases in motor performance (Bangert et al. 2010) are associated with decrements in musculoskeletal as well as brain architectural and/or functional integrity, including loss of gray (e.g. van Ruitenbeek et al. 2017; Chalavi et al. 2018) and white matter (e.g. Serbruyns et al. 2015; Zivari Adab et al. 2020), alterations in functional interactions among brain regions (King et al. 2018) and neurotransmitter system functioning (Minati et al. 2007; Hermans et al. 2018; Levin et al. 2019). In addition, brain research has convincingly demonstrated that older adults present over-activation of relevant brain areas (e.g. Angel et al. 2016; Hakun and Johnson 2017). Two principal hypotheses have been put forward to account for such over-activation. On the one hand, over-activation reflects inefficient activation as a result of reduced input from neuromodulatory transmitter systems, i.e. a sign of sub-optimal brain functioning (dedifferentiation hypothesis: Li and Lindenberger 1999; Koen and Rugg 2019). On the other hand, a more optimistic perspective suggests that the aged brain is able to compensate for the structural deficits (compensation hypothesis). Consistent with this perspective, some studies (including those on motor function e.g. Heuninckx et al. 2005; Goble et al. 2010) have demonstrated that increased brain activity in older adults correlates with better performance (Reuter-Lorenz and Cappell 2008). In the cognitive task domain, performance in high

Received: August 5, 2022. **Revised:** December 2, 2022. **Accepted:** December 3, 2022

performing older adults is aided by recruiting additional (i.e. bilateral) areas, whereas low performing older adults and younger adults appear to not show such additional recruitment (Cabeza et al. 2002). However, patterns of increased activation in older adults are not unequivocal; brain under-activation can also occur (Santos Monteiro et al. 2017) and not all age-related brain over-activation is accompanied by better performance. Moreover, patterns of brain over- and under-activation seem to depend on the type of process or task and specifically on the complexity of that task, i.e. task demands (Madden et al. 2004; Persson et al. 2004), suggesting that a view in which up- and/or downregulation of brain activity is solely a sign of sub-optimal brain functioning is too simplistic.

The Compensation Related Utilization of Neural Circuits Hypothesis (CRUNCH: Reuter-Lorenz and Cappell 2008) provides a framework within which brain activation increases and decreases associated with compensation and resource limits can be predicted. In brief, this hypothesis states that, in order to meet higher demands, resources are utilized by older adults by increasing brain activation as compared with younger adults when task demands are relatively low (e.g. Heuninckx et al. 2005). When task demands increase, in both age groups, activation increases (e.g. Goble et al. 2010) until resource limits are reached (e.g. Mattay et al. 2006), upon which it may decrease. In older adults, these limits may be reached at a lower level of task demands as compared with younger adults (Mattay et al. 2006; Cappell et al. 2010).

In more detail, upregulation of activation can occur in brain areas directly involved in the task (Jonides et al. 1997; Mattay et al. 2002; Ward and Frackowiak 2003; Heuninckx et al. 2005, 2008; Goble et al. 2010), can occur bilaterally (e.g. Cabeza et al. 1997; Klingberg et al. 1997; Rypma et al. 1999; Cabeza et al. 2002; Maguire and Frith 2003) and/or in additional supportive areas (Grady et al. 1998; McIntosh et al. 1999; DiGirolamo et al. 2001; Cabeza et al. 2002; Heuninckx et al. 2005, 2008), such as generic (e.g. pre-frontal) regions that become particularly activated in older adults when performing complex motor control tasks.

Despite the clear predictions that can be made for the sensorimotor domain in accordance with the model, and which only partially have been tested (e.g. Heuninckx et al. 2005, 2008; Zapparoli et al. 2022), some crucial characterizations remain unknown as the main focus of this type of research has been on cognitive functions (Zapparoli et al. 2022). First, it is unclear if older adults upregulate activation in the same brain areas as younger adults do. Second, it is unclear if upregulation in older adults occurs to the same extent as in younger adults when demands increase. Assuming that both age-related decline in brain function/structure and increase in task complexity increase resource demands, it may be predicted that older adults upregulate brain activation disproportionately with increased task complexity. Third, it is unclear how the brain responds when resource limits are reached. In this respect, 2 opposing hypotheses can be proposed: (i) brain activation is decreased, (ii) activation is upregulated and reaches a plateau or not. In other words, either the hypothesized compensatory increased resource recruitment has reached its limits and resource recruitment appears to fail (i) or it remains fully engaged (ii).

The current study aimed to address these outstanding questions by assessing characteristics of brain activation upregulation in older adults when meeting increased demands. A bimanual coordination task with 4 levels of complexity was used for this purpose. In addition, as previous motor fMRI studies primarily assessed age-related brain activation differences by comparing 2 groups (young vs. older adults) at the extremes of the lifespan spectrum, we compared brain activation patterns in younger, middle-aged, and older adults. This enabled us to assess whether the anticipated brain activation differences are already present at an earlier age, providing a closer view on the timeline of age-related brain activation changes.

Multiple specific patterns of brain activation associated with age and motor task complexity were predicted based on the CRUNCH framework. It was hypothesized that: (i) Brain activation will increase in all 3 age groups as a function of task demands, indicating ability to recruit additional resources in all age groups; (ii) Older adults will show higher brain activation levels at lower levels of task complexity, suggesting the need for increased resource recruitment by the older brain; (iii) Older adults will show more activation increases towards higher levels of task complexity than younger adults, reflecting the increased resource recruitment due to both task- and age-related demands; and (iv) Older adults reach their limits before younger adults do, as reflected by a reduction of brain activation at the highest levels of task complexity (failing compensation) while performance is reduced. In addition, the anticipated age-related increase in brain activation becomes already evident in the middle-aged group.

Materials and methods

Participants

Healthy participants aged between 18 and 80 years were recruited from the general population by means of advertisements and entered the study ($n = 106$, 47 female). Functional network, structural (white matter) brain, and neurochemical analyses on this sample were reported in previous articles (King et al. 2018; Levin et al. 2019; Monteiro et al. 2020; Zivari Adab et al. 2020). For the purpose of the present task-related fMRI analysis, data from 7 participants were excluded due to technical/recording issues. All remaining 99 participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield 1971), resulting in an average handedness score of 91 ± 14 (mean $\pm$ SD) out of a maximum of 100. The resulting sample consisted of participants aged between 20 and 75 years (mean $\pm$ SD: 48.64 ± 17.3), divided into 3 age groups: 32 young adults (YA) aged 20–39 years (mean $\pm$ SD: 27.6 ± 6.4), 33 middle-aged adults (MA) aged 40–59 years (mean $\pm$ SD: 49.2 ± 5.6), and 34 older adults (OA) aged 60–75 years (mean $\pm$ SD: 67.8 ± 3.8). Participants took no psychoactive medication or illegal drugs, reported no sleep disturbances, and had normal or corrected to normal vision. Non-removable ferromagnetic objects inside or on their bodies were absent as assessed using a standard MR safety questionnaire. None of the participants showed any signs of depression (Beck and Beck 1972). All participants gave written informed consent prior to the start of the experiment. The protocol (nr: S51615) was approved by the local Medical Ethics Committee of KU Leuven, Belgium and was conducted in accordance with the Declaration of Helsinki and its amendments (World-Medical-Association 1964, 1996, 2008, 2013).

Design and procedures

For this cross-sectional study, participants visited our facilities 3 times. The first visit consisted of a comprehensive screening of each participant's health status and suitability for participating in the study by using the several questionnaires mentioned above. All participants then performed eight 6-min blocks of the bimanual tracking task (BTT; see details below) inside a dummy scanner to become familiarized with the task procedures and mock MRI environment. These data were not further analyzed

other than to ensure an acceptable baseline performance. More specifically, subjects were excluded from the study if their score (line coverage, see below for an explanation and see Monteiro et al. 2020) was below 50% on the trials with the highest level of complexity as assessed over the last 2 blocks of this practice session. Four participants did not meet the performance criteria and thus did not enter the formal part of the study. The second and third visits consisted of magnetic resonance imaging (MRI) sessions, including acquisition of data for GABA and glutamate content (MRS; MEGA-PRESS and PRESS, respectively), brain structure (MPRAGE), perfusion (pCASL), resting state brain activation (EPI), and myelin (GRASE) on the second visit and task-related activation (task-fMRI, EPI) and white matter (DWI) on the third visit as part of an extensive imaging protocol. For the current paper, only the functional MRI (task-fMRI) data collected during the third visit are reported and the T1 weighted structural images collected during the second visit are used during the analysis.

Bimanual tracking task

The bimanual tracking task (BTT) was used to assess bimanual sensori-motor performance (for a more detailed description, see Sisti et al. 2011; Beets et al. 2015). This is the same task and these are the same behavioral data as presented in other papers by our group, but associated with different brain metrics (King et al. 2018; Levin et al. 2019; Monteiro et al. 2020; Zivari Adab et al. 2020). Here, we assessed brain activation associated with increased sesnsori-motor demands as predicted by the CRUNCH framework.

Participants were laying supine in the scanner with a custom made dual manipulandum setup over their upper legs. The manipulandum contained 2 hand crank wheels (5-cm diameter), which could be rotated by holding them between thumb and index finger (Fig. 1A). High precision shaft encoders were mounted on the axis of the crank to record angular displacement (Avago Technologies, sampling frequency = 100 Hz, accuracy = 0.089°). This setup allowed us to address different levels of task complexity by rotating each dial with the same or different speeds, according to the spatial patterns provided and to be drawn by the participants (Fig. 1B).

