scientific reports

OPEN

The neural basis of intuitive approximate number system in board game Go (Baduk) experts

Taeyoung Lee[1,2,3,8], Hang Joon Jo[3,4,8], Minah Kim[2,5] & Jun Soo Kwon[2,6,7]✉

Studies have shown that newborns and nonhuman animals innately estimate quantities using the approximate number system (ANS), raising questions about whether the ANS is a precursor to advanced computational abilities or an independent cognitive function. Professional board game Go players, who can quickly judge territory sizes without explicit calculations, provide a unique insight into the ANS. Using fMRI, we investigated the neural correlates of the approximate number system in professional Go players. Results showed that during the difficult task, professional Go players exhibited significantly increased activity in the right cerebellum compared to the controls, while several parts of the cerebrum were activated during the easy task. The observed activation in the right cerebellum was inversely correlated with the number of years of training required to become professional players. The findings indicate that the ANS is either facilitated by training or reflects an inherent, exceptional ability in certain individuals, suggesting a cerebellar-based alternative to the computational role of the cerebral cortex.

Keywords Approximate number system, Expert brain, Cerebellum, Game of Go (Baduk)

Numerical cognition is the cognitive process involved in understanding and manipulating numerical information and is highly important in daily life. The foundational roots of numerical cognition are established in early developmental stages and undergo notable enhancement over time, particularly with the development of symbolic representation via language acquisition[1]. The triple code model, an extensive framework in the field of numerical cognition, posits three principal representational codes for numbers: the visual Arabic form, the auditory-verbal word frame, and analog nonsymbolic magnitude representations[2,3]. These codes play a crucial role in various tasks related to numerical cognition, including size comparisons, arithmetic calculations, and the processing of abstract numerical concepts. Previous investigations have predominantly focused on the first two codes, and specific neural correlates, including the occipitotemporal areas, inferior parietal areas, and perisylvian areas, have been shown to play pivotal roles in cognitive processes related to numerical operations[4,5]. Interestingly, research has shown that even newborns, who lack language and symbolic numerical concepts, and other nonhuman animals possess inherent cognitive capabilities for estimating object numerosity or quantity[6,7]. This finding underscores the approximate number system (ANS) as an integral aspect of numerical cognition, enabling humans to estimate and compare quantities without relying on precise counting or symbolic representation[8–10]. The intraparietal sulcus (IPS) is central to processing numerical magnitudes, as supported by convergent findings across methods, species, and ages[11–13]. However, the question remains as to whether the ANS serves merely as a transitional mechanism toward sophisticated mathematical operations that engage extensive brain cortical regions or whether it functions autonomously and intuitively without computational processing.

Although the IPS is traditionally regarded as a primary neural substrate for numerical cognition, growing evidence suggests that the cerebellum may also be involved in certain aspects of approximate number processing, particularly when tasks become more difficult or demand rapid judgments[14]. Recent neuroimaging and lesion studies have indicated that the cerebellum can be active during complex numerical tasks that extend beyond its

[1]Department of Psychiatry, Kyungpook National University School of Medicine, Daegu, Republic of Korea. [2]Institute of Human Behavioral Medicine, Seoul National University Medical Research Center, Seoul, Republic of Korea. [3]Department of Biomedical Engineering, Graduate School of Biomedical Science and Engineering, Seoul, Republic of Korea. [4]Department of Physiology, Hanyang University, Seoul, Republic of Korea. [5]Department of Neuropsychiatry, Seoul National University Hospital, Seoul, Republic of Korea. [6]Department of Psychiatry, Hanyang University Hospital, Seoul, Republic of Korea. [7]Department of Psychiatry, Hanyang University College of Medicine, 222-1, Wangsimni-ro, Seongdong-gu, Seoul 110-744, Republic of Korea. [8]Taeyoung Lee and Hang Joon Jo contributed equally to this work. ✉email: kwonjs@snu.ac.kr

established roles in motor coordination and procedural learning[15]. These findings propose that the cerebellum may facilitate the automatization of numeric or spatial routines, potentially supporting the IPS in tasks requiring high cognitive load or refined visuospatial skills[16,17]. Investigating how the cerebellum interacts with parietal regions in approximate number estimation could thus broaden our understanding of the neural architecture underlying the ANS.

In addition to investigations into developmental disorders, brain injuries, and neuropsychiatric disorders, the study of the brain's functionality by experts in various fields is gaining popularity. Research on experts spans various domains, including memory, computation, and motor skills[18,19]. Studying experts in board games such as chess and Go (Baduk) could provide distinct insight into the development of expertise, as these games engage brain functions that operate on fixed rules[20]. Go is a board game that has been popular in East Asia for thousands of years and has recently been further developed in the field of AI research, as exemplified by AlphaGo[21,22]. Go is a game in which two players take turns placing stones on a 19 × 19 board, trying to capture their opponent's stones or secure their own territory[23]. Players must estimate the size of the territory and strategize where to place the next stone. Professional Go players have a unique ability to make split-second judgments without counting the size of the territories. Professional Go players are excellent candidates for exploring the ANS due to their years of dedication, beginning in childhood, to learn how to discern the size of their territory intuitively and reflexively without reliance on arithmetic calculations.

