Developmental fronto-parietal shift of brain activation during mental arithmetic across the lifespan: A registered report protocol

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Abstract

Arithmetic processing is represented in a fronto-parietal network of the brain. However, activation within this network undergoes a shift from domain-general cognitive processing in the frontal cortex towards domain-specific magnitude processing in the parietal cortex. This is at least what is known about development from findings in children and young adults. In this registered report, we set out to replicate the fronto-parietal activation shift for arithmetic processing and explore for the first time how neural development of arithmetic continues during aging. This study focuses on the behavioral and neural correlates of arithmetic and arithmetic complexity across the lifespan, i.e., childhood, where arithmetic is first learned, young adulthood, when arithmetic skills are already established, and old age, when there is lifelong arithmetic experience. Therefore, brain activation during mental arithmetic will be measured in children, young adults, and the elderly using functional near-infrared spectroscopy (fNIRS). Arithmetic complexity will be manipulated by the carry and borrow operations in two-digit addition and subtraction. The findings of this study will inform educational practice, since the carry and borrow operations are considered as obstacles in math achievement, and serve as a basis for developing interventions in the elderly, since arithmetic skills are important for an independent daily life.

Introduction

Arithmetic skills are acquired in school and are later important for everyday life. Hence, it is essential to better understand the underlying mechanisms of these skills not only in children, who just learnt these skills, and in adults, who have already established their arithmetic skills, but also in the elderly, because deficits in these skills have a detrimental impact on their independent life. Therefore, the current study sets out to investigate the behavioral and neural correlates of arithmetic across the lifespan.

Arithmetic is represented in a fronto-parietal network in the brain [1, for meta-analyses in children and adults see 2, for a review in children see 3, for a model and its extensions in adults see 4, 5], but the extent of frontal and parietal activation in this network changes during
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processing—the continuous carry and borrow operations instead require place-value activation [20]. Continuous processing characteristics of the carry operation are indicated by the unit sum (e.g., $58 + 36$ has a unit sum of $8 + 6 = 14$), which theoretically ranges from 0 to 18 (carry operation necessary when unit sum $\geq 10$); continuous processing characteristics of the borrow operation are indicated by the unit difference (e.g., $94 - 36$ has a unit difference of $4 - 6 = -2$), which theoretically ranges from $-9$ to $+9$ (borrow operation necessary when unit difference $< 0$). The carry operation is characterized by both categorical and continuous processing characteristics [31, 36]. The nature of the borrow operation, however, remains unclear, since continuous processing characteristics might not necessarily increase the difficulty of subtraction in a similar way as it is the case for addition [37].

During development, children get better in arithmetic and place-value processing [38, for a review see 39]. Children learn the carry and borrow operations for single-digit and two-digit arithmetic in the first two years of elementary school and afterwards are able to use these skills [27]. Place identification, the first level of place-value processing, serves as a precursor for arithmetic performance and place-value computation later in elementary school [29]. The carry and borrow effects decrease during adolescence from grade 5 to 7 and to young adulthood [30], but not before [8, 27, 40]. Besides general increases in reaction times and error rates during aging, the carry and borrow operations are not impaired and might be even superior in older as compared to younger adults, as reflected by similar or smaller carry and borrow effects [32, 33, 41]. This reflects a general decrease in the carry and borrow effects during lifespan development with increasing proficiency in place-value processing. Furthermore, the underlying processing characteristics for these effects might change, since the carry and borrow effects seem to be categorical effects in elementary school children [27], while the carry effect in young adults relies on continuous processing characteristics as well, as assessed by the unit sum [26, 31, 36]. This suggests that primarily domain-general processes are driving the carry and borrow effects in children, while in young adults, domain-specific processes are additionally driving the carry effect. Considering the general cognitive decline during aging, the carry and borrow effects might be mainly driven by domain-specific processes in the elderly, but empirical evidence is still missing. The next step is now to replicate the developmental changes of arithmetic in general and place-value computation in particular (i.e., carry and borrow effects), to identify the underlying processing characteristics (i.e., categorical and continuous aspects) across the lifespan, and to complement the behavioral findings by neural data.

The neural representation of the carry and borrow effects is located in the fronto-parietal network of arithmetic processing [26]. Mainly, carry and borrow effects are associated with higher prefrontal activation in the left IFG and bilateral MFG [23–26, 42, 43], mostly reflecting domain-general demands like working memory for task difficulty due to the categorical effects [44, 45]. Additionally, parietal activation, particularly in the left IPS, was observed with increasing unit sum or when carry and borrow effects were confounded with problem size, mostly reflecting domain-specific magnitude processing associated with the continuous effects [23, 24, 26]. Furthermore, the only study on the neural correlates of the carry and borrow effects that was not conducted in young adults found the left AG to be reversely related to the carry effect in adolescents, reflecting the role of arithmetic fact retrieval for decomposed addition [8]. Taken together, the carry and borrow effects are associated with increases in frontal and parietal activation. Due to the developmental fronto-parietal shift in brain activation for arithmetic in general, the neural activation might also change for processing arithmetic complexity. For instance, frontal activation associated with the carry and borrow operations might decrease during lifespan development due to automatization, since the use of domain-general processes becomes more efficient from childhood to adulthood, and the general cognitive decline restricts further efficient use of domain-general processes during aging. On the other
hand, a study on interindividual differences in math ability showed that smaller behavioral carry and borrow effects might be associated with larger neural effects (in high- as compared to low-skilled individuals), since high-skilled individuals efficiently used the frontal resources for the carry and borrow operations whereas low-skilled individuals needed these resources even for problems without carry or borrow operation [25]. Thus, a decrease of the behavioral carry and borrow effects during lifespan development—with individuals getting better in the carry and borrow operations—might be associated with an increase in the neural carry and borrow effects in frontal brain regions. The current study aims to investigate the behavioral and neural correlates of the carry and borrow effects in children, young adults, and the elderly, and to explore developmental changes.

