Graph-theoretical network analysis shows changes of functional brain connectivity in motor learning

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Introduction and methods

- Motor control is guided by sensory feedback to optimize concurrent motor performance.
- This study applied graph-theoretical network analysis (GTNA) (Bullmore and Sporns, 2009) to fMRI data to examine functional brain connectivity in the context of motor learning under different sensory feedback conditions (auditory and visual).
- Two age- and gender-matched groups ('AUD' and 'VIS') of right-handed adults (N=17+17, mean age 23) were trained on a bimanual flexion-extension '90 deg out-of-phase' coordination pattern (one hand led the other by a quarter-cycle) (Fig. 1a). This task requires intensive practice before it can be performed stably (Swinnen et al., 1997).
- Training feedback AUD group: high and low pitch tones (pitch = hand-coded) played back at the points of max. flexion or extension (subjects had to aim for 'galloping horse' pattern of these tones) (Fig 1b).
- Training feedback VIS group: Lissajous figure (Fig. 1b), each hand controlling one axis of the figure, optimal motor performance indicated by circular trajectory of the figure.
- fMRI scanning occurred before (day 0, PRE) + after (day 5, POST) training (Fig. 1c).
- For the GTNA, network nodes were defined by the fMRI activation foci (Fig. 3), selecting regions of interest (ROIs) by placing a sphere with radius 7.5 mm around the MNI coordinates of each ROI's activation maximum.
- For each subject, the average time series (AVT) for each ROI was extracted for PRE and POST runs. Based on the AVT data, matrices of partial correlations were calculated, quantifying the unique functional relationships between each pair of ROIs. Resulting network node connections were accepted as 'valid' below p<0.001.

