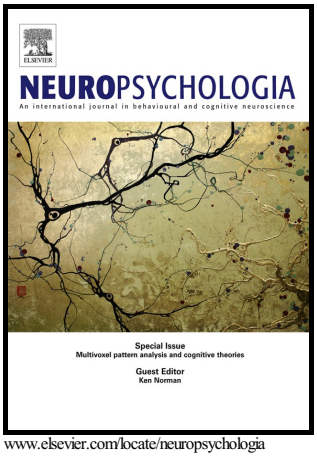
Author's Accepted Manuscript



www.elsevier.com/locate/neuropsychologia

Impaired math achievement in patients with acute vestibular neuritis

Ivan Moser, Dominique Vibert, Marco D. Caversaccio, Fred W. Mast

PII: S0028-3932(17)30408-6
DOI: https://doi.org/10.1016/j.neuropsychologia.2017.10.032
Reference: NSY6551

To appear in: *Neuropsychologia*

Received date: 2 June 2017
Revised date: 12 October 2017
Accepted date: 27 October 2017

Cite this article as: Ivan Moser, Dominique Vibert, Marco D. Caversaccio and Fred W. Mast, Impaired math achievement in patients with acute vestibular neuritis, *Neuropsychologia,* https://doi.org/10.1016/j.neuropsychologia.2017.10.032

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting galley proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

ACCEPTED MANUSCRIPT

Impaired **math achievement** in patients with acute vestibular neuritis

Ivan Moser[a,b], Dominique Vibert[c,], Marco D. Caversaccio[c], and Fred W. Mast[a,b]

[a] Department of Psychology, University of Bern, Fabrikstrasse 8, 3012 Bern, Switzerland

[b] Center for Cognition, Learning and Memory, University of Bern, Fabrikstrasse 8, 3012 Bern, Switzerland

[c] Department of Otorhinolaryngology, Head and Neck Surgery, Inselspital, University of Bern, Bern, Switzerland

Correspondence should be addressed to:

Ivan Moser

Department of Psychology

University of Bern

Fabrikstrasse 8

CH-3012 Bern

e-mail: ivan.moser@psy.unibe.ch

phone: +41 31 631 36 31

Accepted manuscript

ACCEPTED MANUSCRIPT

Abstract

Broad cognitive difficulties have been reported in patients with peripheral vestibular deficit, especially in the domain of spatial cognition. Processing and manipulating numbers relies on the ability to use the inherent spatial features of numbers. It is thus conceivable that patients with acute peripheral vestibular deficit show impaired numerical cognition. Using the number Stroop task and a short **math achievement** test, we tested 20 patients with acute vestibular neuritis and 20 healthy, age-matched controls. On the one hand, patients showed normal congruency and distance effects in the number Stroop task, which is indicative of normal number magnitude processing. On the other hand, patients scored lower than healthy controls in the **math achievement test**. We provide evidence that the lower **performance** cannot be explained by either differences in prior math knowledge (i.e., education) or slower processing speed. Our results suggest that peripheral vestibular deficit negatively affects numerical cognition in terms of the efficient manipulation of numbers. We discuss the role of executive functions in **math performance** and argue that previously reported executive deficits in patients with peripheral vestibular deficit provide a plausible explanation for **the lower math achievement scores**. In light of the handicapping effects of impaired numerical cognition in daily living, **it is crucial to further investigate the mechanisms that cause mathematical deficits in acute PVD and eventually develop adequate means for cognitive interventions.**

Keywords: vestibular deficit, numerical cognition, **math achievement**, dyscalculia, executive functions