Arithmetic processing in general and the carry and borrow effects in particular are represented in a fronto-parietal network of arithmetic processing. Here, we address the question of how arithmetic and the underlying brain activation in the arithmetic network change during development across the lifespan. The study will target crucial stages of development: elementary school children in grades 3 and 4, because they just acquired the skills for two-digit arithmetic and thus serve as a starting point of lifespan development, young adults, because they have already established their arithmetic skills and thus serve as a reference for development, and the elderly, because they are experienced in using their arithmetic skills but might show a general cognitive decline and thus serve as a final point of lifespan development. A neural activation shift is hypothesized from frontal activation, mostly representing domain-general processes, to parietal activation, mostly representing domain-specific numerical processes, during development. Using three different approaches [29], we address the following hypotheses on behavioral and neural levels:

- H1: In a task-based approach, arithmetic performance is expected to be better in young adults than in children and in the elderly. According to the developmental fronto-parietal shift for arithmetic processing, children should show increased frontal activation (left IFG and bilateral MFG) and less parietal activation (left IPS) in comparison to young adults, replicating previous research. Moreover, the neural correlates of arithmetic will be explored in the elderly: if the developmental fronto-parietal shift generalizes to the whole lifespan, the elderly might show less frontal activation (left IFG and bilateral MFG) and increased parietal activation (left IPS) in comparison to young adults; however, if arithmetic is not affected by aging or is affected and needs compensation, the elderly might show similar or increased frontal activation and similar or less parietal activation in comparison to young adults.

- H2: In an effect-based approach, the carry and borrow effects are expected to decrease arithmetic performance on a behavioral level (i.e., reaction times and error rates) and to be associated with larger frontal activation (left IFG and bilateral MFG) on a neural level in all age groups. Regarding the lifespan development, the behavioral carry and borrow effects are expected to be larger in children than in young adults and larger or similar in young adults as compared to the elderly, replicating previous research. The neural development of the effects will be explored here for the first time: the neural carry and borrow effects might either decrease during the lifespan, reflecting the fronto-parietal activation shift particularly for complex arithmetic, or increase during the lifespan, reflecting the more efficient use of frontal resources with increasing performance.

- H3: In an effect-based approach on the underlying processing characteristic, the carry and borrow effects are expected to be rather categorical in children, both categorical and continuous in young adults, and rather continuous in the elderly. On a neural level, the continuous
carry and borrow effects (unit sum and unit difference) should rely on parietal activation (left IPS) in all age groups.

The carry and borrow effects will be investigated concerning arithmetic complexity in two-digit addition and subtraction, respectively. The processes underlying these arithmetic operations are similar, while subtraction is more difficult than addition [25]. However, there is not yet evidence for operation-specific differences in relation to lifespan development. To assess brain activation during two-digit arithmetic, the optical neuroimaging method fNIRS will be used. Compared to fMRI, fNIRS is less restrictive, allows an upright body position, and is relatively insensitive to motion artifacts--but at the cost of a lower spatial and depths resolution [46]. The current study makes use of the advantages of fNIRS to study arithmetic in an ecological valid task paradigm (verbal production) in critical populations such as children and the elderly.

Methods

Participants

Three age groups will be considered: children (3rd and 4th grade), young adults (18–34 years), and the elderly (above 60 years). Each age group will be characterized by age (M, SD, Range), gender, and education. All subjects will be right-handed, native German speakers (or at least school education in German), with no history of neurological or mental disorders, and without a disease that influences brain metabolism. Informed consent will be obtained from all adult participants, from the parents of the participating children, and from the participating children in a simplified way. For participation, all subjects will receive monetary compensation and the children additionally a little present. The study was approved by the Ethics Committee for Psychological Research of the University of Tuebingen.

To emphasize the focus on healthy aging in the current study, elderly subjects will additionally be assessed by the Montreal Cognitive Assessment [MoCA; 47], which is a brief cognitive screening tool for mild cognitive impairment. This instrument measures cognitive abilities such as short-term memory, visuo-spatial and executive functions, attention, language, and orientation to time and space. A cut-off score of ≥ 26 (Theoretical Range = 0–30 with correction in case of education years ≤ 12) will be used to exclude cognitive impairment in elderly. Additionally, processing speed, working memory, and verbal and non-verbal intelligence will serve as control measures to compare general cognitive abilities between the age groups.