In this study, we investigated the neural correlates of approximate number system in professional Go players using functional magnetic resonance imaging (fMRI). Our research aimed to elucidate how the brain processes numerical intuition independently of higher cognitive functions, thereby advancing our understanding of the cerebral mechanisms underpinning numerical cognition. Specifically, we hypothesized that Go expertise would be associated with enhanced ANS acuity, reflected in faster and more accurate approximate numerical judgments, and that this enhancement would manifest in distinct neural activity patterns. In addition to examining known parietal contributions, we focused on whether Go experts would show greater cerebellar activation during more difficult ANS tasks. We also expected that the duration of Go training would correlate with more efficient neural mechanisms as expertise increases, providing further insight into how both cortical and cerebellar circuits might be shaped by long-term practice.

Materials and methods

Participants

To enroll Go experts, we targeted Go professionals with the cooperation of the Korean Baduk (Go) Association. Twenty-three experts (mean age = 22.7, SD = 3.2, range = 19 to 33) and twenty controls matched for age, sex, handedness, and IQ received verbal and written information about the study and provided informed consent. The inclusion criteria for board game experts were professional Go players certified by the Korean Baduk Association, while the control group was composed of healthy individuals who had never played the Go board game. The exclusion criteria included the presence of any irremovable metallic objects, history of head trauma with loss of consciousness for more than an hour, neurologic disorders, psychiatric disorders, or recent psychotropic medication use. The demographic characteristics of each group are presented in Table 1. The present study was approved by the Institutional Review Board of Seoul National University Hospital, Seoul, Korea (no. 1207-090-418) and was conducted in accordance with the Helsinki Declaration of 1975, as revised in 2008.

Stimuli and tasks

Participants performed a block-designed visual decision-making task. For the task, we used the board game "Go," which is commonly played in Asia. In Go, the board generally consists of 19 horizontal and 19 vertical lines, and stones are placed at the intersections of these lines, thus there are a total of 361 houses on a Go board. The spots where the stones can be placed are called "houses" or "territory." When a territory is completely surrounded by my stones and no one else can enter it, this territory becomes my own. For more detailed information on the rules and strategies of Go, please refer to the following webpage[24]. Few studies have directly investigated the cognitive functions required for playing Go; however, longitudinal research on the effects of Go has reported its contribution to working memory, attention and executive function[25,26]. In this study, a smaller Go board with 9 horizontal and 9 vertical lines, containing 81 houses, was used as the visual stimulus. The Go board was filled with black stones, and visual stimuli presenting territories of 6, 16, 18, and 20 houses were prepared. Participants were shown two Go boards with different numbers of houses during each trial and were asked which board had the larger territory. The study included tasks with two difficulty levels: an easy task in which anyone could recognize and distinguish at a glance, and a difficult task that was difficult to distinguish without counting exactly (Fig. 1A). In the easy task, the territory sizes in the visual stimulus were 20 and 6, and the difference in

	Experts (n = 23)	Controls (n = 20)	p value
Female	0 (0%)	2 (10%)	0.120
Age	22.8 (3.3)	21.2 (1.8)	0.060
Education (years)	13.1 (2.0)	14.0 (1.3)	0.091
IQ	107.7 (12.9)	110.2 (11.4)	0.539
Training duration (years)	15.9 (3.4)		

Table 1. Demographic characteristics of the experts and controls. The values are presented as the means (standard deviations).