Fig. 1

Study protocol

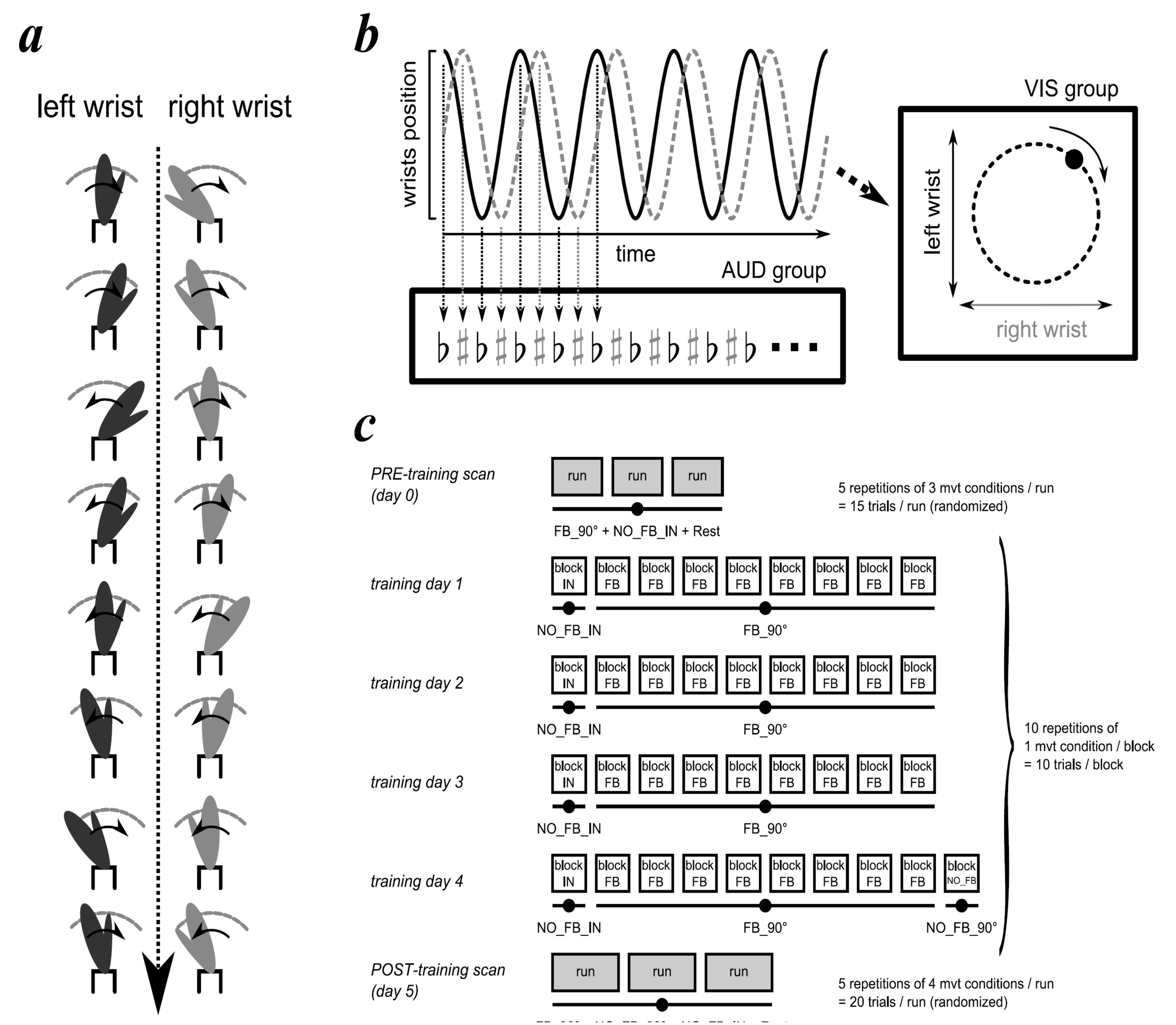
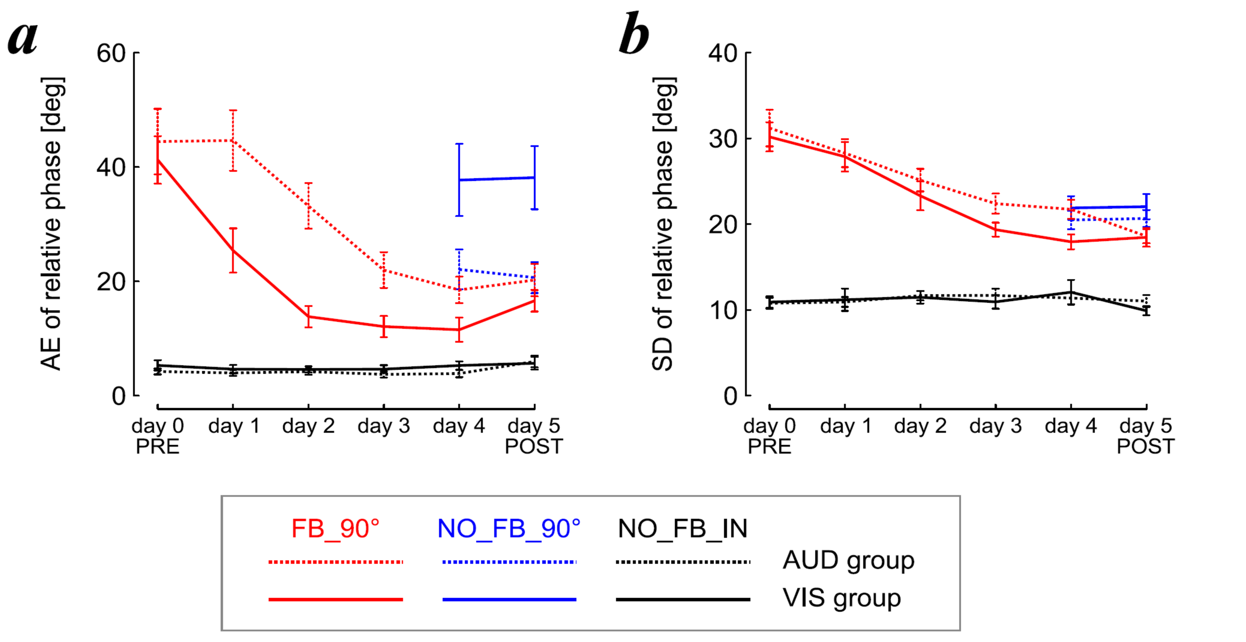