Arithmetic task

The arithmetic task will consist of two-digit addition and subtraction problems with two operands resulting in a two-digit solution [https://osf.io/6emdy/]. The carry and borrow operations will be manipulated categorically, i.e., addition problems with and without carrying (e.g., 51 + 43 vs. 58 + 36) as well as subtraction problems with and without borrowing (e.g., 94–43 vs. 94–36), and continuously, i.e., unit sum in addition (e.g., 14 in 58 + 36) and unit difference in subtraction (e.g., –2 in 94–36).

The stimulus set consists of 128 arithmetic problems with 32 trials per condition, i.e., addition with/without carrying and subtraction with/without borrowing. The stimulus generation will consider unit sum in addition and unit difference in subtraction to be relatively equally distributed. This means that addition problems \((a + b = r)\) cannot be directly transformed by inversion into subtraction problems \((r - b = a)\). Nevertheless, the numerical properties will be matched across conditions: \(a\) and \(b\) will be closely matched in their numerical magnitude and
parity; the position of the larger operand will be counterbalanced; pure decades as well as ties within and between $a$, $b$, and $r$ will be excluded [25, 42, for decades see 48, for ties see 49].

The task will be computerized in the program OpenSesame [50]. Each arithmetic problem will be presented centered in white against a black background. In an oral production paradigm, the subjects will be asked to mentally solve the problem as quickly and accurately as possible and to respond while pressing the space bar. Button press and button release will be recorded and the experimenter will blindly note the given responses. Each stimulus will be presented with a time limit of 30 s and disappear upon button press to emphasize mental arithmetic before responding. In the inter-trial interval, a black screen will be shown with a duration of 4–7 s (jittered in steps of 0.5 s, mean of 5.5 s), including a white fixation point in the last 0.5 s. The 128 trials will be presented in 4 runs of 32 trials each (8 trials per condition) and the trial order will be pseudorandomized for every subject with no more than two trials of the same condition presented consecutively. As dependent variables, error rates (ER) are defined as the number of incorrectly solved and time-out trials divided by the total number of completed trials, and reaction times (RT) as the duration between stimulus onset and button press.

Cognitive tests

Processing speed will be assessed by the subtest symbol search of the German version of the Wechsler Adult Intelligence Scale IV [WAIS-IV; 51]. In this paper-pencil test, subjects will be asked to decide whether or not two target symbols are present among a group of five symbols. The overall time limit is 120 s for a maximum of 60 items. The raw score (Theoretical Range = 0–60) is defined as the number of correctly solved items minus the number of incorrectly solved items (unsolved items are not considered). The retest reliability of the German version is good ($r_{rt} = .81$).

Working memory will be assessed by a verbal 2-back paradigm with letters [https://osf.io/6emdy/; 52]. The task is computerized in the program OpenSesame [50]. In this task, subjects will be asked to determine for every letter (consonants in lower and upper case) whether it matches the letter presented two positions before or not by a button press. The 92 trials consist of 30 match trials (match to the letter presented two positions before), 48 mismatch trials (no match to a letter presented one to five positions before), 6 1-back lures (match to the letter presented one position before), 6 3-back lures (match to the letter presented three positions before), and 2 start letters (presented first). Each stimulus will be presented until the button press with a time limit of 2.5 s followed by an SOA of 3 s. Accuracy (ACC) will be defined as the number of correct trials divided by the total number of trials, and RT as the duration between stimulus onset and button press. Note that the comparison between the groups will focus on ACC.

Intelligence will be assessed by the German version of the Reynolds Intellectual Screening Test [RIST; 53], consisting of subtests for verbal and nonverbal intelligence. Depending on age, each subtest is started at a certain item (with the option of going back to preceding items until two consecutive items are correctly solved in the first attempt) and stopped when three consecutive items are not correctly solved. In the subtest “guess what”, indicating verbal intelligence, subjects are orally asked to find out the concept that matches the given two to four clues. With a maximum of 62 orally presented items, the raw score (Theoretical Range = 0–62) is defined as the sum of all correctly solved items (including the unsolved items before the age-dependent start item). In the subtest “odd item out”, indicating nonverbal intelligence, subjects are asked to choose the picture that does not belong to the set of five to seven pictures. The time limit is 30 s for the first attempt and 20 s for the second attempt (if incorrectly or unsolved in the first attempt), with a maximum of 51 visually presented items. The raw score
Theoretical Range = 0–102) is calculated as the double sum of all correctly solved items in the first attempt (including the unsolved items before the age-dependent start item) and the single sum of all correctly solved items in the second attempt. Raw scores for both subtests will be further transformed into T scores ($M = 50$, $SD = 10$) dependent on German age norms and converted into IQ scores ($M = 100$, $SD = 15$). The reliability of the German version is good (Cronbach’s $\alpha$ of .92 for verbal intelligence and .90 for nonverbal intelligence).

**Procedure**

During the fNIRS measurements, the arithmetic task will be conducted in a light-attenuated room. Afterwards, processing speed, working memory, and intelligence will be assessed. Each test is preceded by instructions and practice items. The practice phase of the arithmetic task will consist of 12 trials to familiarize the subjects with the response format (which can be repeated). In the end, a screening of cognitive abilities will be conducted for older adults only.