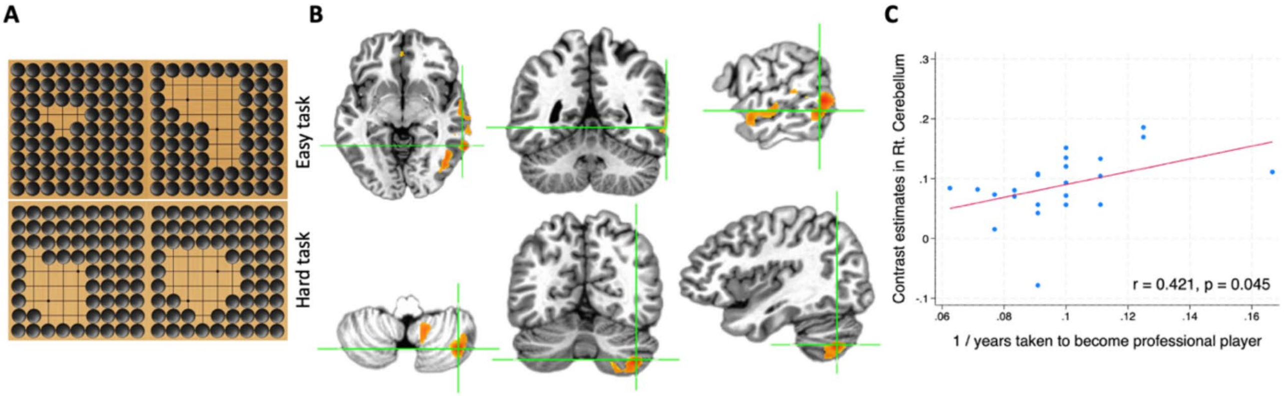

Fig. 1. (**A**) The top two images depict an easy task, while the bottom two images depict a hard task in the Game of Go. (**B**) There was a significant group difference in activation maps between board game experts and healthy control subjects. The overlaid colors indicate areas (specifically, the right cerebellum: regions VII, VIII, IX, and Crux II) where the activity level for the hard task in the expert group was greater than that in the control group. (**C**) A shorter duration between the start of training and the Game of Go to becoming a professional player (inverse of years to become a professional) was associated with greater contrast estimates in the right cerebellum ($r=.0.421$, $p=0.045$).

size of 14 houses was easily distinguishable. For the difficult task, the territory sizes were 16 and 18, which was a difference of 2 houses and was hard to distinguish at first glance without actually counting the stones. Each block consisted of 24 easy trials and 24 difficult trials. The fixation time was 3,000 ~ 5,000 ms. The stimuli were presented for 800 ms. After presenting the visual stimulus, the subject was given a response time of 800 ms to choose which picture had a larger territory. Each participant completed a total of six sessions, consisting of two easy tasks and four difficult tasks. Each session lasted 220 s, resulting in a total experimental duration of 1,320 s (22 min) per participant. One of the most common tasks in ANS research involves determining which of two clusters of randomly distributed points contains a greater number of points[27,28]. Our task of comparing the size of territories in a Go game is quite similar to this ANS task. We designed this study under the assumption that Go professionals possess highly developed ANS capabilities.

Data acquisition and processing, and quality assurance

BOLD signal was acquired using a 3T Siemens Trio MRI scanner (Siemens Healthcare, Erlangen, Germany) with T2-weighted gradient echo planar imaging. A total of 110 functional images were acquired (repetition time [TR] = 2,000 ms; echo time [TE] = 30 ms; flip angle = 90°; isotropic voxel size of 3 mm^3; 27 axial slices). T1-weighted (T1W) images were obtained in the sagittal plane using a three-dimensional magnetization-prepared rapid acquisition gradient echo (3D MPRAGE) sequence with the following parameters: isotropic voxel size of 1 mm^3, repetition time (TR) = 1,670 ms, echo time (TE) = 1.89 ms, flip angle = 9°, and 208 slices.

The functional imaging data were preprocessed and analyzed using the Analysis of Functional NeuroImaging (AFNI) package[29]. We performed despking to account for any potential rapid head motion in the EPI data[30], and then removed physiological noise using PESTICA (Physiologic EStimation by Temporal ICA)[31]. The first four images of each fMRI run were discarded. Slice timing correction was performed using a middle slice as a reference, and images within each run were aligned to the first image of the first run to correct for head motion. All imaging data were spatially normalized to the MNI N27 brain template[32] and then spatially smoothed using a Gaussian kernel with a FWHM of 6 mm. The 13 noise time series extracted to remove physiological noise during preprocessing (8 for RETROICOR and 5 for RVT)[33,34] and the 6 head motion estimates (3 translations and 3 rotations) were later used in regression analysis along with the task design matrix. All images and processed interim results were assessed by AFNI quality control reports[35]. EPI time points with head-motion displacement over 0.3 mm and/or overall intensity change over 10% outliers were statistically censored in the analysis stage. In this study, the outlier time points accounted for less than 2% of the total time points per session.

Analysis

At the individual subject level, we estimated neural activity for each experimental condition using a general linear model. This model incorporated both the task blocks, and the periods designated for instructions and ratings. The primary interest of the current study was neural activation during approximate numerical calculations. Given the two-by-two design of the experiment (two groups; two task difficulties for each group), interactions between the experimental factors were both expected and observed. For the group-level analysis, a two-sample t test was performed to observe the difference between control subjects and professional Go players. To explore these interactions, we contrasted images of BOLD signal changes associated with task difficulties for each subject and used these contrasts as inputs for a two-sample t-test. The statistical results were corrected for multiple comparisons using a familywise error-corrected threshold of $p<.05$. Following this, we identified clusters showing significant differences in the group and interaction statistics map and extracted beta coefficients for each participant within these clusters. We then used Spearman correlation analysis to examine

Anatomical region	Cluster volume (mm^3)	MNI coordinates			z value	*p* value
		x	y	z		
Right superior, middle temporal gyrus	14,013	−64.5	49.5	−3.5	4.29	0.000018
Right middle, posterior cingulate cortex	4131	1.5	34.5	11.5	3.34	0.000838
Left rectal gyrus, bilateral orbital gyrus	2970	4.5	-43.5	−12.5	3.8	0.000145
Right cerebellum (VIII, IX, VII, Crus 2)	3861	−37.5	61.5	−42.5	3.97	0.000072

Table 2. Peak coordinates of significant between-group brain activations between go professional players and healthy comparison subjects.