Accepted manuscript

ACCEPTED MANUSCRIPT

Introduction

A peripheral vestibular deficit (PVD) leads to severe vertigo, nausea, vomiting, and imbalance (Brandt, 2003). Interestingly, in addition to the typical symptoms of PVD, patients frequently report having cognitive difficulties in daily life (Bigelow, Semenov, Trevino, et al., 2015; Black, Pesznecker, & Stallings, 2004; Harun, Semenov, & Agrawal, 2015). These complaints have received empirical support in a growing body of evidence with regard to many cognitive domains including attention, memory, executive function, and spatial cognition (see Bigelow & Agrawal, 2015; Hanes & McCollum, 2006; Mast, Preuss, Hartmann, & Grabherr, 2014). It is intriguing that cognitive deficits have not only been found in dynamic situations (i.e., dual-tasks that combine cognitive tasks with postural challenges) but are also evident in static situations with no concomitant head or body movement (Redfern, Talkowski, Jennings, & Furman, 2004; Talkowski, Redfern, Jennings, & Furman, 2005; Yardley et al., 2001).

Since the vestibular system is crucial for the cognitive representation of space (Angelaki & Cullen, 2008), deficits have been extensively studied in the area of visuo-spatial abilities (i.e., spatial cognition). It has been shown that bilateral vestibular failure is associated with hippocampal loss and impaired spatial navigation (Brandt et al., 2005; Kremmyda et al., 2016; Russell, Horii, Smith, Darlington, & Bilkey, 2003; Schautzer, Hamilton, Kalla, Strupp, & Brandt, 2003; Stackman & Herbert, 2002). Similarly, patients with unilateral PVD also perform worse than healthy controls in navigation tasks (Borel et al., 2004; Cohen, 2000; Guidetti, Monzani, Trebbi, & Rovatti, 2008; Péruch et al., 1999; Péruch, Borel, Magnan, & Lacour, 2005 but see Hufner et al., 2007). Patients with PVD are also impaired in tasks that involve the mental rotation of one's own body without actual displacement (i.e, mental imagery; Candidi et al., 2013; Grabherr, Cuffel, Guyot, & Mast, 2011; Péruch et al., 2011; but see Deroualle et al.,

Accepted manuscript

ACCEPTED MANUSCRIPT

2017). Taken together, there is strong evidence that PVD leads to an impaired internal representation of space (Borel, Lopez, Péruch, & Lacour, 2008).

The notion of impaired cognitive representation of space might not only explain the frequently found deficits in navigation and spatial memory following PVD. It may also play a crucial role in other cognitive functions that rely on rather abstract representations of magnitude and space. For example, the spatial organization of numbers has coined the term "mental number line" (Dehaene, Bossini, & Giraux, 1993). These number-space associations are consistently found across various experimental paradigms. For example, in parity (odd vs. even) judgment tasks, participants typically respond faster to large numbers with the right hand, while responses to small numbers are faster with the left hand (SNARC effect; Nuerk, Wood, & Willmes, 2005). Other intriguing findings have been reported by means of random number generation tasks. Passive or active body-motion towards the left lead to the generation of smaller numbers compared to head motion towards the right (Hartmann, Grabherr, & Mast, 2012; Loetscher, Schwarz, Schubiger, & Brugger, 2008; Shaki & Fischer, 2014).

Following this idea of number-space associations, Smith (2012) stated the hypothesis that there might be a link between PVD and **dyscalculia. According to common definitions, individuals with dyscalculia perform poorly in mathematical achievement tests while showing normal intelligence (Butterworth, 2005; Butterworth, Varma, & Laurillard, 2011; Cohen Kadosh & Walsh, 2007; von Aster & Shalev, 2007). At a lower cognitive level, the syndrome is characterized by a single core deficit in processing number magnitude (i.e., numerosity), which correlates with functional and anatomical abnormalities in parietal areas (Isaacs, Edmonds, Lucas, & Gadian, 2001; Kucian et al., 2006; Mussolin et al., 2010; Price, Holloway, Rasanen, Vesterinen, & Ansari, 2007). Interestingly**, there is first evidence

Accepted manuscript

ACCEPTED MANUSCRIPT

in support of impaired processing and manipulation of numbers in vestibular disorders. Risey and Briner (1990) found that vestibular patients make more mistakes counting backwards, and score lower on the arithmetic subtests and the backward digit span task of the Wechsler Adult Intelligence Scale (WAIS). However, it has to be pointed out that the patients who took part in their study suffered from vertigo due to central origin. Nevertheless, deficits have also been found in patients with PVD in a double-task that required the participants to count backwards during a continuous body orientation task on an oscillatory chair (Yardley et al., 2002).