**fNIRS data acquisition**

The NIRS data will be acquired using the continuous wave ETG-4000 Optical Topography System (Hitachi Medical Corporation, Tokyo, Japan). This fNIRS device uses wavelengths of $695 \pm 20$ nm and $830 \pm 20$ nm as light sources and a sampling rate of 10 Hz. The optodes (10 sources and 8 detectors) will be embedded in a cap (Brain Products GmbH, Herrsching, Germany) with an inter-optode distance of 30 mm. The probesets will consist of 4 parietal channels (IPS, SMG, AG) and 5 frontal channels (MFG, IFG) per hemisphere (see Fig 1), which is a

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![Fig 1. fNIRS probesets covering frontal and parietal areas of the left and right hemisphere. The probesets were fixed at P3/P4 and oriented towards F3/F4; the positions of channels and optodes (sources and detectors) including empty positions are marked [cf. 25]. Abbreviations of the channel labels: IFG—inferior frontal gyrus, MFG—middle frontal gyrus, SPL/IPS—superior parietal lobule/intraparietal sulcus, SMG—supramarginal gyrus, AG—angular gyrus.

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subset of channels that were previously used as a probeset [for more details on the location about the probeset see 25]. The correspondence of fNIRS channels to the underlying cortical areas was estimated based on a virtual registration method [54–56] and labeled according to the automated anatomic labeling (AAL) atlas [57].

Data analysis

Data exclusion for subjects. Subjects will be excluded from all analysis when the inclusion criteria are not met (regarding age, handedness, language, health, and, for elderly subjects, cognition), when more than 50% of the behavioral data of the arithmetic task is missing (due to drop out or experimental or technical problems), or when the error rate in the arithmetic task is larger than 50% (because of the exclusion of incorrectly solved trials). Moreover, an outlier analysis will be conducted specific to the respective age group to exclude subjects deviating more than 3 median absolute deviations from the group’s median in RT of the arithmetic task from all analysis [58]. Subjects will be excluded only from neural data analysis in case of more than 50% missing neural data of the arithmetic task (due to drop out, experimental or technical problems, trial exclusion and artifact rejection), or in case of more than 3 noisy channels (restricting channel interpolation to a maximum of 3 channels). Furthermore, a case-wise exclusion of subjects from the respective analysis of the demographic variables (age, gender, education) or control measures (processing speed, working memory, and verbal and non-verbal intelligence) applies in case of missing or incomplete data, or an ACC below 33% in the working memory task.

Data exclusion for trials. Trials will be excluded from the RT analysis (arithmetic and working memory task) as well as from the fNIRS analysis (arithmetic task) when the trial was not correctly solved, when the RT was below 200 ms (anticipations), when the RT deviates more than 3 median absolute deviations from the subject’s median in the respective task, and when the duration between button press and button release deviates more than 3 median absolute deviations from the subject’s median in the arithmetic task [58].

fNIRS data preprocessing. The relative concentration changes of oxygenated (O$_2$Hb) and deoxygenated hemoglobin (HHb) will be calculated for every fNIRS channel. The fNIRS signal will be preprocessed by using the temporal derivative distribution repair (TDDR; 59) to correct for high-amplitude motion artifacts and by applying a bandpass filter of 0.005–0.2 Hz. To reduce low-amplitude motion artifacts, correlation-based signal improvement (CBSI; 60) will be used, which is based on the negative correlation between O$_2$Hb and HHb and is considered one of the best artifact correction methods [61]. Next, remaining noisy channels will be interpolated by surrounding channels, and incorrectly solved trials as well as trials containing uncorrectable artifacts will be excluded.

To analyze the fNIRS data within a model-based approach, the peak latency of the hemodynamic response function will be determined by the overall maximum across channels, subjects, and conditions [in the interval between 4 and 10 s rounded to half a second; 25]. In the model-based approach, a general linear model will be computed for each channel, subject, and condition according to the hemodynamic response function. For every region of interest (10 ROIs: IFG, MFG, IPS, AG, SMG on the left and right hemisphere), the channel with the highest resulting beta value based on the grand average across conditions and subjects will be used for the statistical analysis of the neural data.

Statistical data analysis. This study applies Bayesian hypothesis testing and thus Bayes factors (BF) are calculated that determine how much more likely the observed data will be under the alternative hypothesis (H$_1$) as compared to the null hypothesis (H$_0$) for $BF_{10}$ (evidence for a difference when $BF_{10} > 1$) and vice versa for $BF_{01}$ (evidence for no difference when
Bayes factor design analysis

For sample size estimation, the sequential Bayes factor design with maximal $n$ will be used [65, 66]. In this design, data collection (1) will start with a minimum sample size of $n_{\text{min}} = 20$ per group, (2) will continue until a $BF_{10}$ or $BF_{01} \geq 6$ is obtained for all effects of interest, or (3) will be stopped when a maximum sample size of $n_{\text{max}} = 60$ per group has been reached. The properties of the planned research design were estimated with Monte Carlo simulations according to Schönbrodt and Wagenmakers [65]: The minimum sample size was set for reducing false positive rates, and the maximum sample size was set to ensure feasibility, while 80% of studies with an infinite sequential sampling stop earlier than $n_{\text{max}}$. If sampling is terminated because of reaching $n_{\text{max}}$ only with a probability of 5% will the study obtain misleading evidence. This design detects an expected medium effect size of $\delta = 0.5$ with a probability of 61% before the $n_{\text{max}}$ is reached. The chosen medium effect size accounts for the bias of small samples in the reported large effect sizes ($\delta \approx 0.5$) for differences between children, young adults, and the elderly in the neural distance effect [67, for large effect sizes ($d \approx 1.2–1.6$) see also for children vs. adults: 68, for younger adults vs. the elderly: 69].