Anatomical region	Cluster volume (mm^3)	MNI coordinates			z value	*p* value
		x	y	z		
Left and right Lingual gyri and Precuneus	317	-1.5	55.5	11.5	3.59	0.0003
Left and right medial orbitofrontal gyri / Rostral anterior cingulate cortex	309	-1.5	−43.5	2.5	3.46	0.0005
Right inferior parietal gyrus /Suparamarginal gyrus	240	-52.5	49.5	44.5	3.30	0.001
Right postcentral gyrus /Precentral gyrus	158	-37.5	61.5	−42.5	3.97	0.0008
Bilateral frontal pole	121	7.5	-64.6	−3.5	3.11	0.0019
Right thalamus	118	−7.5	31.5	5.5	3.51	0.0004
Right lateral occipital gyrus /Middle temporal gyrus	117	−49.5	70.5	-3.5	3.15	0.0016
Left entorhinal cortex /Lateral orbitofrontal gyrus	110	19.5	−1.5	−15	3.45	0.0006

Table 3. Peak coordinates of significant interaction effects between go professional players and healthy comparison subjects across easy and hard tasks.

the relationship between these neural activity scores from significant clusters and the inverse of the duration taken by participants to achieve certification as professional players by the Korean Go Association, starting from their initial Go training.

Results

During the easy-level task of approximate numerical calculations, a significant increase in activity in the right superior and middle temporal gyri, middle and posterior cingulate corteces, left rectal gyrus, and bilateral orbital gyri was observed in the expert group compared to the control group (Fig. 1; Table 2). During the hard-level task, however, the expert group showed a significant increase in activity in the right cerebellum (VII, VIII, IX, and Crux II) compared to the control group. To rule out the possibility of deactivation effects, we examined the activation maps for each group and session using a one-sample t-test. However, we did not find any significant results. In the analysis of interaction effects, significant activation was observed in several brain regions in the expert group; however, no significant activation was found in the cerebellum (Table 3). The contrast estimates in the right cerebellum showed a significant inverse correlation with the number of years required to become a professional player ($r = .421$, $p = .045$).

Discussion

In this research, we examined the neural basis of the approximate number system by subjecting board game experts to tasks requiring instantaneous approximate calculation at two levels of complexity. The findings indicate that the right superior and middle temporal gyri, middle and posterior cingulate cortices, left rectal gyrus, and bilateral orbital gyri were engaged during the simpler task, whereas the right cerebellum was more active during the more challenging task. The level of activation in the right cerebellum was significantly associated with the time required to achieve their level of expertise. The involvement of the cerebellum in tasks requiring approximate calculations offers new insights into the neural mechanisms underlying expert ability in the cognition of numbers that do not involve symbols or linguistic systems.

The primary finding of this research was that activity in the right cerebellum was significantly greater during high-demand approximate numerical calculation tasks among board game experts than among controls. This pattern suggests that as the demand for numerical approximation increases, the cerebellum facilitates rapid and accurate computations necessary for high-level strategic gameplay. Traditionally, the cerebellum has been associated primarily with motor control and coordination[36,37], whereas regions such as the IPS and the superior parietal lobe are typically highlighted for their robust activation during arithmetic operations involving numerical signs and symbols, possibly engaging linguistic processing[38–40]. Our results, however, revealed that despite the IPS's well-established role in both symbolic and nonsymbolic number processing[11,13], the cerebellum—rather than the IPS—showed especially pronounced activation as the approximate calculations became more difficult. This aligns with recent work revealing the cerebellum is implicated in complex cognitive and affective functions, including rapid, intuitive decision-making[18,19], and may act as a complementary or alternative pathway under high-cognitive-load conditions. Research with children demonstrates cerebellar engagement in nonsymbolic numerical processing[3,41,42], although this contribution may be overshadowed by higher-level cognitive functions as language and arithmetic skills develop[43]. Moreover, studies on developmental dyscalculia indicate that mathematical ability often relies on cooperation between the cerebellum and the cerebrum[44], and various brain circuits involving the cerebellum are engaged in arithmetic, reinforcing its role in bolstering cognitive abilities[45,46]. In light of this, our findings do not negate the longstanding emphasis on the IPS but indicate that the cerebellum may be selectively or additionally recruited under highly demanding conditions. Consequently, the cerebellum may complement cortical processes by performing specialized and intuitive computations, particularly in nonverbal and nonsymbolic estimation contexts. It is plausible that Go experts, through extensive practice, employ a cerebellar-based mechanism for rapid approximate judgments, whereas more routine tasks may continue to rely on the IPS-centered parietal network. Future studies are warranted to clarify how these networks dynamically interact during varying levels of cognitive load and expertise in numerical cognition.