To date, despite ample anecdotal evidence of impaired numerical abilities in clinical practice, empirical evidence is still rather scarce. For example, it is yet unclear whether numerical deficits also appear under static conditions when no physical movements could interfere with cognitive processes. Furthermore, more research is needed to better specify which aspects of numerical cognition are impaired in patients with PVD. Poor mathematical skills can substantially impair performance at the workplace (Parsons & Bynner, 2005) and in daily life. Indeed, a recent report found that vestibular dysfunction was more strongly associated with difficulty managing finances than with motor-based activities of daily living (Harun et al., 2015).

In order to test the hypothesis of dyscalculia in patients with PVD , we set out to examine two key aspects that are implicated in dyscalculia. First, on a high level of numerical cognition, we wanted to investigate whether patients with PVD and healthy controls differ with respect to the efficient manipulation of numbers in complex tasks (i.e., **math achievement**). We expected that healthy controls outperform patients with PVD in a short math achievement test. **Math achievement** relies on a set of domain-general skills such as working memory or executive functions (De Rammelaere, Stuyven, & Vandierendonck, 1999; DeStefano & LeFevre, 2004; Passolunghi & Pazzaglia, 2004; van der Sluis, de Jong, & van der Leij, 2007; von Aster &

Accepted manuscript

ACCEPTED MANUSCRIPT

Shalev, 2007), which were repeatedly found to be impaired in vestibular dysfunction (Bigelow, Semenov, du Lac, Hoffman, & Agrawal, 2015; Black et al., 2004; Grimm, Hemenway, Lebray, & Black, 1989; Hanes & McCollum, 2006; Moser, Vibert, Caversaccio, & Mast, 2016).

Second, we were also interested whether PVD results in basic problems in processing the magnitude of numbers. Impaired performance in a number processing task would support the hypothesis of Smith (2012) since it is reflects a key aspect of dyscalculia. For this reason, we used the number Stroop task, which typically produces abnormal results in children and adults with impaired numerical cognition (e.g., Algom, Dekel, & Pansky, 1996; Ashkenazi, Rubinsten, & Henik, 2009; Girelli, Lucangeli, & Butterworth, 2000; Rubinsten & Henik, 2005; Rubinsten, Henik, Berger, & Shahar-Shalev, 2002). In its original form, the number Stroop task consists of two subtests, subsequently referred to as the *physical* and *numerical* number Stroop. Both subtests require the participants to compare two simultaneously presented digits. In the *physical* number Stroop, the participants are instructed to indicate which digit is physically larger (i.e., has the larger font size). In contrast, the *numerical* number Stroop requires a response to the digit that has the higher numerical value. The trials differ with respect to three congruity conditions. (1) *Congruent* trials consist of two digits, where one digit is larger with respect to both dimensions (i.e., physical size and numerical value). (2) In i*ncongruent* trials, the digit with the smaller numerical value is displayed with larger font size or vice versa. (3) In *neutral* trials, two identical digits are presented with different font size (*physical* subtest) or two different digits are presented with the same font size (*numerical* subtest).

First, we were motivated to investigate the size congruity effect (SCE), which refers to the difference in response times between *congruent*, *incongruent*, and *neutral* trials in the *physical* number Stroop. The SCE can be divided into a facilitation and interference component.