The effects of interest according to the hypotheses include the main effect of age (ANOVAs) for RT and activation in left IFG, bilateral MFG, and left IPS according to H1; the main effect of complexity and the interaction effect of complexity and age (ANOVAs) for RT and activation in left IFG and bilateral MFG according to H2; the categorical carry/borrow effect and the
continuous effect of unit sum/difference in each age group (regressions) in RT and neural activation in left IPS according to H3.

Proposed timeline
After in-principle-acceptance of the registered report in stage I, data collection can start whenever the current global pandemic situation permits testing with children and elderly subjects. Data collection is estimated to last 1 year (planned for September 2021 – August 2022), followed by approximately 3 months for data analysis and preparation of the registered report for stage II (planned for September–November 2022).

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References
1. Arsalidou M, Taylor MJ. Is 2+2 = 4? Meta-analyses of brain areas needed for numbers and calculations. Neuroimage. 2011; 54: 2382–93. https://doi.org/10.1016/j.neuroimage.2010.10.009 PMID: 20946958
2. Arsalidou M, Pawliw-Levac M, Sadeghi M, Pascual-Leone J. Brain areas needed for numbers and calculations in children: Meta-analyses of fMRI studies. Dev Cogn Neurosci. 2017; 1–12. https://doi.org/10.1016/j.dcn.2017.08.002 PMID: 28644728
3. Peters L, De Smedt B. Arithmetic in the developing brain: A review of brain imaging studies. Dev Cogn Neurosci. 2017; 0–1. https://doi.org/10.1016/j.dcn.2017.05.002 PMID: 28566139
4. Dehaene S, Piazza M, Pinel P, Cohen L. Three parietal circuits for number processing. Cogn Neuropsychol. 2003; 20: 487–506. https://doi.org/10.1080/02643290244000239 PMID: 20957581
5. Klein E, Suchan J, Moeller K, Karnath HO, Knops A, Wood G, et al. Considering structural connectivity in the triple code model of numerical cognition: differential connectivity for magnitude processing and arithmetic facts. Brain Struct Funct. 2016; 221: 979–995. https://doi.org/10.1007/s00429-014-0951-1 PMID: 25432772
6. Rivera SM, Reiss AL, Eckert MA, Menon V. Developmental changes in mental arithmetic: evidence for increased functional specialization in the left inferior parietal cortex. Cereb cortex. 2005; 15: 1779–90. https://doi.org/10.1093/cercor/bhi055 PMID: 15716474
7. Ansari D, Garcia N, Lucas E, Hamon K, Dhital B. Neural correlates of symbolic number processing in children and adults. Neuroreport. 2005; 16: 1769–1773. https://doi.org/10.1097/01.wnr.0000183905.23396.f1 PMID: 16237324
8. Artemenko C, Soltanlou M, Ehils AC, Nuerk HC, Dresler T. The neural correlates of mental arithmetic in adolescents: A longitudinal fNIRS study. Behav Brain Funct. 2018; 14: 1–13. https://doi.org/10.1186/s12939-017-0133-4 PMID: 29296719
9. Chang T-T, Metcalfe AWS, Padmanabhan A, Chen T, Menon V. Heterogeneous and nonlinear development of human posterior parietal cortex function. Neuroimage. 2016; 126: 184–195. https://doi.org/10.1016/j.neuroimage.2015.11.053 PMID: 26655682
10. Kucian K, von Aster M, Lobbestra T, Dietrich T, Martin E. Development of neural networks for exact and approximate calculation: a FMRI study. Dev Neuropsychol. 2008; 33: 447–73. https://doi.org/10.1080/87565640802101474 PMID: 18568899
11. Kaufmann L, Wood G, Rubinstein O, Henik A. Meta-analyses of developmental fMRI studies investigating typical and atypical trajectories of number processing and calculation. Dev Neuropsychol. 2011; 36: 763–87. https://doi.org/10.1080/87565641.2010.549884 PMID: 21761997
12. Grabner RH, Ansari D, Koschatnig K, Reishofer G, Ebner F, Neuper C. To retrieve or to calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem solving. Neuropsychologia. 2009; 47: 604–8. https://doi.org/10.1016/j.neuropsychologia.2008.10.013 PMID: 19007800
13. Menon V. Developmental cognitive neuroscience of arithmetic: implications for learning and education. ZDM Math Educ. 2010; 42: 515–525. https://doi.org/10.1007/s11858-010-0242-0 PMID: 22003371