Each trial started with the presentation of a blue target line with varying orientation and shape. At the origin of the blue line, 2 s after the initial presentation of the target line, a white target dot was presented, which began to move along the line towards the endpoint. For each trial, the target dot moved at a constant rate and reached the endpoint 10 s following movement onset. Thereafter, the screen turned black and the next target line appeared after a 3-s interval. Participants were instructed to rotate the 2 dials in order to track the white target dot as accurately as possible, generating the correct direction and velocity and keeping the deviation from the target line as small as possible. Participants received real-time visual feedback by means of a red tail drawn behind the cursor and representing the actual position of the cursor for the last 1,000 ms. Rotating the left dial clockwise and counter-clockwise moved the cursor upward and downwards (on the Y-axis), respectively. Rotating the right hand dial clockwise and counter-clockwise moved the cursor to the right and left (on the X-axis), respectively. The gain was set to 10 arbitrary units per rotation (U*rotation^{-1}), such that drawing the spatial pattern on the screen consisting of 162 Us, required 16.2 complete rotations of the left/right dial, respectively.

Four levels of task complexity were defined based on previous experiments by our group (e.g. Beets et al. 2015; van Ruitenbeek et al. 2017) and pilot data indicating significant performance decline with increased complexity in younger adults. In order, the following 4 levels were defined: (i) Tracking the white dot across a straight line by rotating the hands with a 1:1 (Left:Right hand) isofrequency ratio (Ratio1), i.e. with the same speed; (ii) Tracking the dot across a straight line, such that the hands rotated with a 5:2- or 2:5-frequency ratio, i.e. for every 2 rotations of one hand the other rotated 5 times (Ratio2); (iii) Tracking of a line with 1:1 isofrequency ratio, with a 90-degree angle in the middle of the line, requiring the participants to switch movement direction with one hand, whereas the other hand continued along the same direction (Angle); and (iv) Tracking of a 1:1 ratio line with 4 angles forming a toothed shape, requiring the participant to make multiple directional switches with one hand (ZigZag). All 4 levels of complexity were presented according to 2 orientations such that the start of the target dot varied, resulting in 8 trial types.

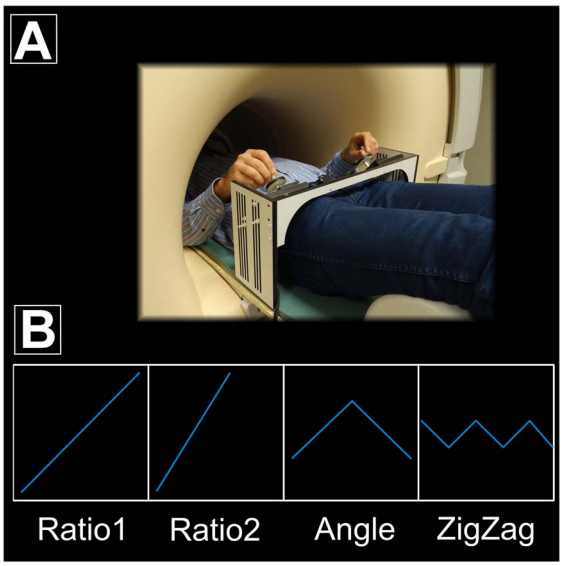

Fig. 1. Panel A: Experimental setup. In the MR scanner, participants controlled a cursor on a screen by rotating 2 discs. Left controlled movement on the vertical axis and right on the horizontal axis. Panel B: Four movement patterns along which the cursor moved and participants were instructed to track.

Although positioned inside the scanner as part of the third experimental session, eight 6-min blocks were performed by the participant, each consisting of 24 target lines presented as sub-blocks of 6 trials per complexity level. The order of the sub-blocks was varied across the 6-min blocks, such that the same order did not occur twice. The x- and y-positions of the target dot and the subject's cursor were sampled at 100 Hz. Performance was defined as the percentage of the target line that was successfully covered in space and time. Line coverage was calculated by projecting a line with shortest distance from the participant's cursor to the target line every 10 ms. The projection point on the target line was "marked" when the white moving dot had passed that point. Therefore, moving away from the line, moving too slow or fast resulted in fewer markings and, consequently, a lower score. Also, changing directions early (i.e. cutting corners) in the Angle and ZigZag condition resulted in a lower score. Finally, a percentage of the total number of points on the line that were "marked" was calculated. In addition, a pre-recorded block of trials was shown halfway performance of the 8 task blocks that served as baseline for functional imaging analyses, enabling the removal of any brain activation associated with visual information processing. The pre-recorded trials were exactly the same as the actual performance trials except that participants did not track the moving dot (i.e. no actual movement took place).

All individual behavioral data were recorded and pre-processed using LabVIEW 8.5 (National Instruments, Austin, TX, United States). The log-files generated by LabVIEW 8.5 software were then concatenated in Matlab R2011a (The MathWorks Inc., Natick, MA, 2011) and processed for individual means using MS Excel 2013 for windows (Microsoft Office Professional Plus 2013, version 15.0.5153.1000). From the resulting file, values for line coverage per trial type were extracted and used as dependent variable.

Image acquisition

All images were collected using a Phillips 3T Achieva Magnetic Resonance scanner, with a 32 channel receiver head coil located at Academic Hospital Gasthuisberg, Leuven, Belgium. T1 weighted anatomical images were collected with a Magnetization Prepared Rapid Gradient Echo (MPRAGE) sequence (time repetition, TR = 9.6 ms, time echo, TE = 4.6 ms, flip angle = 8°). The data consisted of 160 slices covering the brain. Slices were 1.2-mm thick, with no gap between the slices. Voxel size was 0.98 × 0.98 × 1.2 mm arranged in a 256 × 256 matrix with a 250 mm^2 field of view (FOV).

Functional images were collected using an Echo Planar Imaging sequence (TR = 3,000 ms, TE = 30 ms, flip angle = 90°). Functional data consisted of 120 volumes for each of the 9 runs (8 motor task; 1 baseline with no movement). The order of the runs was identical for all participants. Each volume consisted of 54 bottom-to-top sequentially collected slices and each slice was 2.5-mm thick with a 0.2-mm gap between the slices. Voxels were 2.5 × 2.5 × 2.5 mm arranged in an 84 × 84 voxel matrix resulting in a FOV of 210 mm^2.

Image processing

All MR data were analyzed using FMRIB software library (FSL 5.0.9: Smith et al. 2004; Woolrich et al. 2009; Jenkinson et al. 2012). For the T1-weighted anatomical images, brain tissue data were extracted using FSL's brain extraction tool (BET2; Smith 2002). To assist with the extraction, brain centre coordinates (i.e. massa intermedia if present) were given as an argument to the BET2 procedure. For pre-processing of the functional data, FSL's FMRI expert analysis tool (FEAT) was used and consisted of slice time correction, brain extraction, motion correction using FMRIB's Linear Image Registration Tool (MCFLIRT), applying a high pass filter with a cut-off wave length of 60 s, and smoothing using a 5-mm full width at half maximum (FWHM) Gaussian kernel. Average framewise displacement (displacement from a given volume to the next) differed between age groups ($F_{2,96} = 13.2$, $P < 0.001$). As expected, OA showed a larger displacement (M = 0.284 mm, SD = 0.111) compared with MA (M = 0.170 mm, SD = 0.107, $P < 0.001$) and YA (M = 0.161 mm, SD = 0.109, $P < 0.001$). Therefore, additional measures were taken to reduce the influence of head motion on our imaging results (using FIX, see below), particularly as head motion has relatively large effects on the signal and conventional correction methods perform less optimally (Power et al. 2012). Fieldmap images were recorded per participant and used to correct for local distortions using B0 unwarping. Functional images were coregistered with the brain extracted anatomical image and normalized to standard space (MNI) using FMRIB's Linear Image Registration Tool (FLIRT) with the Boundary Based Registration (BBR) algorithm (Jenkinson and Smith 2001; Jenkinson et al. 2002). Next FMRIB's ICA-based Xnoiseifier (FIX: Salimi-Khorshidi et al. 2014) was used to automatically classify components to represent signal or noise. To do so, independent component analysis was performed using multivariate exploratory linear optimized decomposition into independent components (MELODIC: Beckmann and Smith 2004) to determine components of activation that can either represent signal, or noise due to movement, cardiac-related factors, white matter signal, large veins, or reconstruction artifacts. FIX classifiers were trained using 2 runs of 16 randomly chosen participants approximately evenly distributed across the age groups. All components were manually classified as noise or signal by visual inspection of the statistically thresholded spatial maps, temporal power spectra and the time-series, as described by Salami-Khorshidi et al. (2014). This manually classified sample was used to train a classifier which was used to remove noise in the full data set (including the training sample). In addition, after applying FIX, residual noise appearing as activation in white matter (WM) and cerebrospinal fluid (CSF) following first-level contrasts was identified. To reduce the presence of this noise, the structural T1-weighted images were segmented into gray matter, WM and CSF using FMRIB's Automated Segmentation Tool (FAST4). Next, parameter values from the previous coregistration step using FLIRT were used to coregister the segmented images with the functional images. The segmented coregistered WM and CSF images were then thresholded (WM = 1, CSF = 0.98) and transformed into binary masks, which were used to extract the time-series data (averaged across voxels) from the functional images in these areas. These average time-series were used as a covariate to control for any variance that may be explained by these noise components.

Statistical analyses

Behavioral data

Performance data were analyzed according to a 4 × 3 model using repeated measures analysis of variance (ANOVA), with Complexity (4 levels: Ratio1, Ratio2, Angle, and ZigZag) as a factor with repeated measures and Age-group (3 levels: YA, MA, and OA) as a between-subjects factor. Mauchly's test for sphericity was performed to test for equal variances between the levels of the Complexity factor. If the assumption of sphericity was violated ($P < 0.05$), Greenhouse–Geisser corrections were applied. *F*-tests for the main effect of Complexity, Age-group or the Complexity × Age-group interaction were considered significant when $P < 0.05$. Upon a significant *F*-test, subsequent hypothesis-driven post-hoc comparisons were performed using repeated contrasts within Age-group, Complexity, and contrasts for Complexity per level of Age-group, and contrasts for Age-group per level of Complexity specifying the interaction.