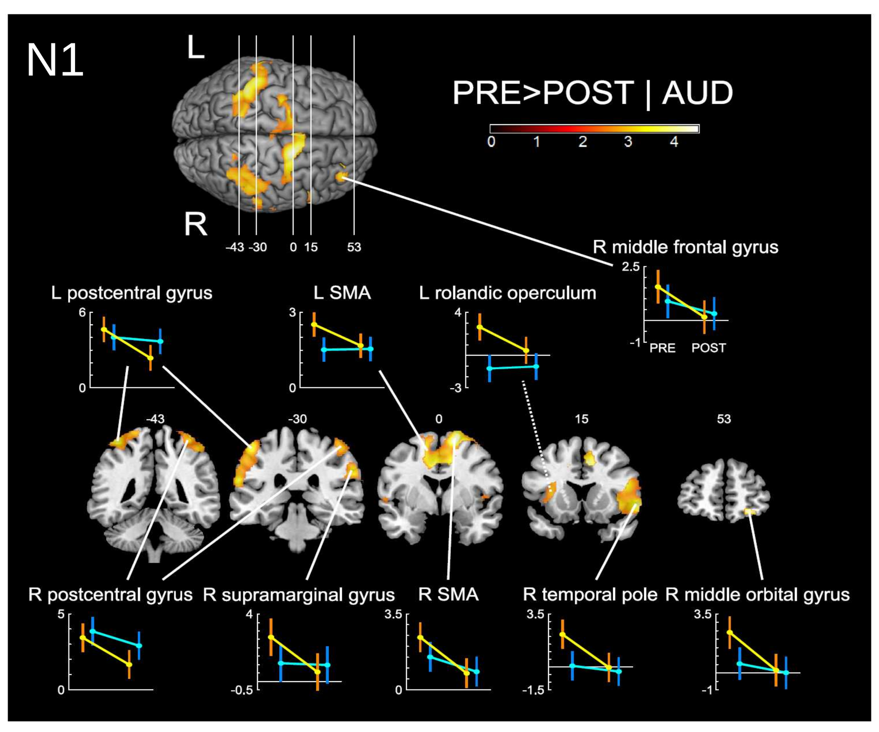
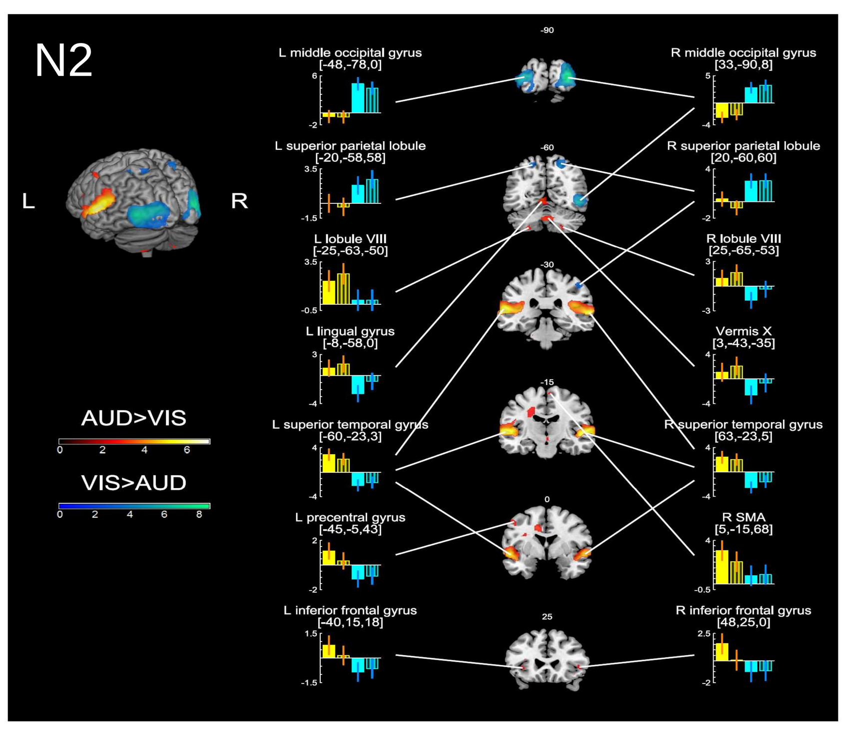