14. Salthouse TA, Atkinson TM, Berish DE. Executive Functioning as a Potential Mediator of Age-Related Cognitive Decline in Normal Adults. J Exp Psychol Gen. 2003; 132: 566–594. https://doi.org/10.1037//0096-3445.132.4.566 PMID: 14640849
15. Lemke U, Zimprich D. Longitudinal Changes in Memory Performance and Processing Speed in Old Age abstract Keywords Longitudinal Changes in Memory Performance and Processing Speed in Old Age. Aging, Neuropsychol Cogn. 2005; 12: 57–77. https://doi.org/10.1080/13825580590925116
16. Geary DC, Wiley JG. Cognitive addition: strategy choice and speed-of-processing differences in young and elderly adults. Psychol Aging. 1991; 6: 474–483. https://doi.org/10.1037/0882-7974.6.3.474 PMID: 1930764
17. Delazer M, Girelli L, Granà A, Domains F. Number Processing and Calculation—Normative Data from Healthy Adults. Clin Neuropsychol. 2003; 17: 331–350. https://doi.org/10.1080/13825580590925116
18. Duverne S, Lemaire P. Aging and Mental Arithmetic. In: Campbell JID, editor. Handbook of Mathematical Cognition. New York and Hove: Psychology Press; 2005. pp. 397–411. https://doi.org/10.1037/h0087479 PMID: 16459884
19. Thevenot C, Dewi J, Bagnoud J, Wolfer P, Fayol M, Thevenot C, et al. The Use of Automated Procedures by Older Adults With High Arithmetic Skills During Addition Problem Solving. Psychol Aging. 2019; 35: 411–420. https://doi.org/10.1037/pag0000431 PMID: 31829658
20. Nuerk H-C, Moeller K, Willmes K. Multi-digit number processing. In: Cohen Kadosh R, Dowker A, editors. Oxford Handbook of Mathematical Cognition. Oxford, UK: Oxford University Press; 2015. pp. 106–139.
21. Deschuyteneer M. The addition of two-digit numbers: exploring carry versus no-carry problems. Psychol Sci. 2005; 47: 74–83.
22. Imbo I, LeFevre J-A. The role of phonological and visual working memory in complex arithmetic for Chinese- and Canadian-educated adults. Mem Cognit. 2010; 38: 176–185. https://doi.org/10.3758/_mc.38.2.176 PMID: 20173190
23. Kong J, Wang C, Kwong K, Vangel M, Chua E, Gollub R. The neural substrate of arithmetic operations and procedure complexity. Cogn brain Res. 2005; 22: 397–405. https://doi.org/10.1016/j.cogbrainres.2004.09.011 PMID: 15722210
24. Yi-Rong N, Si-Yun S, Zhou-Yi G, Si-Run L, Yun B, Song-Hao L, et al. Dissociated brain organization for two-digit addition and subtraction: an fMRI investigation. Brain Res Bull. 2011; 86: 395–402. https://doi.org/10.1016/j.brainresbull.2011.08.016 PMID: 21906662
25. Artemenko C, Soltanlou M, Dresler T, Ehlis A-C, Nuerk H-C. The neural correlates of arithmetic difficulty depend on mathematical ability: Evidence from combined fNIRS and ERP. Brain Struct Funct. 2018. https://doi.org/10.1007/s00429-018-1618-0 PMID: 29525887
26. Klein E, Willmes K, Dressel K, Domahs F, Wood G, Nuerk H-C, et al. Categorical and continuous—disentangling the neural correlates of the carry effect in multi-digit addition. Behav brain Funct. 2010; 6: 70. https://doi.org/10.1186/1744-9081-6-70 PMID: 21092129
27. Artemenko C, Pixner S, Moeller K, Nuerk H-C. Longitudinal development of subtraction performance in elementary school. Br J Dev Psychol. 2018; 36: 188–205. https://doi.org/10.1111/bjdp.12215 PMID: 28980340
28. Moeller K, Klein E, Nuerk H-C. (No) small adults: children’s processing of carry addition problems. Dev Neuropsychol. 2011; 36: 702–20. https://doi.org/10.1080/87565641.2010.549880 PMID: 21761994
29. Moeller K, Pixner S, Zuber J, Kaufmann L, Nuerk H-C. Early place-value understanding as a precursor for later arithmetic performance—a longitudinal study on numerical development. Res Dev Disabil. 2011; 32: 1837–51. https://doi.org/10.1016/j.ridd.2011.03.012 PMID: 21498043

30. Lemaire P, Callies S. Children’s strategies in complex arithmetic. J Exp Child Psychol. 2009; 103: 49–65. https://doi.org/10.1016/j.jecp.2008.09.007 PMID: 19027917

31. Moeller K, Klein E, Nuerk H-C. Three processes underlying the carry effect in addition—evidence from eye tracking. Br J Psychol. 2011; 102: 623–45. https://doi.org/10.1111/j.2044-8295.2011.02034.x PMID: 21752011

32. Geary DC, Frensch PA, Wiley JG. Simple and complex mental subtraction: strategy choice and speed-of-processing differences in younger and older adults. Psychol Aging. 1993; 8: 242–256. https://doi.org/10.1037/0882-7974.8.2.242 PMID: 8323728