Imaging data

Functional imaging data were analyzed on 3 levels; run-level, participant-level, and group-level. The first-level analysis (run) was performed to determine activation occurring during task performance. The haemodynamic response was modeled using a double gamma response function during task performance on different trials. Using a random-effects analysis, the fMRI signal was modeled with 34 regressors: 4 task complexity regressors (Ratio1, Ratio2, Angle, and ZigZag) of interest and 10 regressors of no interest, and their temporal derivatives, and 6 head motion parameters (3 rotational and 3 translational). The 10 regressors of no interest consisted of: average CSF and WM signal per volume, and 8 regressors representing the total degrees that the hand rotated per trial per level of complexity, as part of the motor task. Total rotations for each hand for each condition were included as covariates as the amount of movement may explain variance in the blood oxygen level-dependent response and confound the results. First, Ratio1 > baseline and Ratio2 > baseline contrasts were calculated to explore Age-group differences in brain activation associated with sensori-motor processes at a low level of task-complexity. Baseline was defined as activation occurring

during passively watching a pre-recorded execution of trials. Second, the following contrasts were created to assess effects of task complexity: Ratio2 > Ratio1, Angle > Ratio1, and ZigZag > Ratio1, in which the Ratio1 condition served as baseline for the latter 3 contrasts to restrict the analysis to brain activation changes associated with task complexity and exclude changes associated with movement execution. These contrasts will be referred to as Ratio2, Angle, and ZigZag, respectively, excluding Ratio1 in the naming to avoid confusion.

The contrasts from the first-level analysis were used in the second-level analysis (participant), which concatenated task activations from the 8 task runs using a fixed-effects regression model.

Third level analyses (group) were performed to test specific predictions in line with and further specifying the general CRUNCH hypothesis and explore differences among task conditions, age groups, and the interaction between age groups and task conditions. Statistical analyses were performed using Randomize in FSL (10,000 permutations), a non-parametric permutation program to model inferences, not sensitive to skewed distributions (Nichols and Holmes 2001). Contrast of parameter estimates (COPEs) from the second level analysis were concatenated into a 4D file. A design matrix was created enabling comparisons between the second level contrasts as a repeated measures analysis by modeling every subject as a factor and limiting permutation to be performed between (not within) participants. Contrast weights were indicated in a separate file as an argument for the randomize command, such that it enabled performing contrasts of interest and main effects analyses of Age-group, Complexity, and the Age-group ^{x} Complexity interaction.

Hypotheses testing

Four specific hypotheses derived from the CRUNCH framework were defined as follows:

- Hypothesis 1 (shared upregulation with task complexity) was defined as both YA and OA age groups showing an upregulation of activation with an increase in task complexity (e.g. conjunction between Ratio1 < Ratio2 for YA and Ratio1 < Ratio2 for OA).
- Hypothesis 2 (greater activation at lower complexity level) was defined as OA showing greater activation during Ratio1 and/or Ratio2. Therefore, a statistical map was generated using OA > YA for Ratio1 > baseline, and for Ratio2 > baseline for which a separate 4D COPE file and design were created. Only lower levels of task complexity were included as no resource limits were expected to be reached based on the behavioral data.
- Hypothesis 3 (greater upregulation in OA with task complexity increase) states that the increase in activation with task complexity is greater in OA as compared with YA; specifically, greater increases for OA during Angle: (Ratio2 < Angle for OA) > (Ratio2 < Angle for YA) and/or ZigZag: (Angle < ZigZag for OA) > (Angle < ZigZag for YA).
- Hypothesis 4 (reaching limits) was defined as OA showing smaller activation increase or reduced activation at higher levels of complexity. For OA reaching limits at Angle: (Ratio2 < Angle for OA) < (Ratio2 < Angle for YA) and for OA reaching limits at ZigZag: (Angle < ZigZag for OA) < (Angle < ZigZag for YA).

In addition, MA may already show increased activation that is typically associated with OA, such that the above hypotheses also hold true for MA. Therefore, the hypotheses were tested for OA and MA separately.

As a statistical association between performance level and brain activation would possibly suggest that brain activation contributes to performance, the above analyses were repeated but with task performance represented as 4 regressors, one for each level of difficulty at the first-level analyses. These regressors replaced the boxcar functions representing the trials within the 4 levels of task complexity. If increased brain activation, associated with either task complexity, age group or both, is compensatory, an overlap may be observed between these upregulated brain areas and the brain areas showing increased statistical association between activation and performance. Reports of any overlap are presented in the results section. All other results displaying the differences in the association between activation and performance are presented in the supplementary materials.

Results are presented as brain areas constituting a motor/visuospatial network and a network underlying higher cognitive functions as determined by Ray et al. (2013) since these are of primary interest in view of the nature of the task, comprising both elements of explicit motor control and higher cognitive functions (Zapparoli et al. 2022). Ray et al. (2013) determined brain networks using independent component analysis of a database of 8,637 task-related fMRI studies. The "motor/visuospatial network" included bilateral pre- and postcentral gyri, supplementary motor area, superior parietal lobule (anterior), lateral occipital cortex, and supramarginal gyrus. The "higher cognitive network" included bilateral frontal pole, superior- and middle frontal gyri, paracingulate gyri, superior parietal lobule (posterior), anterior and posterior supramarginal gyrus, angular gyrus, middle- and inferior temporal gyri, and occipital pole. Based on our previous experiments with a similar task we expected the hypothesized activation patterns to occur particularly in pre- and postcentral gyri, middle frontal gyri, lateral occipital cortex, and inferior temporal gyrus (Santos Monteiro et al. 2017).

Complexity, age group and interaction effects

For completeness, we assessed the main effects of Complexity and Age-group and the interaction between Complexity and Age-group. Main effect of the factor Complexity was tested for significance using an *F*-test for bidirectional contrasts: Ratio2 vs. Angle, Ratio2 vs. ZigZag, and Angle vs. ZigZag. Main effect of Age-group was determined using an *F*-contrast in a model with bidirectional YA vs. MA, YA vs. OA, and MA vs. OA contrasts. Any significant *F*-contrast was followed by further testing the rationale driven contrasts separately (Ratio2 < Angle, Angle < ZigZag, and YA < MA, MA < OA) to determine whole-brain differences. The interaction was explored assessing Age-group contrasts (YA < MA, MA < OA, and YA < OA) for Complexity contrasts (Ratio2 < Angle, Angle < ZigZag). As these analyses did not test our hypotheses directly, the corresponding results can be found in the supplementary materials (Supplementary Figs. S1, S2, and S3, see online supplementary material for a color version of the figures and Supplementary Tables S1, S2, and S3). Data are available upon reasonable request using the acronym CRUNCH.

Results

Behavioral performance

Figure 2 shows the obtained results for the 3 age groups across the 4 task complexity levels. A lower score is indicative of worse performance. Performance difference among levels of Complexity across all age groups was established by the significant main

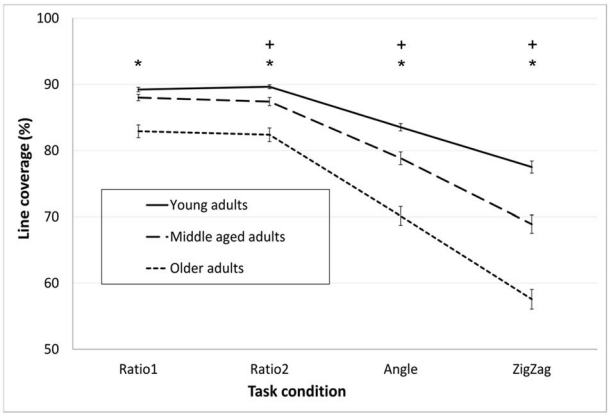

Fig. 2. Performance on the bimanual tracking task. Performance decline with increased task complexity was age-group dependent. Older adults displayed a sharper decline with increased task demands. + indicates $P < 0.05$ for MA < YA, and * indicates $P < 0.05$ for OA < MA.

effect of Complexity ($F_{1.834,\ 176.021} = 681.8$, $P < 0.001$). Pair-wise comparisons showed that performance scores in the Ratio2 condition were not significantly different compared with those in the Ratio1 condition. In contrast, performance scores for Angle were lower compared with those for Ratio2 ($P < 0.001$) and performance scores in the ZigZag condition were lower compared with those in the Angle task condition ($P < 0.001$).

Similarly, differences in performance among age groups were established by the significant main effect of Age-group ($F_{2,96} = 52.5$, $P < 0.001$). Pair-wise comparisons showed that the groups scored poorer on the task as a function of increasing age. MA scored significantly worse compared with YA ($P < 0.001$), and OA scored worse compared with MA ($P < 0.001$).

The decrease in performance with higher levels of complexity was age-group dependent as indicated by the Complexity (4 levels) × Age-group (3 levels) interaction ($F_{3.667,\ 176.021} = 28.7$, $P < 0.001$; see Fig. 2). Further analysis per age group specifying the interaction showed that, for each age group, performance decreased from Ratio2 to Angle, and Angle to ZigZag, but not Ratio1 to Ratio2 (see Table 1 for statistical details). Older adults appeared to struggle more with increased task complexity compared with the other age groups. Differences between age groups were observed for the performance differences between Ratio2 and Angle ($F_{1,96} = 15.4$, $P < 0.001$), and between Angle and ZigZag ($F_{1,96} = 20.46$ $P < 0.001$), but not between Ratio1 and Ratio2. Further analyses of the effects of Age-group per level of Complexity showed that for Ratio1, MA did not perform significantly worse than YA, but OA scored worse than MA ($P < 0.001$). For Ratio2, MA performed worse than YA ($P < 0.032$), and OA scored worse than MA ($P < 0.001$). The same pattern was seen for the Angle and ZigZag conditions; MA performed worse than YA ($Ps < 0.002$), and OA scored worse than MA ($Ps < 0.001$).

In summary, all age groups decreased performance with increased task complexity (except from Ratio1 to Ratio2). However, the performance decline was largest for OA.

Functional imaging results

Hypotheses tests

Hypothesis 1: Shared increased activation with task complexity

YA and OA both increased brain activation during Ratio2 compared with Ratio1, in spite of a lack of behavioral differences (see Fig. 3A and Table 2A for a complete overview of all shared activation differences). Both age groups increased activation in the motor/visuospatial network (i.e. premotor cortex, supplementary motor area, inferior parietal cortex, inferior frontal gyrus, lateral occipital cortex, thalamus, putamen, and cerebellum). In addition, both groups increased activation in the middle frontal gyrus representing higher cognitive functions.