Fig. 2

Kinematic data







N3 Areas with significant practice-related decrease (PRE>POST) or increase (POST>PRE) for the two groups combined, during the execution of the FB_90° condition. These comparison tests reached $p < 0.05$ after correction for False Discovery Rate (FDR). L: left, R: right, BA: Brodmann Area.

Brain region	Side	Significant effect	Peak activation coordinate (MNI) X	Y	Z	BA	T-value
Primary sensory and (pre)motor cortex							
postcentral gyrus	L	PRE>POST	-50	-33	63	BA 1/2	3.69
Supplementary motor area							
superior frontal gyrus	R	PRE>POST	15	0	68	BA 6	4.48
Frontal and prefrontal area							
middle orbital gyrus	R	PRE>POST	30	50	-13	BA 11	3.89
middle frontal gyrus (DLPFC)	R	PRE>POST	43	43	25	BA 45	3.36
Occipital cortex							
superior occipital gyrus	R	POST>PRE	20	-103	18	BA 17	5.5
Temporal cortex							
middle temporal gyrus	L	PRE>POST	-58	-68	3	BA 37	3.94
temporal pole	R	PRE>POST	60	18	-8	BA 38	3.67
Parietal cortex							
superior parietal lobule	R	PRE>POST	50	-35	58	BA 1	4.21
supramarginal gyrus	L	PRE>POST	-65	-28	23	BA 48	3.61

Figure 3 - Network definitions (examples)
fMRI analyses resulted in 5 networks (Fig. 3 summarizes 3 of these networks), split into 2 types – networks of areas wherein both groups 'behaved' the same in terms of activation change PRE vs. POST in all network nodes (N3) and networks wherein both groups were not identical with regard to activation change PRE to POST (N1 and N2; for a list of all N1 & N2 network nodes see Fig.5). There was partial overlap between these networks. GTNA was applied to each of these networks in each participant to examine possible differences in improvement in GTNA measures between the networks and groups. **Line graph insets in N1:** BOLD response change PRE to POST for AUD (yellow) and VIS (cyan); **Bar plots in N2:** BOLD response for activated areas PRE (plain) and POST (hatched).

Results

- Motor performance in both groups improved similarly with training (Fig. 2)
- Similar learning effects on all GTNA measures in both groups with significant effects on all GTNA measures for SESSION (all p<0.00001) but no significant GROUP x SESSION interactions (statistical results were the same in all 5 networks and when combining the results across all networks, see Fig. 4).