33. Green HJ, Lemaire P, Dufau S. Eye movement correlates of younger and older adults’ strategies for complex addition. Acta Psychol (Amst). 2007; 125: 257–278. https://doi.org/10.1016/j.actpsy.2006.08.001 PMID: 17007804

34. Imbo I, Vandierendonck A, Vergauwe E. The role of working memory in carrying and borrowing. Psychol Res. 2007; 71: 467–83. https://doi.org/10.1007/s00426-006-0044-8 PMID: 16622702

35. Imbo I, Vandierendonck A, De Rammelaere S. The role of working memory in the carry operation of mental arithmetic: number and value of the carry. Q J Exp Psychol. 2007; 60: 708–31. https://doi.org/10.1080/17470210600762447 PMID: 17455078

36. Klein E, Moeller K, Dressel K, Domahs F, Willmes K, et al. To carry or not to carry—is this the question? Disentangling the carry effect in multi-digit addition. Acta Psychol (Amst). 2010; 135: 67–76. https://doi.org/10.1016/j.actpsy.2010.06.002 PMID: 20580340

37. Salthouse TA, Coon VE. Interpretation of Differential Deficits: The Case of Aging and Mental Arithmetic. J Exp Psychol Learn Mem Cogn. 1994; 20: 1172–1182. https://doi.org/10.1037//0278-7393.20.5.1172 PMID: 7931099

38. Nuerk H-C, Kaufmann L, Zoppoth S, Willmes K. On the development of the mental number line: more, less, or never holistic with increasing age? Dev Psychol. 2004; 40: 1199–211. https://doi.org/10.1037/0012-1649.40.6.1199 PMID: 15535767

39. Nuerk H-C, Moeller K, Klein E, Willmes K, Fischer MH. Extending the Mental Number Line. Zeitschrift für Psychol / J Psychol. 2011; 219: 3–22. https://doi.org/10.1027/2151-2604/a000041

40. Huber S, Moeller K, Nuerk H-C. Differentielle Entwicklung arithmetischer Fähigkeiten nach der Grundschule: Manche Schere öffnet und schließt sich wieder. Lernen und Lernstörungen. 2012; 1: 119–134. https://doi.org/10.1024/2235-0977/a000014

41. Salthouse TA, Coon VE. Interpretation of Differential Deficits: The Case of Aging and Mental Arithmetic. J Exp Psychol Learn Mem Cogn. 1994; 20: 1172–1182. https://doi.org/10.1037//0278-7393.20.5.1172 PMID: 7931099

42. Klein E, Nuerk H-C, Wood G, Knopps A, Willmes K. The exact vs. approximate distinction in numerical cognition may not be exact, but only approximate: How different processes work together in multi-digit addition. Brain Cogn. 2009; 69: 369–81. https://doi.org/10.1016/j.bandc.2008.08.031 PMID: 18929439

43. Verner M, Herrmann MJ, Troche SJ, Roebers CM, Rammsayer TH. Cortical oxygen consumption in mental arithmetic as a function of task difficulty: a near-infrared spectroscopy approach. Front Hum Neurosci. 2013; 7: 1–9. https://doi.org/10.3389/fnhum.2013.00001 PMID: 2335817

44. Zago L, Pesenti M, Mellet E, Crivello F, Mazoyer B, Tzourio-Mazoyer N. Neural correlates of simple and complex mental calculation. Neuroimage. 2001; 13: 314–27. https://doi.org/10.1006/nimg.2000.0697 PMID: 11162272

45. Kazui H, Kitagaki H, Mori E. Cortical activation during retrieval of arithmetical facts and actual calculation: a functional magnetic resonance imaging study. Psychiatry Clin Neurosci. 2000; 54: 479–85. https://doi.org/10.1046/j.1440-1819.2000.00739.x PMID: 10997866

46. Soltau-Mol, Shtirkova M, Nuerk H-C, Dresler T. Applications of functional near-infrared spectroscopy (fNIRS) in studying cognitive development: the case of mathematics and language. Front Psychol. 2018; 9. https://doi.org/10.3389/fpsyg.2018.00277 PMID: 2966589

47. Nasreddine ZS, Phillips NA, Bédirian V, Charbonneau S, Whitehead V, Collin I, et al. The Montreal Cognitive Assessment, MoCA: A Brief Screening Tool For Mild Cognitive Impairment. J Am Geriatr Soc. 2005; 53: 695–699. https://doi.org/10.1111/j.1532-5415.2005.53221.x PMID: 15817019

48. Nuerk H-C, Geppert BE, van Herten M Van, Willmes K. On the impact of different number representations in the number bisection task. Cortex. 2002; 38: 691–715. https://doi.org/10.1016/s0010-9452(08)70038-8 PMID: 12507040

49. LeFevre J-A, Shanahan T, DeStefano D. The tie effect in simple arithmetic: an access-based account. Mem Cognit. 2004; 32: 1019–31. https://doi.org/10.3758/bf03196878 PMID: 15673188
50. Mathôt S, Schreij D, Theeuwes J. OpenSesame: An open-source, graphical experiment builder for the social sciences. Behav Res Methods. 2012; 44: 314–324. https://doi.org/10.3758/s13428-011-0168-7 PMID: 22083660

51. Petermann F. Wechsler Adult Intelligence Scale—Fourth Edition. Deutschsprachige Adaptation der WAIS-IV von D. Wechsler. Frankfurt: Pearson; 2014.