Both YA and OA further increased brain activation when performing the Angle condition in many cortical brain areas within the motor/visuospatial network (i.e. primary- and premotor cortex, supplementary motor area, superior- and middle frontal gyri, superior parietal lobule, primary somatosensory cortex, precuneus, and cerebellum). Both groups also activated parts of the inferior temporal gyrus more within the network for higher cognitive functions.

Finally, both YA and OA increased activation of the premotor cortex, supplementary motor area and superior parietal lobule in the motor/visuospatial network during the ZigZag condition.

The activation increase during Ratio2 common to YA and MA was very similar to the activation increase common to YA and OA as described above. (See Fig. 3B and Table 2B for a complete overview of all shared activation differences.) Both YA and MA increased activation in motor/visuospatial areas (i.e. premotor cortex, supplementary motor area, primary motor cortex, inferior frontal gyrus, superior- and inferior parietal lobule, lateral occipital cortex, and cerebellum). Only some brain areas associated with higher cognitive functions were activated by both age groups (i.e. frontal pole, superior- and middle frontal gyrus, and opercular cortex).

Both YA and MA further increased activation during the Angle condition in the premotor cortex, superior parietal lobule, lateral occipital cortex, paracingulate, and cerebellum.

Finally, YA and MA increased activation further during ZigZag in the motor/visuospatial network (i.e. premotor cortex, superior frontal gyrus, supplementary motor area, and superior parietal lobule).

Overlap between over-activation and performance-activation association: No overlap was observed between brain areas that showed increased activation with task complexity which was shared by OA and YA, and by MA and YA (hypothesis 1), and brain areas that showed increased association between performance and activation with increased task complexity (see supplementary materials).

Hypothesis 2: Greater activation for OA and MA at lower levels of task complexity

No differences in activation were observed between OA and YA, and between MA and YA for contrasts between Ratio1 and baseline. Therefore, at the lowest level of task complexity MA and OA did not exhibit greater brain activation.

Group differences between OA and YA were observed for the contrast between Ratio2 and baseline (see Fig. 4.1 and Table 3). Within the motor/visuospatial network, increased activation was observed in the superior parietal lobule, lateral occipital cortex, and cuneal cortex in OA.

Increased activation in MA compared with YA was not observed when comparing Ratio2 over baseline.

Overlap between over-activation and performance-activation association: No overlap was observed between brain areas that showed increased activation in OA compared with YA at lower levels of task complexity (hypothesis 2), and brain areas that showed increased association between performance and

Table 1. Main effects of task complexity within the age groups and subsequent post-hoc univariate analyses of variance comparing performance on levels of complexity.

Age group	Contrast	*F*	*df*	*P*
Young adults	Main effect	173.8	1.783, 55.266	<0.001
	Ratio1 vs. Ratio2	1.9	1, 31	0.183
	Ratio2 vs. Angle	143.6	1, 31	<0.001
	Angle vs. ZigZag	86.7	1, 31	<0.001
Middle-aged adults	Main effect	226.3	1.549, 49.569	<0.001
	Ratio1 vs. Ratio2	2.8	1, 32	0.103
	Ratio2 vs. Angle	137.7	1, 32	<0.001
	Angle vs. ZigZag	162.6	1, 32	<0.001
Older adults	Main effect	299.5	1.952, 64.415	<0.001
	Ratio1 vs. Ratio2	.564	1, 33	0.458
	Ratio2 vs. Angle	146.7	1, 33	<0.001
	Angle vs. ZigZag	293.0	1, 33	<0.001

Results support a decrease in performance in all age groups from Ratio2 to higher complexity levels.

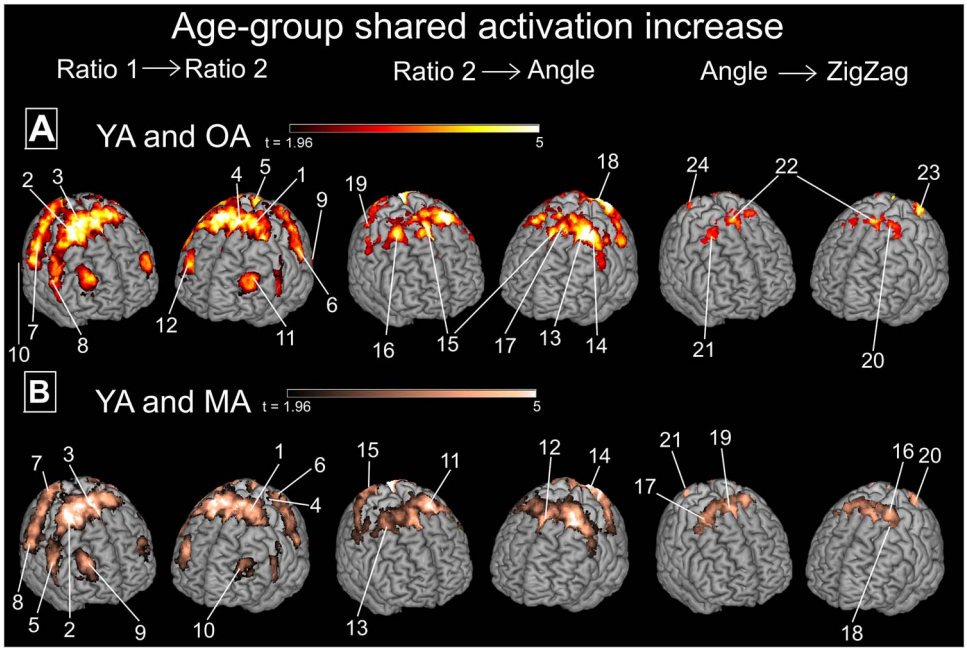

Fig. 3. Shared brain activation increases between younger (YA) and older adults (OA) (panel A), and between YA and middle-aged (MA) adults (panel B). All age groups show significantly more brain activation in motor/visuospatial and higher cognition networks in stepwise comparisons between increased task complexity levels. Numbers refer to clusters described in Table 2. $P < 0.05$, FWE corrected Threshold-Free Cluster Enhancement (TFCE) applied for all significant activation differences.

activation in OA compared with YA during Ratio 2 performance (Supplementary Fig. S4, see online supplementary material for a color version of this figure and Supplementary Table S4).

Hypothesis 3: Greater activation increases with increased complexity in OA and MA compared with YA

With increased task complexity (Angle > Ratio2), OA recruited brain areas more in both the motor/visuospatial network (i.e. precuneous, inferior/middle frontal gyrus) and the network for higher cognitive functions (i.e. frontal pole, paracingulate, and inferior parietal lobule) compared with YA. OA did not increase brain activation more compared with YA during performance on the other task complexity levels.

Compared with YA, MA only increased activation more in an area within the frontal pole in the Angle condition compared with Ratio2. Similar to OA, MA also did not activate brain areas more during performance on the other task complexity levels. See Fig. 4.2 and Table 4 for a complete overview of all activation differences.

Overlap between over-activation and performance-activation association: Overlap was observed in the inferior frontal gyrus between brain areas that showed larger increases in activation in OA compared with YA for Angle > Ratio2 (hypothesis 3), and brain areas that showed a greater association between performance and activation in OA compared with YA for Angle > Ratio2. (Supplementary Fig. S5 Area A, see online supplementary material for a color version of this figure and Supplementary Table S5).

Hypothesis 4: OA and MA reach activation limits

Both OA and MA did not appear to have reached activation limits before YA did at the Ratio2, Angle or ZigZag complexity level, as defined by a smaller increase or a decrease in brain activation with increased task complexity compared with YA.

Table 2. Brain areas showing joint increases in activation with task complexity between young adults (YA) and older adults (OA) and between YA and middle aged adults (MA; see also Fig. 3).

Area Number Figure 3	Network	Sub area	Lat.	BA	Peak *t*-value (FWE)	Peak coordinates (MNI) X	Y	Z
A								
Ratio1 < Ratio2 common to YA and OA								
1	Motor/Visuospatial	Premotor cortex Inferior parietal sulcus	L	6	4.74	−30	−6	57
2			R	6	5.82	26	−8	58
3				6	5.77	22	−4	74
4		Supplementary motor area	L/R	6	5.58	0	−4	72
5		Precuneus cortex	R	5	5.00	7	−54	58
6		Inferior parietal lobule	L	40	4.29	−58	−34	38
7			R	2	4.95	62	−26	46
8		Inferior frontal gyrus	R	48	4.48	54	10	8
9		Lateral occipital cortex	L	37	4.02	−52	−72	2
Not visible			R	39	2.81	36	−68	20
Not visible				7	2.18	32	−78	44
Not visible		Inferior parietal sulcus	L	48	2.05	−44	−42	30
10		Middle temporal gyrus/Lateral occipital cortex	R	37	3.49	52	−56	2
Not visible		Thalamus	L	—	4.44	−16	−14	10
Not visible		Putamen	L	—	3.08	−26	6	10
Not visible		Cerebellum VI	L	—	5.93	−32	−54	−26
Not visible			R	—	6.02	36	−50	−28
11	Higher cognition	Middle frontal gyrus	L	9	3.92	−42	40	32
12			R	8/9	4.28	34	48	32
Not visible				10	2.06	48	50	16
Not visible				—	2.33	36	54	14
Ratio2 < Angle common to YA and OA								
13	Motor/Visuospatial	Superior frontal gyrus	L	6	5.61	−24	0	54
14		Premotor cortex	L	6	6.59	−32	−6	64
Not visible				6	2.34	−2	−14	54
15		Premotor cortex	L/R	6	5.97	0	10	56
16		Middle frontal gyrus	R	6	4.95	34	2	66
17		Supplementary motor area	L/R	6	6.06	0	6	58
Not visible		Primary motor cortex	R	31	2.71 2.34	2	−20	52
18		Superior parietal lobule	L	7	7.71	−6	−70	62
Not visible		Precuneus	R	7	6.69	2	−54	56
Not visible		Primary somatosensory cortex	R	3	3.11	46	−16	56
Not visible		Cerebellum VIIIb	R	—	5.39	14	−58	−48
19	Higher cognition	Superior parietal lobule	R	40	4.46	36	−46	46
Not visible		Inferior temporal gyrus	R	—	2.42	50	−50	−8
Angle < ZigZag common to YA and OA								
20	Motor/Visuospatial	Premotor cortex	L	6	3.69	−22	−10	62
21			R	6	3.83	26	−2	56
22		Supplementary motor area	L/R	6	4.08	0	−2	72
23		Superior parietal lobule	L	7	4.86	−24	−58	62
24			R	—	3.52	24	−56	70
B								
Ratio1 < Ratio2 common to YA and MA								
1	Motor/Visuospatial	Premotor cortex	L	6	4.54	−20	−10	70
2			R	6	4.25	26	−6	58
3		Supplementary motor area	L/R	6	5.87	0	0	64
4		Primary motor cortex	L	—	2.08	−26	−34	76
5		Inferior frontal gyrus	R	44	4.44	52	10	6
6		Superior parietal lobule	L	7	4.50	−32	−52	70
Not visible			L	7	2.97	−12	−70	54
7			R	7	5.44	8	−62	58
8		Inferior parietal lobule	R	48	4.38	60	−32	28
Not visible		Lateral occipital cortex	R	39	3.12	38	−70	20
Not visible			R	19	1.98	30	−80	44
Not visible		Cerebellum VI	L	—	6.67	−32	−52	−26
Not visible			R	—	6.00	36	−50	−28