Our findings indicate a significant group effect in cerebellar activation, suggesting that Go experts and control participants may utilize cerebellar functions differently during approximate numerical calculations. However, the absence of a significant interaction effect requires careful interpretation. One possible explanation is that the cerebellum's involvement with the approximate number system (ANS) may be relatively independent of task difficulty. Rather than modulating cerebellar activation in a continuous manner with increasing task complexity, the cerebellum might engage more fundamentally in supporting motor or procedural aspects once a certain threshold of difficulty is reached. Additionally, it is possible that the task difficulty levels employed in our study were not sufficiently calibrated to reveal interaction effects. Specifically, the simpler tasks might not have required meaningful cerebellar engagement, thus masking any potential differential effects between groups. Future studies should consider employing a wider range of task difficulties to clarify the cerebellum's role in these cognitive processes. Despite these limitations, the observed group differences emphasize the cerebellum's significant role in the cognitive strategies employed by Go experts. These results provide valuable insights into cerebellar involvement in numerical approximation and suggest that the mechanisms at play may be more nuanced than initially hypothesized. Our findings contribute to a deeper understanding of how expertise shapes cerebellar activation patterns, paving the way for future research to explore these complex interactions further.

Our analysis revealed an inverse association between the extent of right cerebellar activation and the time required for participants to achieve professional status. Our findings diverge from previous research suggesting that consistent training enhances brain function and contributes to neural plasticity[47–49]. This finding suggests two possible interpretations: either the cerebellum's numerical processing capacity can be condensed training over a short period, or inherent individual differences in cerebellar functionality predispose certain individuals to achieve expertise more quickly than others. When considering innate factors, the potential for children to excel in sports can often be seen early on and is largely influenced by genetic factors[50]. Longitudinal studies on athletes suggest that early motor skills or cerebellar function may be associated with athletic performance in adulthood[51,52]. Moreover, inborn traits present from infancy may act as a foundation for further musical development over time[53]. Based on these findings, our results suggest that a shorter duration to reach a certain level, rather than a reduced period of training, combined with enhanced cerebellar ability for approximate numerical calculations, contributes to a quicker attainment of Go expertise. The inverse correlation between cerebellar activation and the number of years of training suggests a refined tuning of neural efficiency with increased expertise. This could indicate that as Go players advance, they rely more on ingrained, intuitive processes rather than conscious, deliberate calculations. However, our study is a cross-sectional examination of cerebellar activation and achievement levels. To substantiate these findings, well-designed longitudinal studies will be necessary.

By highlighting the role of the cerebellum, our findings suggest possible dual-network involvement in numerical cognition, where both cortical and cerebellar regions are crucial, particularly in the context of professional expertise that requires rapid and accurate numerical approximations. The observed cerebellar activity could reflect an automatization of cognitive processes, a hallmark of expert performance in many domains[54–56]. These processes are likely honed through repetitive practice or innate talent and may become so routine and automatic that they involve distinct neural pathways from those used by novices.

While our findings are promising, they also highlight several areas for further research. Although the sample size was adequate for detecting significant cerebellar activity, it could be expanded in future studies to explore variability in neural adaptation across a broader demographic. Additionally, longitudinal studies could elucidate how these neural mechanisms develop over time with training and whether early intervention or training in specific strategies can enhance the efficiency of these neural networks. Moreover, various approaches, such as fMRIPrep, ICA-AROMA techniques, have been explored to minimize noise, highlighting the need to investigate the reliability of studies using a broader range of preprocessing methods[57]. The relationship between cerebellar functionality and other cognitive skills in Go players, such as spatial awareness and decision-making under pressure, could also be explored in future research to determine whether there are common neural substrates enhanced across these cognitive domains. Additionally, studies employing more precise designs to examine various factors related to interaction effects will be necessary. Comparing these results with those obtained from experts in other board games, such as chess, or from individuals in fields that heavily rely on both approximate and precise numerical calculations, such as mathematicians, could provide deeper insights into the generalizability and specificity of cerebellar involvement in expert cognition.