Accepted manuscript

ACCEPTED MANUSCRIPT

Facilitation implies faster response times in *congruent* compared to *neutral* trials. Interference implies slower response times in *incongruent* compared to *neutral* trials. The SCE is considered to be a measure of automatic processing of the task-irrelevant number magnitude (Bugden & Ansari, 2011; Girelli et al., 2000; Rubinsten et al., 2002). Second, the number Stroop task allowed us to compare the distance effect, which is characterized by faster responses with increasing numerical distance between two simultaneously presented digits. **For example, comparing two digits separated by a distance of 1 (e.g., "6" and "7") leads to larger response time than comparing two digits separated by a distance of 5 (e.g., "2" and "7").** The distance effect serves as a marker of intentional number processing in the *numerical* number Stroop (Rubinsten et al., 2002). In contrast, a reversed distance effect (faster responses with decreasing numerical distance) has previously been observed in the *physical* number Stroop and has been interpreted as automatic number processing (Heine et al., 2010; Pina, Castillo, Kadosh, & Fuentes, 2015; Tang, Critchley, Glaser, Dolan, & Butterworth, 2006).

If patients with PVD suffer from a severe impairment of number magnitude processing similar to individuals with impaired numerical cognition (i.e., dyscalculia), we might observe a weaker SCE in the *physical* number Stroop (Ashkenazi, Henik, Ifergane, & Shelef, 2008; Ashkenazi et al., 2009; Girelli et al., 2000; Kadosh et al., 2007; Rubinsten & Henik, 2005, 2009). Furthermore, we might expect a stronger distance effect in the *numerical* number Stroop, which is another typical finding in individuals with weak numerical cognition (Bugden & Ansari, 2011; De Smedt et al., 2009; Heine et al., 2010; Holloway & Ansari, 2009; Mussolin et al., 2010; Pina et al., 2015; Rubinsten et al., 2002; Tang et al., 2006). However, **as mentioned above**, the term "dyscalculia" usually refers to a learning disability, which is characterized by a specific deficiency in core numerical abilities with intact function in other cognitive domains

Accepted manuscript

ACCEPTED MANUSCRIPT

(Butterworth, 2005; Butterworth, Varma, & Laurillard, 2011; Cohen Kadosh & Walsh, 2007). Since cognitive deficits in PVD were frequently observed in non-numerical tasks (Bigelow & Agrawal, 2015; Hanes & McCollum, 2006; Mast et al., 2014; Smith, Zheng, Horii, & Darlington, 2005), it is unclear whether numerical deficits in PVD follow a dyscalculic pattern of number Stroop performance **(i.e., weaker SCE and/or stronger distance effect).**

Methods

Participants

We tested 20 participants (9 female) with acute vestibular neuritis attributed to reactivation of neurotropic viruses in the vestibular ganglion, generating an inflammation of the vestibular nerve. Diagnosis of vestibular neuritis was based on extensive neurotological examination including electronystagmography with bithermal caloric testing, pendular rotatory chair testing, cervical vestibular evoked myogenic potentials (cVEMPs), video head impulse test (V-HIT), and dynamic visual acuity test (DVA). Additionally, all patients rated subjective handicap of the vestibular deficit by means of the dizziness handicap inventory (DHI; Jacobson and Newman 1990). Testing was performed during a routine follow-up shortly after initial admission to the emergency ENT-unit of the University Hospital Bern (mean interval = 11.10 days + 5.48 SD). We included patients according to the following criteria: (1) Canal paresis ≥ 20 % in bithermal caloric testing, (2) no hearing loss, (3) no vertigo due to a central lesion, (4) no history of previous neurotologic diseases. Additionally, we included 21 healthy participants (10 female) in our study. Patients with AVN (mean age = 47.11, SD = 13.55) and healthy controls (mean age = 46.19, SD = 13.75) did not differ with respect to age or gender. In order to control for the level of formal education, all participants indicated their highest academic qualification.

Accepted manuscript

ACCEPTED MANUSCRIPT

We categorized the level of education according to the typical academic qualifications obtained in the Swiss educational system: compulsory education, vocational training, university entrance diploma, higher vocational training, college of higher education, and university degree. More detailed demographic and clinical data of the participants is provided in Table 1. Before starting data collection, the study was approved by the ethics committee of the Canton Bern. The experimental procedure adhered to the ethical standards defined by the Declaration of Helsinki. All participants gave informed consent prior to the experiment. Participants did not receive money or other compensation for participation.