(*Continued*)

Table 2. Continued

Area Number Figure 3	Network	Sub area	Lat.	BA	Peak t-value (FWE)	Peak coordinates (MNI) X	Y	Z
Not visible	Higher cognition	Frontal pole	R	45	2.04	48	42	14
9		Superior frontal gyrus	R	46	4.50	36	44	30
10		Middle frontal gyrus	L	46	3.74	−32	40	24
Not visible		Opercular cortex	R	48	2.07	42	2	16
Ratio2 < Angle common to YA and MA								
11	Motor/Visuospatial	Premotor cortex	L	6	5.49	−24	0	56
Not visible				6	5.19	−24	−2	70
				6	5.69	−30	−2	56
12			R	32	6.18	2	10	54
13				6	3.91	28	−10	58
14		Superior parietal lobule	L	7	8.32	−8	−60	64
15		Lateral occipital cortex	R	19	5.20	22	−82	41
Not visible		Paracingulate cortex	L	32	4.96	−6	14	44
Not visible		Cerebellum VIIIb	R	—	4.72	16	−54	−48
Angle < ZigZag common to YA and MA								
16	Motor/Visuospatial	Premotor cortex	L	6	4.47	−24	−8	74
Not visible				6	4.33	−22	−10	64
17			R	6	4.95	26	−10	56
18		Superior frontal gyrus	R	6	4.05	24	0	54
19		Supplementary motor area	L	6	4.60	−2	−4	64
Not visible				6	4.56	−4	−2	68
20		Superior parietal lobule	L	5	4.57	−18	−60	62
21			R	7	4.40	24	−56	72
					0			
Not visible				7	4.19	8	−60	74
					4.05			

Cognitive and sensori-motor areas are upregulated in all age groups with an increase in task complexity up until the highest complexity levels. Shared increase in brain areas underlying higher cognitive functions is observed at only relatively low task complexity levels. Lat. = laterality, BA = Brodmann area, FWE = family wise error, MNI = Montreal neurological institute coordinate system.

Table 3. Brain areas showing larger brain activation in older adults (OA) in motor/visuospatial networks during performance in the Ratio2 condition compared with younger adults (YA; see also Fig. 4.1).

Area Number Figure 4.1	Network	Sub area	Lat.	BA	Peak t-value (FWE)	Peak coordinates (MNI) X	Y	Z
Larger activation increases for OA compared with YA for Ratio2 > baseline								
1	Motor/Visuospatial	Superior parietal lobule 5L	R	5	4.37	4	−48	74
2				4	3.11	16	−38	68
3				1	2.99	18	−44	78
4		7A	L	7	4.21	−18	−64	60
5		7P	L	7	3.76	−6	−82	50
6		Cuneal cortex	R	19	4.41	8	−84	38

Lat. = laterality, BA = Brodmann area, FWE = family wise error, MNI = Montreal neurological institute coordinate system.

Discussion

Within the CRUNCH framework, we identified several predictions concerning the features of brain activation at older age, which we attempted to assess. Based on previous observations, we predicted that (i) brain activation scales up with increases in task demands, being evident in both younger and older adults, (ii) older as compared to younger adults show increased brain activation in motor/visuospatial and possibly higher cognition related networks at lower levels of task complexity, (iii) due to increased demands of both the aged brain and task complexity, older as compared to younger adults show greater increases in brain activation with increased task complexity (yet attenuated at the highest task complexity level according to the CRUNCH hypothesis), (iv) compared with younger adults, older adults show smaller activation increases or even decreases at the highest levels of task complexity, representing a deficient supply of brain resources (consistent with the CRUNCH hypothesis). All predictions were also tested for middle-aged adults to explore the emergence of age-related differences in brain activation in this relatively under-investigated age group.

Our results confirmed that older and younger adults, and middle-aged and younger adults shared upregulation of brain activation with increased task complexity. In addition, older adults recruited motor/visuospatial brain areas more during performance at a lower complexity level (Ratio2). This increased activation in motor/visuospatial and higher cognitive brain areas was even more pronounced during performance in the Angle condition as compared with younger adults. Finally, there were no indications of older adults reaching upregulation limits earlier than younger adults, as defined by smaller increases or even

Table 4. Brain areas showing age group dependent increases in activation with increases in task complexity.

Area Number Figure 4.2	Network	Sub area	Lat.	BA	Peak t-value (FWE)	Peak coordinates (MNI) X	Y	Z
A								
Larger activation increases for OA compared with YA for Ratio2 < Angle								
Not visible	Motor/Visuospatial	Precuneous	R	—	5.25	2	−62	30
1		Middle frontal gyrus	L	6	5.06	−40	6	42
2		Inferior/middle frontal gyrus	L	48	4.14	−46	24	18
3	Higher cognition	Frontal pole	L	11	4.49	−24	54	2
4			R	10	4.69	14	72	0
Not visible				11	5.25	18	50	2
5		Inferior parietal lobule	R	39	5.72	44	−60	30
B								
Larger activation increases for MA compared with YA for Ratio2 < Angle								
1	Motor/Visuospatial	Frontal pole	R	10	5.52	14	72	2

Older adults (OA) show larger brain activation increases in motor/visuospatial and higher cognitive networks from Ratio2 to Angle condition performance compared with younger adults (YA). Middle aged adults (MA) increased brain activation in the frontal pole (see also Fig. 4.2). Lat. = laterality, BA = Brodmann area, FWE = family wise error, MNI = Montreal Neurological Institute coordinate system.

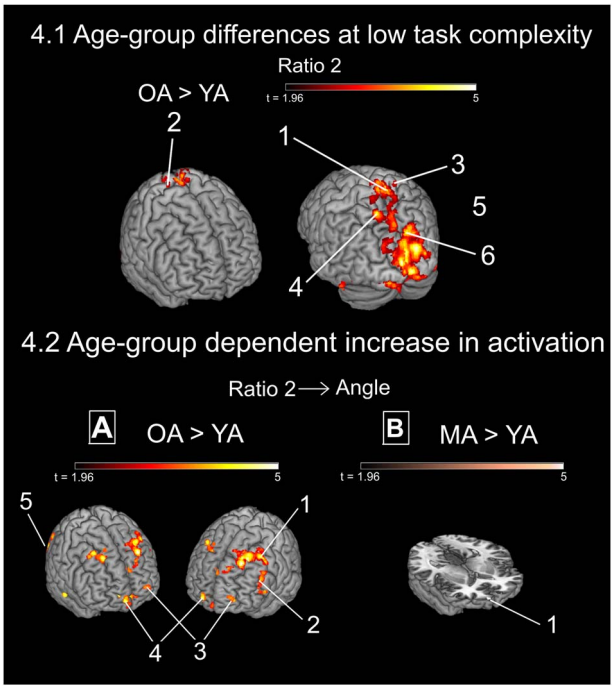

Fig. 4. 1) Older adults (OA) showing increased brain activation in sensorimotor/visuospatial networks at relatively low level of task complexity (Ratio2) as compared with younger adults (YA). Numbers refer to clusters described in Table 3. 2) Greater increases in brain activation in older- (OA) and middle-aged (MA) adults with stepwise increase in task complexity. Panel A: OA displayed greater increases in activation in areas in motor/visuospatial and higher cognitive networks only for the complexity increase from Ratio2 to Angle. Panel B: The enlarged increase in activation observed in MA was also limited to the complexity increase from Ratio2 to Angle. Cluster details are presented in Table 4. $P < 0.05$, FWE corrected TFCE applied for all significant activation differences.

decreases in activation during the ZigZag as compared with the Angle task level. Middle-aged adults showed a similar pattern with a task complexity-dependent increase in brain activation, no elevated brain activation at lower task level and no diminished activation increase at the highest level of complexity, as compared with younger adults. These results suggest similarities between all 3 age groups in coping with increased brain resource demands. In other words, older adults showed more brain activation as a result of increased task complexity (and up to the highest task level) in much the same way as younger and middle-aged adults did.

A critical prerequisite to assess hypotheses within the CRUNCH framework is to establish effective increases in task complexity as evidenced by decreased performance across complexity levels, thus leading to lowest performance at the highest complexity level by older adults. When this requirement is met, as it was in the present study, brain activation patterns can be assessed and interpreted in the context of increased task demands as well as the effects of aging. Here, performance decreased with task complexity in all age groups. Older adults performed the task more poorly at every level of complexity compared with middle-aged adults who were worse than the younger adults. Importantly, performance by older adults was increasingly affected at higher task complexity levels compared with younger adults and middle-aged adults. In addition, older adults frequently reported that they considered the ZigZag complexity level to be extremely difficult. Therefore, the possibility that older adults were not appropriately challenged due to the task not being sufficiently complex appears rather unlikely. Taken together, these results suggest successful task manipulations that enabled determining brain activation levels associated with CRUNCH predicted patterns.