Conclusions

Our study indicated that the cerebellum plays a significant role in the numerical cognitive functions of highly trained individuals. It supports existing theories of numerical cognition and extends them by illustrating the cerebellum's potential role in facilitating intuitive and automatic processing of numerical approximations.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 30 May 2024; Accepted: 14 April 2025
Published online: 12 May 2025

References

1. Vanbinst, K., Ceulemans, E., Peters, L., Ghesquiere, P. & De Smedt, B. Developmental trajectories of children's symbolic numerical magnitude processing skills and associated cognitive competencies. *J. Exp. Child. Psychol.* **166**, 232–250. https://doi.org/10.1016/j.jecp.2017.08.008 (2018).
2. Dehaene, S. *The Number Sense: How the Mind Creates Mathematics* (OUP USA, 2011).
3. Skagenholt, M., Traff, U., Vastfjall, D. & Skagerlund, K. Examining the triple code model in numerical cognition: an fMRI study. *PLoS One.* **13**, e0199247. https://doi.org/10.1371/journal.pone.0199247 (2018).
4. Moeller, K., Willmes, K. & Klein, E. A review on functional and structural brain connectivity in numerical cognition. *Front. Hum. Neurosci.* **9** https://doi.org/10.3389/fnhum.2015.00227 (2015).
5. Pesenti, M., Thioux, M., Seron, X. & De Volder, A. Neuroanatomical substrates of Arabic number processing, numerical comparison, and simple addition: a PET study. *J. Cogn. Neurosci.* **12**, 461–479. https://doi.org/10.1162/089892900562273 (2000).
6. Dehaene, S., Dehaene-Lambertz, G. & Cohen, L. Abstract representations of numbers in the animal and human brain. *Trends Neurosci.* **21**, 355–361. https://doi.org/10.1016/s0166-2236(98)01263-6 (1998).
7. Howard, S. R., Avargues-Weber, A., Garcia, J. E., Greentree, A. D. & Dyer, A. G. Numerical cognition in honeybees enables addition and Subtraction. *Sci. Adv.* **5**, eaav0961. https://doi.org/10.1126/sciadv.aav0961 (2019).
8. Odic, D. & Starr, A. An introduction to the approximate number system. *Child. Dev. Perspect.* **12**, 223–229. https://doi.org/10.1111/cdep.12288 (2018).
9. Park, J. & Brannon, E. M. Training the approximate number system improves math proficiency. *Psychol. Sci.* **24**, 2013–2019. https://doi.org/10.1177/0956797613482944 (2013).
10. Dietrich, J. F., Huber, S. & Nuerk, H. C. Methodological aspects to be considered when measuring the approximate number system (ANS) - a research review. *Front. Psychol.* **6**, 295. https://doi.org/10.3389/fpsyg.2015.00295 (2015).
11. Faye, A. et al. Numerical cognition: A meta-analysis of neuroimaging, transcranial magnetic stimulation and brain-damaged patients studies. *Neuroimage Clin.* **24**, 102053. https://doi.org/10.1016/j.nicl.2019.102053 (2019).
12. Ashkenazi, S., Henik, A., Ifergane, G. & Shelef, I. Basic numerical processing in left intraparietal sulcus (IPS) acalculia. *Cortex* **44**, 439–448. https://doi.org/10.1016/j.cortex.2007.08.008 (2008).
13. Hubbard, E. M. et al. The evolution of numerical cognition: from number neurons to linguistic quantifiers. *J. Neurosci.* **28**, 11819–11824. https://doi.org/10.1523/JNEUROSCI.3808-08.2008 (2008).
14. Stoodley, C. J. & Schmahmann, J. D. Functional topography in the human cerebellum: a meta-analysis of neuroimaging studies. *Neuroimage* **44**, 489–501. https://doi.org/10.1016/j.neuroimage.2008.08.039 (2009).
15. De Smet, H. J., Paquier, P., Verhoeven, J. & Marien, P. The cerebellum: its role in Language and related cognitive and affective functions. *Brain Lang.* **127**, 334–342. https://doi.org/10.1016/j.bandl.2012.11.001 (2013).
16. Saban, W., Pinheiro-Chagas, P., Borra, S. & Ivry, R. B. Distinct contributions of the cerebellum and basal ganglia to arithmetic procedures. *J. Neurosci.* **44** https://doi.org/10.1523/JNEUROSCI.1482-22.2023 (2024).
17. Miri Ashtiani, S. N. & Daliri, M. R. Identification of cognitive load-dependent activation patterns using working memory task-based fMRI at various levels of difficulty. *Sci. Rep.* **13**, 16476. https://doi.org/10.1038/s41598-023-43837-w (2023).