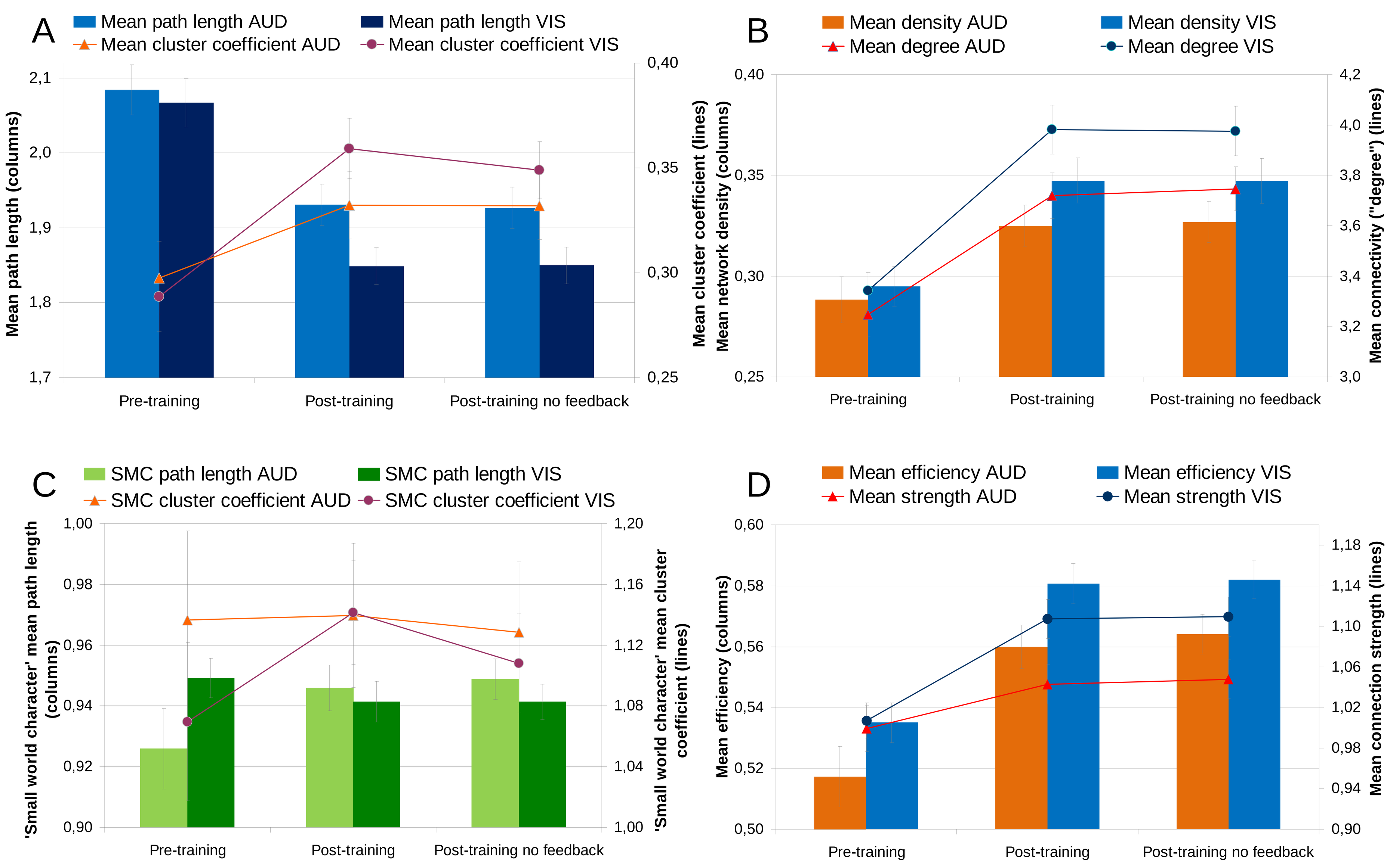


Figure 4 - Improvement in GTNA measures: Both groups had significant increases in cluster coefficients (A), connectivity degree + network density (B), together with decreases in mean path length (A). There were significant effects of GROUP for density, efficiency, and mean path length (all p<0.05), with the auditory group performing poorer than the visual group. The network functionality of both groups had 'small world character' PRE and POST (C). **Cluster coefficient** = measure of how well the neighbors of a network node are connected to each other (measure of network connectivity); **path length** = shortest connection between 2 network nodes (in no. of nodes); **network density** = proportion of the number of present connections in the network to the maximum possible number of connections; **efficiency** = composite of clustering coefficient and path length, based upon the calculation of the harmonic mean of neighbor-neighbor distances; **connectivity degree** = number of connections for individual nodes; **connection strength** = sum of connection weights as defined by the summed partial correlations for each network node.