In accordance with increases in task complexity, all age groups increased brain activation. Moreover, younger and older adults, and younger and middle-aged adults shared brain activation increases in motor/visuospatial and higher cognitive networks with gradually increased task demands, suggesting similar brain coping properties in all age groups. Interestingly, shared activation increases in areas supporting higher cognitive functions were mostly present when task complexity increased from lower levels to intermediate levels, as defined in the current study (i.e. Ratio1 to Ratio2), and not at the higher levels of complexity (e.g. Angle). This was unexpected as it may be argued that, at lower levels of task complexity, younger adults may not need to recruit higher cognitive networks (as in Cabeza et al. 2002) and, therefore, the conjunction analysis would not result in shared activation in these brain areas. Nevertheless, the current results suggest that all 3 groups already recruited additional brain areas that subserve higher cognitive functions at lower complexity levels. In addition to the shared increases, older adults showed greater increases of pre-frontal activation during the Angle condition compared with younger adults, which is line with previous studies. Heuninckx et al. (2005) observed upregulated activation in

the dorsolateral prefrontal cortex (DLPFC) comparable to the presently observed middle frontal gyrus activation in older adults during performance in the Ratio2 condition. Several studies using non-motor tasks (Grady et al. 1998; McIntosh et al. 1999; Cabeza et al. 2002) also reported greater pre-frontal cortex activation in older adults compared with younger adults. This suggests that the PFC is recruited with increased task demands and plays a general purpose role (e.g. implementing behavioral goals (Holroyd and Yeung 2012)). Taken together, all age groups appeared to recruit the DLPFC with increased task demands, and older adults did this to a greater extent at higher levels of complexity.

The lowest level of task complexity at which we observed the older adults to upregulate activation is Ratio2. The pattern of upregulated brain activation is in accordance with that observed in a recent meta-analysis (Zapparoli et al. 2022), such that the most prominent upregulation was observed in posterior brain areas. The latter authors argued that older adults might use mental visual imagery to aid their performance (see also Allali et al. 2014). Similar processes may have occurred in the present study as well, as performance relied heavily on visual feedback, spatiotemporal orientation, and motor planning.

As a result of age-related tissue changes, for example, changes in gray and white matter volume (e.g. Serbruyns et al. 2015; Van Ruitenbeek et al. 2017) or neurochemistry (Minati et al. 2007; Levin et al. 2019), older adults may exhibit decreased information processing and transmission capacity and this may require additional recruitment of brain areas (e.g. Ramanoel et al. 2019; Kong et al. 2020). Our findings of larger increases in brain activation during the Angle condition in older adults compared with younger adults support this notion. In more detail, older adults recruited the bilateral middle frontal gyrus and frontal pole. The activated middle frontal gyrus closely resembles the frontal eye fields (FEF). The FEF are well known to play a role in voluntary saccadic eye movements, guiding attention (Schall 2004) and pursuit eye movements (Mustari et al. 2009) and have been considered part of the executive control network (Hermans et al. 2014). These FEF functions fit well with the processes required to perform the visual tracking task (BTT) in our study. Older adults may have increased their mental efforts in trying to track the moving dot visually. In addition, the medial frontal pole has been shown to subserve planning and evaluation of behavioral goals (Koechlin et al. 2002). More specifically, it has been associated with comparing expected and actual sensory feedback upon which behavioral performance is being adjusted (Bar 2007). Taken together, older adults appeared to engage in increased top down control in the Angle condition.

The remarkable absence of age group differences in increased brain activation at the current highest levels of complexity suggests that all age groups were equally capable of recruiting brain areas as a function of task demand. Despite the fact that older adults were less successful in performing the ZigZag pattern, they clearly remained committed to recruit the required brain resources to perform the task. Thus, instead of the predicted failure to recruit additional resources (as suggested by the CRUNCH hypothesis), older adults appeared equally able to recruit brain areas as compared with younger adults. Compliance with increased resource demands was apparently present in all age groups, even though it did not enable the older adults to match their behavioral performance with that of the other age groups.

Conjunction analyses among the age groups in upregulation of activation resulted in striking similarities (Fig. 3), suggesting that all age groups utilized large scale upregulation of activation to meet task demands. The largest observed difference between the results for middle-aged adults and older adults was that middle-aged adults did not upregulate brain activation during the Angle condition as much as older adults did (Fig. 4.2). Exploratory analyses were performed providing more insight into these complexity and age group dependent activations. Activation in many brain areas within the motor/visuospatial network and the network for higher cognitive functions was higher with increased age, which is in line with previous results (Heuninckx et al. 2005, 2008; Goble et al. 2010; Berghuis et al. 2019). More specifically and in line with the main analyses, the exploratory analyses revealed brain activation differences between middle-aged adults and younger adults, and not between older adults and middle-aged adults, placing middle-aged adults more closely to older adults (Supplementary Fig. S2B, see online supplementary material for a color version of this figure).

As most previous studies compared older adults with younger adults, little is known about middle-aged adults as being the transitional age range from young adulthood to older age. The present results suggest that over-activation of brain areas is not limited to older adults, and in fact may start at an earlier age, i.e. between 40 and 60 years of age. In the present study, this age group also performed worse compared with younger adults, suggesting relatively early declines of complex motor function. On a structural level, over-activation has often been associated with a decline in brain structure in older adults (Seidler et al. 2010; Berghuis et al. 2019). However, arguing against such association in middle-aged adults is that gray matter decline appears to be small in most cortical areas, even in the prefrontal cortex which is known to show a decline relatively early (Pfefferbaum et al. 2013; Storsve et al. 2014) and white matter volume peaks around the age of 50 (Liu et al. 2016).

Besides the increased brain activation by older adults during the Angle compared with the Ratio2 condition, diminished deactivations (Supplementary Fig. S3, see online supplementary material for a color version of this figure) in many subareas of the default mode network (DMN; Buckner et al. 2008) in older as compared with younger adults were also prominent. In fact, most areas that showed this activation pattern were located in the DMN. It is well known that increased age is associated with reduced deactivation of the DMN during task execution (e.g. Sambataro et al. 2010; Gordon et al. 2014; Berghuis et al. 2019), which is generally interpreted as impaired switching from task-irrelevant to task-relevant networks (Sambataro et al. 2010; Li et al. 2015). Evidence for an indirect role of the DMN in bimanual performance is provided by the observation that level of performance at retention, following training of bimanual coordination tasks, is positively associated with a decrease in DMN activation in older adults (Pauwels et al. 2018). Other data support a functional decline of DMN with age. Older adults show decreased functional connectivity within DMN (Vidal-Pineiro et al. 2014; Staffaroni et al. 2018) and increased functional connectivity between the DMN and other task-relevant networks during the resting state, which is related to decreased bimanual performance (King et al. 2018). Taken together, next to over-activations of motor/visuospatial and higher cognitive function networks, reduced deactivation of the DMN may also play a prominent role in reduced bimanual coordination performance.

Next to the DMN, additional networks as alternative possibilities for interpretation are provided by Hugdahl et al. (2015) and similarly by Duncan (2013). Hugdahl et al. (2015) suggest the existence of an extrinsic-mode network (EMN) as a counterpart of the DMN. EMN activation is upregulated whenever task

demands increase and general resources are needed. Similarly, Duncan (2013) suggested the existence of a multiple-demand network (MD) that generates attentional episodes required for task performance. Their observed pattern of active brain areas during performance on multiple types of tasks is strikingly similar to the increase in activation with increased task complexity, as presently observed for all age groups. Therefore, besides interpreting the results within motor/visuospatial and higher cognition networks, functional interpretations can also be made from the perspective of the more generic EMN/MD network recruitment. The consequence is that bimanual performance is interpreted as a function of activation of the EMN/MD networks and deactivation of the DMN network. This aligns well with our resource-demand notion of over-activation in older adults. Future studies could be directed at determining such network activation patterns and their interaction with increasing age, and associate these with age-related behavioral decline. For example, it has been shown that activation of the EMN/MD network is negatively correlated with that of the DMN. A testable hypothesis is that DMN and EMN/MD activations may be less downregulated and upregulated, respectively, with task complexity manipulations in older as compared with younger adults.

Some limitations need to be mentioned that may hamper the interpretation of these data. In order to conclude that increases in activation are compensatory in nature, equal performance between the age groups at lower levels of task complexity may be helpful. Given that our study revealed group differences in performance, multiple interpretations (compensatory or maladaptive activation) remain possible. This could mean that the increased recruitment of brain areas is in line with predictions representing dedifferentiation rather than compensation (Li and Lindenberger 1999; Koen and Rugg 2019). However, despite that equal performance at lower complexity levels may be helpful; we do not consider it a prerequisite. Hypothetically, increased activation may be compensatory, but insufficient to preserve high performance levels. To illustrate this point, Schneider-Garces et al. (2009) reported lower levels of performance in older adults at low difficulty levels of a working memory task and over-activation. Crucially, they showed that with equalized subjective task difficulty by expressing the memory load relative to the individual digit span, both younger and older adults showed modulation of brain activation with task difficulty. For the present data, however, it remains inconclusive whether increased activation should be considered compensatory, particularly since we observed no major overlap between areas showing increased recruitment and areas showing associations with performance in older adults.

The task manipulations in the current study were aimed at increasing task complexity. This was achieved by varying 2 components of motor control, namely the hand-to-hand ratio of rotational speed (i.e. isofrequency and non-isofrequency) and directional changes of the rotation. Future studies could identify the separate contributions of each of these manipulations in motor control to obtain a more detailed insight into age-related decline.