---------- Insert Table 1 about here ----------

Stimuli and Procedure

In the number Stroop task, participants were instructed to decide as quickly as possible which number was presented "physically larger" (*physical* subtest) or "numerically larger" (*numerical* subtest). Responses were collected using a custom-made response box. Participants were asked to indicate the side (left vs. right) of the larger stimulus by pressing a key on the corresponding side of the response box. Each subtest consisted of 96 trials, which included 24 congruent, 24 incongruent, and 48 neutral trials. Ten randomly generated additional trials at the beginning of each subtest served as practice trials and were excluded from data analysis. The order of the two subtests was counterbalanced across participants. We used the digits 1 through 9, without 5. The pairs of digits were presented with numerical distances of zero (1-1; 2-2; 3-3; 4-4; 6-6; 7-7; 8-8), one (1-2; 3-4; 6-7; 8-9), two (1-3; 2-4; 6-8; 7-9), and five (1-6; 2-7; 4-9). Each size and digit was presented equally often at each side of the screen. Stimulus presentation

Accepted manuscript

ACCEPTED MANUSCRIPT

was generated with PsychoPy (Peirce, 2007) on a 15'' laptop monitor at a resolution of 1600 x 900 pixels. Viewing distance was approximately 60 cm. The sizes of the digits were set at 100 pixels (15 mm) for the smaller, and 110 pixels (18 mm) for the larger digits. Center-to-center distance between the digits was 90 pixels (12 mm).

Each trial started with a blank screen for a random duration between 800 and 1200 ms. Subsequently, a pair of digits was presented and remained on the screen until the participants pressed a key on the response box. If participants did not respond within 5000 ms of stimulus onset, the pair of digits disappeared and a prompt on the screen reminded the participants to provide a response on the next trial. Feedback for wrong answers was only given for the ten practice trials at the beginning of the two subtests.

After the number Stroop task was completed, participants received the brief math assessment (BMA-3; Steiner & Ashcraft, 2012) with an additional empty sheet of paper. **The BMA-3 was used as a time-effective math achievement test**. It consists of ten items that strongly correlate with performance in larger tests of math achievement (i.e., WRAT3 and WRAT4; Wilkinson & Robertson, 2006). Moreover, despite its brevity the BMA-3 covers a wide range of arithmetic problems (addition, subtraction and multiplication of whole numbers and fractions, solving equations, and simplifying complex fractions).

Participants were instructed to solve as many problems as possible within ten minutes. They were informed that the mathematical problems of the BMA-3 are ordered by increasing difficulty. The participants were free to choose in which order they wanted to solve the problems and were allowed to take notes on the empty sheet of paper. After exactly ten minutes, the experimenter collected the test.

Analysis

Accepted manuscript

ACCEPTED MANUSCRIPT

Group performance (patients with PVD vs. healthy controls) was compared using a Bayesian approach. Bayesian inference implies substantial advantages over traditional null hypothesis significance testing (NHST). In contrast to NHST, the interpretation of data in Bayesian inference is unaffected by sampling intentions and time restrictions of the experimenter. Most importantly, the Bayesian approach allows assessing the relative credibility of parameter values given the data, which is not possible with frequentist methods (Kruschke, 2012; Lee & Wagenmakers, 2005; Wagenmakers, 2007).