18. Calvo-Merino, B., Glaser, D. E., Grezes, J., Passingham, R. E. & Haggard, P. Action observation and acquired motor skills: an FMRI study with expert dancers. *Cereb. Cortex.* **15**, 1243–1249. https://doi.org/10.1093/cercor/bhi007 (2005).
19. Tanaka, S., Michimata, C., Kaminaga, T., Honda, M. & Sadato, N. Superior digit memory of abacus experts: an event-related functional MRI study. *Neuroreport* **13**, 2187–2191. https://doi.org/10.1097/00001756-200212030-00005 (2002).
20. Wan, X. et al. The neural basis of intuitive best next-move generation in board game experts. *Science* **331**, 341–346. https://doi.org/10.1126/science.1194732 (2011).
21. Chen, J. X. The evolution of computing: AlphaGo. *Comput. Sci. Eng.* **18**, 4–7. https://doi.org/10.1109/mcse.2016.74 (2016).
22. Jung, W. H., Lee, T. Y., Yoon, Y. B., Choi, C. H. & Kwon, J. S. Beyond Domain-Specific expertise: neural signatures of face and Spatial working memory in Baduk (Go Game) experts. *Front. Hum. Neurosci.* **12**, 319. https://doi.org/10.3389/fnhum.2018.00319 (2018).
23. Benson, D. B. Life in the game of go. *Inf. Sci.* **10**, 17–29 (1976).
24. Association, K. B. *How to play Baduk*. http://english.baduk.or.kr/sub02_02 (2024).
25. Iizuka, A. et al. Pilot randomized controlled trial of the GO game intervention on cognitive function. *Am. J. Alzheimers Dis. Other Demen.* **33**, 192–198. https://doi.org/10.1177/1533317517753362 (2018).
26. Chen, X. et al. A functional MRI study of high-level cognition. II. The game of GO. *Brain Res. Cogn. Brain Res.* **16**, 32–37. https://doi.org/10.1016/s0926-6410(02)00206-9 (2003).
27. Van Herwegen, J., Ranzato, E., Karmiloff-Smith, A. & Simms, V. Eye movement patterns and approximate number sense task performance in Williams syndrome and down syndrome: A developmental perspective. *J. Autism Dev. Disord.* **49**, 4030–4038. https://doi.org/10.1007/s10803-019-04110-0 (2019).
28. Libertus, M. E., Forsman, L., Aden, U. & Hellgren, K. Deficits in approximate number system acuity and mathematical abilities in 6.5-Year-Old children born extremely preterm. *Front. Psychol.* **8**, 1175. https://doi.org/10.3389/fpsyg.2017.01175 (2017).
29. Cox, R. W. AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. *Comput. Biomed. Res.* **29**, 162–173. https://doi.org/10.1006/cbmr.1996.0014 (1996).
30. Jo, H. J. et al. Effective preprocessing procedures virtually eliminate distance-dependent motion artifacts in resting state FMRI. *J. Appl. Math.* **2013**. https://doi.org/10.1155/2013/935154 (2013).
31. Shin, W., Koenig, K. A. & Lowe, M. J. A comprehensive investigation of physiologic noise modeling in resting state fMRI; time shifted cardiac noise in EPI and its removal without external physiologic signal measures. *Neuroimage* **254**, 119136. https://doi.org/10.1016/j.neuroimage.2022.119136 (2022).
32. Mazziotta, J. et al. A probabilistic atlas and reference system for the human brain: international consortium for brain mapping (ICBM). *Philos. Trans. R Soc. Lond. B Biol. Sci.* **356**, 1293–1322. https://doi.org/10.1098/rstb.2001.0915 (2001).
33. Glover, G. H., Li, T. Q. & Ress, D. Image-based method for retrospective correction of physiological motion effects in fMRI: RETROICOR. *Magn. Reson. Med.* **44**, 162–167. (2000).
34. Birn, R. M., Diamond, J. B., Smith, M. A. & Bandettini, P. A. Separating respiratory-variation-related fluctuations from neuronal-activity-related fluctuations in fMRI. *Neuroimage* **31**, 1536–1548. https://doi.org/10.1016/j.neuroimage.2006.02.048 (2006).
35. Reynolds, R. C., Taylor, P. A. & Glen, D. R. Quality control practices in FMRI analysis: philosophy, methods and examples using AFNI. *Front. Neurosci.* **16**, 1073800. https://doi.org/10.3389/fnins.2022.1073800 (2022).
36. Paulin, M. G. The role of the cerebellum in motor control and perception. *Brain Behav. Evol.* **41**, 39–50. https://doi.org/10.1159/000113822 (1993).