Taken together, the critical observation is that the increase in brain activation in motor/visuospatial and higher cognitive networks with increasing task demands is shared by all age groups. The additional increase in activation by older adults starting for Ratio2, but most clearly pronounced in the Angle condition is in line with the notion that task complexity demands are relatively higher and require more resources in the older adults. However, we did not observe any overlap between areas showing over-activation and areas in which the statistical association between activation and performance was higher in older adults, which appears to contrast with the findings from a previous meta-analysis suggesting compensation (Zapparoli et al. 2022). Zapparoli et al. (2022) showed that when older and younger adults perform equally well, older adults tend to activate pre-/postcentral gyrus during sensori-motor tasks and an occipital-temporal cluster during motor execution tasks. However, as Zapparoli et al. (2022) explicitly acknowledged, tests of the CRUNCH hypothesis have not been consistently tested within the same experimental context via parametric modulations of task difficulty. Our paper did employ such a design and we did not find evidence in support of CRUNCH. In addition, at the highest level of task complexity, older and younger adults similarly upregulated brain activation, indicating intact resource supply–demand mechanisms. In other words, all age groups appeared to share the capacity to upregulate brain activation to meet higher demands. This is an important finding that deviates from the predictions emerging from the CRUNCH hypothesis.

Our inclusion of a third group adds additional unique information to the current literature. Our data show that over-activation across all complexity levels, previously rather uniquely associated with older adults, may already be present in middle-aged adults. This suggests that aging is a very gradual process that sets in after young adulthood.

Finally, brain activation patterns associated with age-related decline in sensori-motor performance can also be expressed as recruitment of extrinsic-mode network/multiple-demand network and de-recruitment of the DMN network. This points to the potential merit of interventions that enable the suppression of the DMN network in association with scaling up activity in the task-relevant networks. Therefore, alternative interpretations within multi-purpose networks to underlie motor and/or cognitive decline with aging may be considered as a future direction in studying age-related changes in brain function.

Acknowledgments

The authors would like to thank René Clerckx for his assistance in programming the task.

Supplementary material

Supplementary material is available at *Cerebral Cortex* online.

Funding

This work was supported by the KU Leuven Research Fund (grant number C16/15/070); the Research Foundation Flanders (grant number G089818N); the Excellence of Science (EOS) grant from the Fonds Wetenschappelijk Onderzoek—Vlaanderen (FWO) and the Fonds de la Recherche Scientifique—FNRS under EOS Project No. (grant number EOS 30446199, MEMODYN), and a postdoctoral fellowship from FWO (grant number K174216N for SC).

Conflict of interest statement: None declared.

References

Allali G, van der Meulen M, Beauchet O, Rieger SW, Vuilleumier P, Assal F. The neural basis of age-related changes in motor imagery of gait: an fMRI study. *J Gerontol A Biol Sci Med Sci*. 2014:69:1389–1398.

Angel L, Bastin C, Genon S, Salmon E, Fay S, Balteau E, Maquet P, Luxen A, Isingrini M, Collette F. Neural correlates of successful

memory retrieval in aging: do executive functioning and task difficulty matter? *Brain Res*. 2016:1631:53–71.

Bangert AS, Reuter-Lorenz PA, Walsh CM, Schachter AB, Seidler RD. Bimanual coordination and aging: neurobehavioral implications. *Neuropsychologia*. 2010:48:1165–1170.

Bar M. The proactive brain: using analogies and associations to generate predictions. *Trends Cogn Sci*. 2007:11:280–289.

Beck AT, Beck RW. Screening depressed patients in family practice. A rapid technic. *Postgrad Med*. 1972:52:81–85.

Beckmann CF, Smith SM. Probabilistic independent component analysis for functional magnetic resonance imaging. *IEEE Trans Med Imaging*. 2004:23:137–152.

Beets IA, Gooijers J, Boisgontier MP, Pauwels L, Coxon JP, Wittenberg G, Swinnen SP. Reduced neural differentiation between feedback conditions after bimanual coordination training with and without augmented visual feedback. *Cereb Cortex*. 2015:25:1958–1969.

Berghuis KMM, Fagioli S, Maurits NM, Zijdewind I, Marsman JBC, Hortobagyi T, Koch G, Bozzali M. Age-related changes in brain deactivation but not in activation after motor learning. *NeuroImage*. 2019:186:358–368.

Buckner RL, Andrews-Hanna JR, Schacter DL. The brain's default network: anatomy, function, and relevance to disease. *Ann N Y Acad Sci*. 2008:1124:1–38.

Cabeza R, Grady CL, Nyberg L, McIntosh AR, Tulving E, Kapur S, Jennings JM, Houle S, Craik FI. Age-related differences in neural activity during memory encoding and retrieval: a positron emission tomography study. *J Neurosci*. 1997:17:391–400.

Cabeza R, Anderson ND, Locantore JK, McIntosh AR. Aging gracefully: compensatory brain activity in high-performing older adults. *NeuroImage*. 2002:17:1394–1402.

Cappell KA, Gmeindl L, Reuter-Lorenz PA. Age differences in prefontal recruitment during verbal working memory maintenance depend on memory load. *Cortex*. 2010:46:462–473.

Chalavi S, Adab HZ, Pauwels L, Beets IAM, van Ruitenbeek P, Boisgontier MP, Monteiro TS, Maes C, Sunaert S, Swinnen SP. Anatomy of subcortical structures predicts age-related differences in skill acquisition. *Cereb Cortex*. 2018:28:459–473.

DiGirolamo GJ, Kramer AF, Barad V, Cepeda NJ, Weissman DH, Milham MP, Wszalek TM, Cohen NJ, Banich MT, Webb A, et al. General and task-specific frontal lobe recruitment in older adults during executive processes: a fMRI investigation of task-switching. *Neuroreport*. 2001:12:2065–2071.

Duncan J. The structure of cognition: attentional episodes in mind and brain. *Neuron*. 2013:80:35–50.

European Commission. *The 2021 ageing report*. In. Luxembourg: European Union. 2021.

Goble DJ, Coxon JP, Van Impe A, De Vos J, Wenderoth N, Swinnen SP. The neural control of bimanual movements in the elderly: brain regions exhibiting age-related increases in activity, frequency-induced neural modulation, and task-specific compensatory recruitment. *Hum Brain Mapp*. 2010:31:1281–1295.

Gordon BA, Tse CY, Gratton G, Fabiani M. Spread of activation and deactivation in the brain: does age matter? *Front Aging Neurosci*. 2014:6:288.

Grady CL, McIntosh AR, Bookstein F, Horwitz B, Rapoport SI, Haxby JV. Age-related changes in regional cerebral blood flow during working memory for faces. *NeuroImage*. 1998:8:409–425.

Hakun JG, Johnson NF. Dynamic range of frontoparietal functional modulation is associated with working memory capacity limitations in older adults. *Brain Cogn*. 2017:118:128–136.

Hermans EJ, Henckens MJ, Joels M, Fernandez G. Dynamic adaptation of large-scale brain networks in response to acute stressors. *Trends Neurosci*. 2014:37:304–314.

Hermans L, Levin O, Maes C, Van Ruitenbeek P, Heise K-F, Edden RAE, Puts NAJ, Peeters R, King BR, Meesen RLJ, et al. GABA levels and measures of intracortical and interhemispheric excitability in healthy young and older adults: a MRS-TMS study. *Neurobiol Aging*. 2018:65:168–177.

Heuninckx S, Wenderoth N, Debaere F, Peeters R, Swinnen SP. Neural basis of aging: the penetration of cognition into action control. *J Neurosci*. 2005:25:6787–6796.

Heuninckx S, Wenderoth N, Swinnen SP. Systems neuroplasticity in the aging brain: recruiting additional neural resources for successful motor performance in elderly persons. *J Neurosci*. 2008:28:91–99.

Holroyd CB, Yeung N. Motivation of extended behaviors by anterior cingulate cortex. *Trends Cogn Sci*. 2012:16:122–128.

Hugdahl K, Raichle ME, Mitra A, Specht K. On the existence of a generalized non-specific task-dependent network. *Front Hum Neurosci*. 2015:9:430.

Jenkinson M, Smith S. A global optimisation method for robust affine registration of brain images. *Med Image Anal*. 2001:5:143–156.

Jenkinson M, Bannister P, Brady M, Smith S. Improved optimization for the robust and accurate linear registration and motion correction of brain images. *NeuroImage*. 2002:17:825–841.

Jenkinson M, Beckmann CF, Behrens TE, Woolrich MW, Smith SM. Fsl. *NeuroImage*. 2012:62:782–790.

Jonides J, Schumacher EH, Smith EE, Lauber EJ, Awh E, Minoshima S, Koeppe RA. Verbal working memory load affects regional brain activation as measured by PET. *J Cogn Neurosci*. 1997:9:462–475.

King BR, van Ruitenbeek P, Leunissen I, Cuypers K, Heise KF, Santos Monteiro T, Hermans L, Levin O, Albouy G, Mantini D, et al. Age-related declines in motor performance are associated with decreased segregation of large-scale resting state brain networks. *Cereb Cortex*. 2018:28:4390–4402.

Klingberg T, O'Sullivan BT, Roland PE. Bilateral activation of fronto-parietal networks by incrementing demand in a working memory task. *Cereb Cortex*. 1997:7:465–471.

Koechlin E, Danek A, Burnod Y, Grafman J. Medial prefrontal and subcortical mechanisms underlying the acquisition of motor and cognitive action sequences in humans. *Neuron*. 2002:35:371–381.

Koen JD, Rugg MD. Neural dedifferentiation in the aging brain. *Trends Cogn Sci*. 2019:23:547–559.

Kong TS, Gratton C, Low KA, Tan CH, Chiarelli AM, Fletcher MA, Zimmerman B, Maclin EL, Sutton BP, Gratton G, et al. Age-related differences in functional brain network segregation are consistent with a cascade of cerebrovascular, structural, and cognitive effects. *Network Neurosci*. 2020:4:89–114.

Levin O, Weerasekera A, King BR, Heise KF, Sima DM, Chalavi S, Maes C, Peeters R, Sunaert S, Cuypers K, et al. Sensorimotor cortex neurometabolite levels as correlate of motor performance in normal aging: evidence from a (1)H-MRS study. *NeuroImage*. 2019:202:116050.