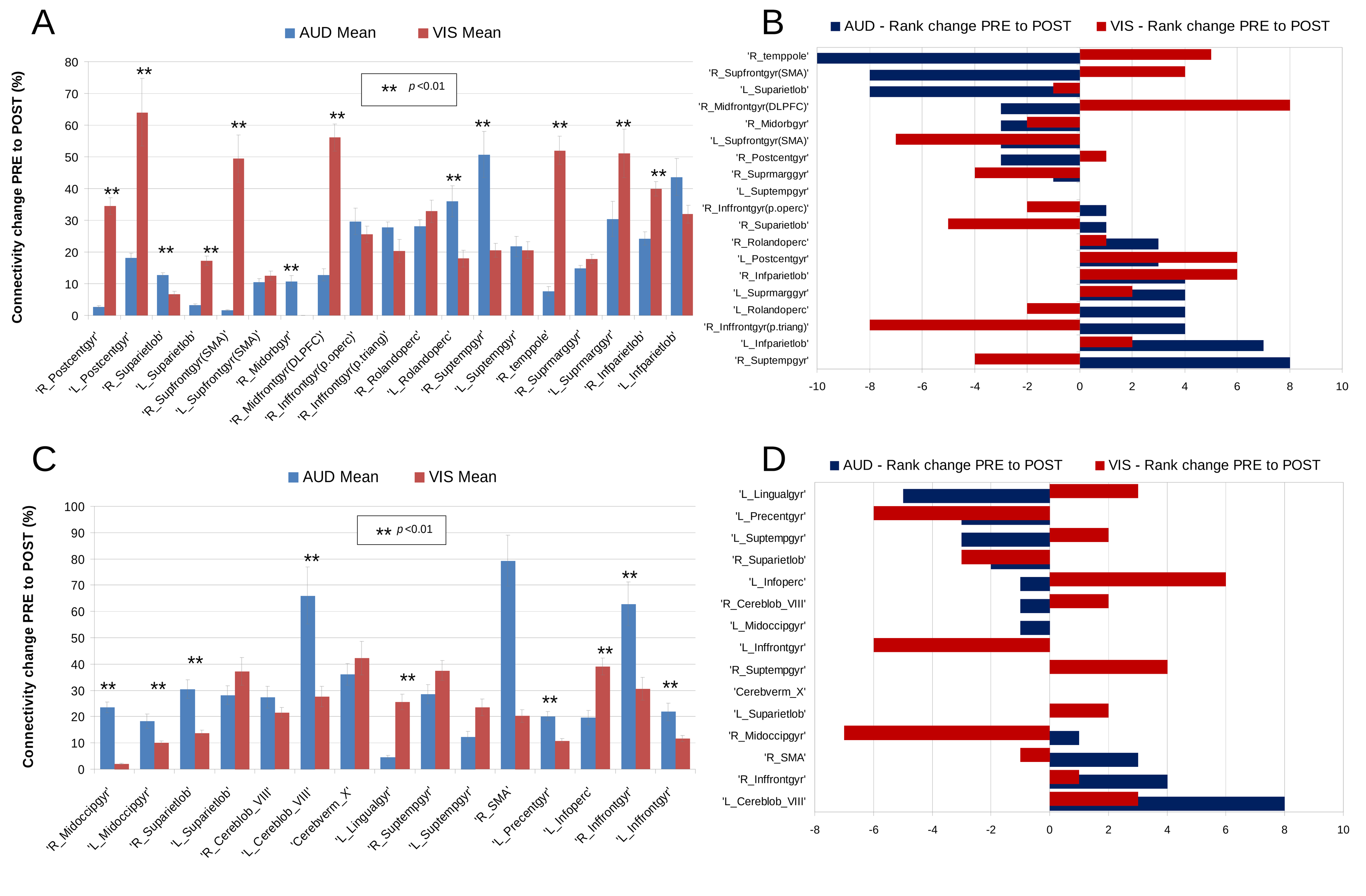


Figure 5 – Connectivity changes PRE to POST (two example networks – N1, see A+B, and N2, see C+D). The majority of network nodes showed an increased connectivity degree in both groups. However, both groups behaved differentially in changing the network integration of several brain regions from PRE to POST. Figures A and C illustrate the %-connectivity change for each of the different nodes/brain regions incorporated into the shown networks and significant group differences. Figures B and D illustrate the 'rank change' of each network region based on the change in connectivity degree (i.e., how the intra-network importance of each region in terms of number of connections changed from PRE to POST when ranking the regions based on their connectivity degree). Results in the other 3 networks showed similar differentiation effects.

Conclusions

- The GTNA measures show that mean network cohesion and functionality increased similarly in both groups as a result of training, indicating that comparable network optimisation can be associated with increases in brain activation (VIS group) but also predominant reduction in brain activation (AUD group).
- The consistent improvement on all network measures in both the AUD and VIS groups indicates that GTNA can detect and quantify the manifestations of motor training on a neural network level.
- The significant group effects for density, efficiency, and mean path length suggest that auditory feedback control may be associated with a slightly greater inertia in inducing performance improvement and subsequent changes in functional connectivity.
- GTNA measures, e.g., analyses of connectivity degree, can add additional information on brain function in motor control compared to more conventional fMRI analysis techniques.

References

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Swinnen SP, Lee TD, Verschueren S, Serrien DJ, Bogaerds H (1997) Interlimb coordination: Learning and transfer under different feedback conditions. Human Movement Science, 16: 749-785.