37. Manto, M. et al. Consensus paper: roles of the cerebellum in motor control–the diversity of ideas on cerebellar involvement in movement. *Cerebellum* **11**, 457–487. https://doi.org/10.1007/s12311-011-0331-9 (2012).
38. Butterworth, B. Foundational numerical capacities and the origins of dyscalculia. *Trends Cogn. Sci.* **14**, 534–541. https://doi.org/10.1016/j.tics.2010.09.007 (2010).
39. Cohen, L., Dehaene, S., Chochon, F., Lehericy, S. & Naccache, L. Language and calculation within the parietal lobe: a combined cognitive, anatomical and fMRI study. *Neuropsychologia* **38**, 1426–1440. https://doi.org/10.1016/s0028-3932(00)00038-5 (2000).
40. Rivera, S. M., Reiss, A. L., Eckert, M. A. & Menon, V. Developmental changes in mental arithmetic: evidence for increased functional specialization in the left inferior parietal cortex. *Cereb. Cortex*. **15**, 1779–1790. https://doi.org/10.1093/cercor/bhi055 (2005).
41. Kucian, K. et al. Impaired neural networks for approximate calculation in dyscalculic children: a functional MRI study. *Behav. Brain Funct.* **2**, 31. https://doi.org/10.1186/1744-9081-2-31 (2006).
42. Kucian, K., von Aster, M., Loenneker, T., Dietrich, T. & Martin, E. Development of neural networks for exact and approximate calculation: a FMRI study. *Dev. Neuropsychol.* **33**, 447–473. https://doi.org/10.1080/87565640802101474 (2008).
43. Barth, H. et al. Non-symbolic arithmetic in adults and young children. *Cognition* **98**, 199–222. https://doi.org/10.1016/j.cognition.2004.09.011 (2006).
44. Vandervert, L. The origin of mathematics and number sense in the cerebellum: with implications for finger counting and dyscalculia. *Cerebellum Ataxias* **4** https://doi.org/10.1186/s40673-017-0070-x (2017).
45. Liu, J. et al. The neural circuits for arithmetic principles. *Neuroimage* **147**, 432–446. https://doi.org/10.1016/j.neuroimage.2016.12.035 (2017).
46. Vandervert, L. & Moe, K. The cerebellum-driven social basis of mathematics: implications for one-on-one tutoring of children with mathematics learning disabilities. *Cerebellum Ataxias*. **8**, 13. https://doi.org/10.1186/s40673-021-00136-2 (2021).
47. Maguire, E. A., Frackowiak, R. S. & Frith, C. D. Recalling routes around London: activation of the right hippocampus in taxi drivers. *J. Neurosci.* **17**, 7103–7110. https://doi.org/10.1523/JNEUROSCI.17-18-07103.1997 (1997).
48. Draganski, B. et al. Neuroplasticity: changes in grey matter induced by training. *Nature* **427**, 311–312. https://doi.org/10.1038/427311a (2004).
49. Kramer, A. F. & Erickson, K. I. Capitalizing on cortical plasticity: influence of physical activity on cognition and brain function. *Trends Cogn. Sci.* **11**, 342–348. https://doi.org/10.1016/j.tics.2007.06.009 (2007).
50. Pickering, C. & Kiely, J. ACTN3: more than just a gene for speed. *Front. Physiol.* **8**, 1080. https://doi.org/10.3389/fphys.2017.01080 (2017).
51. Manto, M., Manto, M. U. & Pandolfo, M. *The Cerebellum and its Disorders* (Cambridge University Press, 2002).
52. Leyhr, D., Kelava, A., Raabe, J. & Honer, O. Longitudinal motor performance development in early adolescence and its relationship to adult success: an 8-year prospective study of highly talented soccer players. *PLoS One*. **13**, e0196324. https://doi.org/10.1371/journal.pone.0196324 (2018).
53. Zuk, J., Vanderauwera, J., Turesky, T., Yu, X. & Gaab, N. Neurobiological predispositions for musicality: white matter in infancy predicts school-age music aptitude. *Dev. Sci.* **26**, e13365. https://doi.org/10.1111/desc.13365 (2023).
54. Schmahmann, J. D. From movement to thought: anatomic substrates of the cerebellar contribution to cognitive processing. *Hum. Brain Mapp.* **4**, 174–198, (1996).
55. Doyon, J. et al. Role of the striatum, cerebellum and frontal lobes in the automatization of a repeated visuomotor sequence of movements. *Neuropsychologia* **36**, 625–641. https://doi.org/10.1016/s0028-3932(97)00168-1 (1998).
56. Puttemans, V., Wenderoth, N. & Swinnen, S. P. Changes in brain activation during the acquisition of a multifrequency bimanual coordination task: from the cognitive stage to advanced levels of automaticity. *J. Neurosci.* **25**, 4270–4278. https://doi.org/10.1523/JNEUROSCI.3866-04.2005 (2005).
57. Esteban, O. et al. fMRIPrep: a robust preprocessing pipeline for functional MRI. *Nat. Methods*. **16**, 111–116. https://doi.org/10.1038/s41592-018-0235-4 (2019).

Acknowledgements
This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2021M3E5D2A0102249311; 2021R1A2C1006718; 2022R1A2C1092667).

Author contributions
TL designed the study, recruited the subjects, collected the data, analyzed the data, drew the image and wrote the manuscript. HJJ analyzed the data and wrote the manuscript. MK recruited the subjects, collected the data, and wrote the manuscript. JSK designed the study and wrote the manuscript. All authors reviewed and revised the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to J.S.K.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.