All analyses were conducted in R (3.3.2; R Core Team, 2015) using the brms package for Bayesian generalized (non-)linear mixed models (Bürkner, in press). The parameter estimates were obtained using Markov Chain Monte Carlo sampling (MCMC) with 4 chains of 2000 iterations each (the first 1000 iterations were used as warm-up). We used weakly informative priors on all estimated parameters to minimize the influence of the priors on the estimated posterior distributions. In order to assess model convergence, we visually inspected the chains and verified that the R-hat diagnostic was close to 1. R-hat values larger than 1 are indicative of insufficient convergence of the MCMC chains (Gelman & Rubin, 1992). The estimated parameters were interpreted in terms of their 95 % credible interval (95 % CrI). The 95 % CrI provides the range which contains the true value of a parameter with a probability of 95 % (given the data). This interpretation is not possible (however often erroneously used) with frequentist confidence intervals (Hoekstra, Morey, Rouder, & Wagenmakers, 2014; Nicenboim, 2016). Consistent with previous research using a Bayesian framework, we considered effects to be "strong" if the 95 % CrI did not include zero, or one for odds ratios respectively (Frank, Trompenaars, & Vasishth, 2016; Hofmeister & Vasishth, 2014; Husain, Vasishth, & Srinivasan, 2014; Kruschke, 2012; Nicenboim, 2016).

Accepted manuscript

ACCEPTED MANUSCRIPT

The odds of giving a correct answer in the BMA-3 were analyzed using a generalized linear mixed model (GLMM) with a binomial link function. We modeled a fixed effect *b_patients*, which refers to the dummy-coded effect of patients with PVD vs. healthy controls (i.e., the reference category). We were interested whether the odds of providing a correct answer was smaller for patients with PVD compared to healthy controls (i.e., the odds ratio being smaller than 1). Additionally, we controlled for the fixed effects of each educational level (*b_educ2*: vocational training; *b_educ3*: higher vocational training or university entrance diploma; *b_educ4*: college of higher education or university degree) compared to compulsory education as the reference category (*b_educ1*). Furthermore, we included two random effects for the intercept in order to account for the variance between participants and between items.

Results from the *numerical* and *physical* number Stroop task were analyzed by means of two separate Bayesian GLMM with an ex-gaussian link function for the response times. We used the ex-gaussian link function since it has repeatedly been shown to yield appropriate fits for response time distributions including Stroop tasks (Gu, Gau, Tzang, & Hsu, 2013; Heathcote, Popiel, & Mewhort, 1991; Hervey et al., 2006; Palmer, Horowitz, Torralba, & Wolfe, 2011; Steinhauser & Hübner, 2009). Fixed effects were estimated for *group* (patients with PVD vs. healthy controls), *numerical distance* (1 vs. 2 vs. 5), and *congruency* (congruent vs. neutral vs. incongruent) and all possible interaction terms. We used effect coding for all predictors in order to ease the interpretation of the regression weights (i.e., interpreting an effect at the grand mean instead of setting all remaining effects to zero with dummy coding). Random effects were added for the intercepts of the participants and trials. Weakly informative priors were used for all effects.

Accepted manuscript

ACCEPTED MANUSCRIPT

Results

Number Processing

Numerical Number Stroop. Visual inspection of the MCMC chains and the R-hat diagnostic (all <= 1.01) indicated good convergence for all estimated parameters. The posterior estimates of the Bayesian GLMM revealed a strong effect for patients vs. controls (b = 64.04; 95 % CrI = [0.38; 125.94]). Irrespective of numerical distance and congruency, patients with PVD (M = 724.96; 95 % CrI = [679.37; 766.13]) responded slower than healthy controls (M = 659.56; 95 % CrI = [620.67; 703.97]). Furthermore, we observed a strong effect for numerical distances of one compared to five (b = 61.70; 95 % CrI = [51.43; 72.41]) and numerical distances of two compared to five (b = 36.55; 95 % CrI = [26.70; 46.26]). Response times for numerical distances of one (M = 721.76; 95 % CrI = [689.75; 750.83]) and two (M = 696.77; 95 % CrI = [665.15; 725.80) were slower compared to numerical distances of five (M = 660.34; 95 % CrI = [628.46; 689.31). Considering the NCE, we observed both a facilitation (b = -28.38; 95 % CrI = [-38.78; -17.97]) and an interference effect (b = 46.18; 95 % CrI = [33.66; 59.46]). Congruent trials (M = 658.73; 95 % CrI = [626.38; 687.80]) lead to faster response times compared to neutral trials (M = 687.13; 95 % CrI = [655.04; 715.91]). In contrast, response times were substantially slower for incongruent trials (M = 733.30; 95 % CrI = [701.00; 763.03]) vs. neutral trials.