Li SC, Lindenberger U. Cross-level unification: A computational exploration of the link between deterioration of neurotransmitter systems and dedifferentiation of cognitive abilities in old age. In: Nilsson LG, Markowitsch HJ, editors. Hogrefe & Huber: Cognitive Neuroscience of Memory Seattle; 1999. pp. 103–146.

Li HJ, Hou XH, Liu HH, Yue CL, Lu GM, Zuo XN. Putting age-related task activation into large-scale brain networks: a meta-analysis of 114 fMRI studies on healthy aging. *Neurosci Biobehav Rev*. 2015:57:156–174.

Liu H, Wang L, Geng Z, Zhu Q, Song Z, Chang R, Lv H. A voxel-based morphometric study of age- and sex-related changes in white matter volume in the normal aging brain. *Neuropsychiatr Dis Treat*. 2016:12:453–465.

Logan JM, Sanders AL, Snyder AZ, Morris JC, Buckner RL. Under-recruitment and nonselective recruitment: dissociable neural mechanisms associated with aging. *Neuron*. 2002:33:827–840.

Madden DJ, Whiting WL, Provenzale JM, Huettel SA. Age-related changes in neural activity during visual target detection measured by fMRI. *Cereb Cortex*. 2004:14:143–155.

Maguire EA, Frith CD. Aging affects the engagement of the hippocampus during autobiographical memory retrieval. *Brain*. 2003:126:1511–1523.

Mattay VS, Fera F, Tessitore A, Hariri AR, Das S, Callicott JH, Weinberger DR. Neurophysiological correlates of age-related changes in human motor function. *Neurology*. 2002:58:630–635.

Mattay VS, Fera F, Tessitore A, Hariri AR, Berman KF, Das S, Meyer-Lindenberg A, Goldberg TE, Callicott JH, Weinberger DR. Neurophysiological correlates of age-related changes in working memory capacity. *Neurosci Lett*. 2006:392:32–37.

McIntosh AR, Sekuler AB, Penpeci C, Rajah MN, Grady CL, Sekuler R, Bennett PJ. Recruitment of unique neural systems to support visual memory in normal aging. *Curr Biol*. 1999:9:1275–1278.

Minati L, Grisoli M, Bruzzone MG. MR spectroscopy, functional MRI, and diffusion-tensor imaging in the aging brain: a conceptual review. *J Geriatr Psychiatry Neurol*. 2007:20:3–21.

Monteiro TS, Zivari Adab H, Chalavi S, Gooijers J, King BBR, Cuypers K, Mantini D, Swinnen SP. Reduced modulation of task-related connectivity mediates age-related declines in bimanual performance. *Cereb Cortex*. 2020:30:4346–4360.

Mustari MJ, Ono S, Das VE. Signal processing and distribution in cortical-brainstem pathways for smooth pursuit eye movements. *Ann N Y Acad Sci*. 2009:1164:147–154.

Nichols TE, Holmes AP. Nonparametric permutation tests for functional neuroimaging: a primer with examples. *Hum Brain Mapp*. 2001:15:1–25.

Nilsson LG. Memory function in normal aging. *Acta Neurol Scand Suppl*. 2003:179:7–13.

Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*. 1971:9:97–113.

Pauwels L, Chalavi S, Gooijers J, Maes C, Albouy G, Sunaert S, Swinnen SP. Challenge to promote change: the neural basis of the contextual interference effect in young and older adults. *J Neurosci*. 2018:38:3333–3345.

Persson J, Sylvester CY, Nelson JK, Welsh KM, Jonides J, Reuter-Lorenz PA. Selection requirements during verb generation: differential recruitment in older and younger adults. *NeuroImage*. 2004:23:1382–1390.

Pfefferbaum A, Rohlfing T, Rosenbloom MJ, Chu W, Colrain IM, Sullivan EV. Variation in longitudinal trajectories of regional brain volumes of healthy men and women (ages 10 to 85years) measured with atlas-based parcellation of MRI. *NeuroImage*. 2013:65:176–193.

Power JD, Barnes KA, Snyder AZ, Schlaggar BL, Petersen SE. Spurious but systematic correlations in functional connectivity MRI networks arise from subject motion. *NeuroImage*. 2012:59:2142–2154.

Ramanoel S, York E, Le Petit M, Lagrene K, Habas C, Arleo A. Age-related differences in functional and structural connectivity in the spatial navigation brain network. *Front Neural Circuits*. 2019:13:69.

Ray KL, McKay DR, Fox PM, Riedel MC, Uecker AM, Beckmann CF, Smith SM, Fox PT, Laird AR. ICA model order selection of task co-activation networks. *Front Neurosci*. 2013:7:237.

Reuter-Lorenz PA, Cappell KA. Neurocognitive aging and the compensation hypothesis. *Curr Dir Psychol Sci*. 2008:17:177–182.

Rypma B, Prabhakaran V, Desmond JE, Glover GH, Gabrieli JD. Load-dependent roles of frontal brain regions in the maintenance of working memory. *NeuroImage*. 1999:9:216–226.

Salimi-Khorshidi G, Douaud G, Beckmann CF, Glasser MF, Griffanti L, Smith SM. Automatic denoising of functional MRI data: combining independent component analysis and hierarchical fusion of classifiers. *NeuroImage*. 2014:90:449–468.

Sambataro F, Murty VP, Callicott JH, Tan HY, Das S, Weinberger DR, Mattay VS. Age-related alterations in default mode network: impact on working memory performance. *Neurobiol Aging*. 2010:31:839–852.

Santos Monteiro T, Beets IAM, Boisgontier MP, Gooijers J, Pauwels L, Chalavi S, King B, Albouy G, Swinnen SP. Relative cortico-subcortical shift in brain activity but preserved training-induced neural modulation in older adults during bimanual motor learning. *Neurobiol Aging*. 2017:58:54–67.

Schall JD. On the role of frontal eye field in guiding attention and saccades. *Vis Res*. 2004:44:1453–1467.

Scherder E, Dekker W, Eggermont L. Higher-level hand motor function in aging and (preclinical) dementia: its relationship with (instrumental) activities of daily life–a mini-review. *Gerontology*. 2008:54:333–341.

Seidler RD, Bernard JA, Burutolu TB, Fling BW, Gordon MT, Gwin JT, Kwak Y, Lipps DB. Motor control and aging: links to age-related brain structural, functional, and biochemical effects. *Neurosci Biobehav Rev*. 2010:34:721–733.

Serbruyns L, Gooijers J, Caeyenberghs K, Meesen RL, Cuypers K, Sisti HM, Leemans A, Swinnen SP. Bimanual motor deficits in older adults predicted by diffusion tensor imaging metrics of corpus callosum subregions. *Brain Struct Funct*. 2015:220:273–290.

Sisti HM, Geurts M, Clerckx R, Gooijers J, Coxon JP, Heitger MH, Caeyenberghs K, Beets IA, Serbruyns L, Swinnen SP. Testing multiple coordination constraints with a novel bimanual visuomotor task. *PLoS One*. 2011:6:e23619.

Smith SM. Fast robust automated brain extraction. *Hum Brain Mapp*. 2002:17:143–155.

Smith SM, Jenkinson M, Woolrich MW, Beckmann CF, Behrens TE, Johansen-Berg H, Bannister PR, De Luca M, Drobnjak I, Flitney DE, et al. Advances in functional and structural MR image analysis and implementation as FSL. *NeuroImage*. 2004:23(Suppl 1):S208–S219.

Staffaroni AM, Brown JA, Casaletto KB, Elahi FM, Deng J, Neuhaus J, Cobigo Y, Mumford PS, Walters S, Saloner R, et al. The longitudinal trajectory of default mode network connectivity in healthy older adults varies as a function of age and is associated with changes in episodic memory and processing speed. *J Neurosci*. 2018:38:2809–2817.

Storsve AB, Fjell AM, Tamnes CK, Westlye LT, Overbye K, Aasland HW, Walhovd KB. Differential longitudinal changes in cortical thickness, surface area and volume across the adult life span: regions of accelerating and decelerating change. *J Neurosci*. 2014:34:8488–8498.

Van Ruitenbeek P, Serbruyns L, Solesio-Jofre E, Meesen R, Cuypers K, Swinnen SP. Cortical grey matter content is associated with both age and bimanual performance, but is not observed to mediate age-related behavioural decline. *Brain Struct Funct*. 2017:222:437–448.

Vidal-Pineiro D, Valls-Pedret C, Fernandez-Cabello S, Arenaza-Urquijo EM, Sala-Llonch R, Solana E, Bargallo N, Junque C, Ros E, Bartres-Faz D. Decreased default mode network connectivity correlates with age-associated structural and cognitive changes. *Front Aging Neurosci*. 2014:6:256.

Ward NS, Frackowiak RS. Age-related changes in the neural correlates of motor performance. *Brain*. 2003:126:873–888.

Wiesmann U, Eisfeld K, Hannich HJ, Hirtz P. Motor competence and quality of life in elderly active persons. *Z Gerontol Geriatr*. 2004:37:377–386.

Woolrich MW, Jbabdi S, Patenaude B, Chappell M, Makni S, Behrens T, Beckmann C, Jenkinson M, Smith SM. Bayesian analysis of neuroimaging data in FSL. *NeuroImage*. 2009:45:S173–S186.

World-Medical-Association. *World medical association declaration of Helsinki: ethical principles for medical research involving human subjects*; In. Helsinki: World Medical Association, 1964, 1996, 2008, 2013.

Zapparoli L, Mariano M, Paulesu E. How the motor system copes with aging: a quantitative meta-analysis of the effect of aging on motor function control. *Commun Biol*. 2022:5:1–15.

Zivari Adab H, Chalavi S, Monteiro TS, Gooijers J, Dhollander T, Mantini D, Swinnen SP. Fiber-specific variations in anterior transcallosal white matter structure contribute to age-related differences in motor performance. *NeuroImage*. 2020:209:116530.