52. Soltanlou M, Nuerk H, Artemenko C. Cognitive enhancement or emotion regulation: The influence of brain stimulation on math anxiety. Cortex. 2018.

53. Hagmann-von Arx P, Grob A. Reynolds Intellectual Assessment Scales and Screening (RIAS). Deutschsprachige Adaptation der Reynolds Intellectual Assessment Scales (RIAS) & des Reynolds Intellectual Screening Test (RIST) von Cecil R. Reynolds und Randy W. Kamphaus. Bern: Verlag Hans Huber; 2014.

54. Tsuzuki D, Jurcak V, Singh AK, Okamoto M, Watanabe E, Dan I. Virtual spatial registration of standalone fNIRS data to MNI space. Neuroimage. 2007; 34: 1506–18. https://doi.org/10.1016/j.neuroimage.2006.10.043 PMID: 17207638

55. Rorden C, Brett M. Stereotaxic Display of Brain Lesions. Behav Neurol. 2000; 12: 191–200. https://doi.org/10.1155/2000/421719 PMID: 11568431

56. Singh AK, Okamoto M, Dan H, Jurcak V, Dan I. Spatial registration of multichannel multi-subject fNIRS data to MNI space without MRI. Neuroimage. 2005; 27: 842–51. https://doi.org/10.1016/j.neuroimage.2005.05.019 PMID: 15979346

57. Tzourio-Mazoyer N, Landeau B, Papathanassiou D, Crivello F, Etard O, Delcroix N, et al. Automated Anatomical Labeling of Activations in SPM Using a Macroscopic Anatomical Parcellation of the MNI MRI Single-Subject Brain. Neuroimage. 2002; 15: 273–289. https://doi.org/10.1006/nimg.2001.0978 PMID: 11771995

58. Leys C, Ley C, Klein O, Bernard P, Licata L. Detecting outliers: Do not use standard deviation around the mean, use absolute deviation around the median. J Exp Soc Psychol. 2013; 49: 764–766. https://doi.org/10.1016/j.jesp.2013.03.013

59. Fishburn FA, Ludlum RS, Vaidya CJ, Medvedev A V. Temporal Derivative Distribution Repair (TDDR): A motion correction method for fNIRS. Neuroimage. 2020; 184: 171–179. https://doi.org/10.1016/j.neuroimage.2018.09.025 PMID: 30217544

60. Cui X, Bray S, Reiss AL. Functional near infrared spectroscopy (NIRS) signal improvement based on negative correlation between oxygenated and deoxygenated hemoglobin dynamics. Neuroimage. 2010; 49: 3039–3046. https://doi.org/10.1016/j.neuroimage.2009.11.050 PMID: 19945536

61. Brigadoi S, Ceccherini L, Cutini S, Scarpa F, Scatturin P, Selb J, et al. Motion artifacts in functional near-infrared spectroscopy: A comparison of motion correction techniques applied to real cognitive data. Neuroimage. 2014; 85: 181–191. https://doi.org/10.1016/j.neuroimage.2013.04.082 PMID: 23639260

62. Faulkenberry TJ, Ly A, Wagenmakers E. Bayesian Inference in Numerical Cognition: A Tutorial Using JASP. 2020; 1–31. https://doi.org/10.31234/osf.io/vg9pw

63. Jeffreys H. Theory of probability. 3rd ed. New York: Oxford University Press; 1961.

64. Lee M, Wagenmakers E-J. Bayesian Modeling for Cognitive Science: A Practical Course. Cambridge: Cambridge University Press; 2013.

65. Schönbrodt FD, Wagenmakers E-J. Bayes Factor Design Analysis: Planning for Compelling Evidence. Psychon Bull Rev. 2018; 25: 128–142. https://doi.org/10.3758/s13423-017-1230-y PMID: 28251595

66. Stefan AM, Gronau QF, Schönbrodt FD, Wagenmakers E. A tutorial on Bayes Factor Design Analysis using an informed prior. Behav Res Methods. 2019; 51: 1042–1058. https://doi.org/10.3758/s13428-018-01189-8 PMID: 30719688

67. Wood G, Ischebeck A, Koppelstaetter F, Gotwald T, Kaufmann L. Developmental Trajectories of Magnitude Processing and Interference Control: An fMRI Study. Cereb Cortex. 2009; 19: 2755–2765. https://doi.org/10.1093/cercor/bhp056 PMID: 19357393

68. Cantlon JF, Libertus ME, Pinel P, Dehaene S, Brannon EM, Pelphrey KA. The neural development of an abstract concept of number. J Cogn Neurosci. 2009; 21: 2217–29. https://doi.org/10.1162/jocn.2008.21159 PMID: 19016605

69. Van Impe A, Coxon JP, Goble DJ, Wenderoth N, Swinnen SP. Age-related changes in brain activation underlying single- and dual-task performance: Visuo-manual drawing and mental arithmetic. Neuropsychologia. 2011; 49: 2400–2409. https://doi.org/10.1016/j.neuropsychologia.2011.04.016 PMID: 21536055