We were particularly interested in possible differences of the SCE or the distance effect in patients vs. controls. However, groups did neither differ in facilitation (b = 0.51; 95% CrI = [-19.34; 21.14]) nor interference (b = 0.60; 95 % CrI = [-23.27; 25.27]). Furthermore, there was no difference between patients and controls with respect to the distance effect. Distance effects of one vs. five (b = -2.26; 95 % CrI = [-22.90; 18.06]) and two vs. five (b = -0.87; 95 % CrI = [-19.98; 18.21]) did not differ between groups.

Accepted manuscript

ACCEPTED MANUSCRIPT

The absence of group differences in facilitation, interference, and the numerical distance effect is depicted in *Figure 1*, and *Figure 2* respectively.

---------- Insert Figure 1 about here ----------

---------- Insert Figure 2 about here ----------

Physical Number Stroop. Computation of the posterior distributions was successful for all estimated parameters as indicated by visual inspection of the MCMC chains and the R-hat diagnostic (all < 1.01). In analogy to the *numerical* number Stroop task, the Bayesian GLMM showed a strong effect of group (b = 69.46; 95 % CrI = [26.19; 112.25]). Patients with PVD (M = 663.34; 95 % CrI = [630.87; 695.78]) responded generally slower than healthy controls (M = 593.98; 95 % CrI = [563.50; 626.21]). We observed no reversed distance effect for numerical distances of one (b = 0.24; 95 % CrI = [-8.55; 9.20]) and two (b = -8.14; 95 % CrI = [-17.57; 1.23]) compared to five. Participants did not respond differently when the irrelevant dimension (i.e., numerical value) of the two stimuli was separated with a distance of one (M = 632.43; 95 % CrI = [601.22; 665.72]), two (M = 623.86; 95 % CrI = [592.22; 657.53]) or five (M = 632.10; 95 % CrI = [600.30; 665.08]). In terms of the SCE, we only found a strong difference between congruent and incongruent trials (b = -39.49; 95 % CrI = [-47.83; -31.30]). Participants responded faster to congruent (M = 612.66; 95 % CrI = [582.66; 640.95]) compared to incongruent trials (M = 652.05; 95 % CrI= [622.53; 680.49]). However, we found no facilitation (b = -9.44; 95 % CrI = [-79.56; 58.27]) or interference effect (b = 30.04; 95 % CrI = [-40.69; 96.96]). Neutral trials (M = 621.64; 95 % CrI = [569.28; 679.65]) did not differ from congruent

Accepted manuscript

ACCEPTED MANUSCRIPT

or incongruent trials. Considering the two-way interactions, there was neither a difference in facilitation (b =6.75; 95 % CrI = [-121.93; 132.03]) nor interference (b = 14.19; 95 % CrI = [-115.44; 138.21]) between groups. Furthermore, patients and controls showed no differences with respect to the distance effects. Distance effects of one vs. five (b = -4.03; 95 % CrI = [-22.13; 14.38]) and two vs. five (b = -6.47; 95 % CrI = [-25.19; 11.78]) did not differ between groups.

Posterior means and credible intervals of the group x congruency interaction are plotted in *Figure 3*. The interaction of group x numerical distance is depicted in *Figure 4*. Both figures indicate that there were no differences in facilitation, interference, and numerical distance effects.

---------- Insert Figure 3 about here ----------

---------- Insert Figure 4 about here ----------

Math achievement

Visual inspection of the MCMC chains indicated good model convergence. Consistently, the R-hat diagnostic was roughly 1 for all parameters (all R-hat <= 1.01). Controlled for educational level, patients with PVD showed more than three times lower odds of providing a correct answer compared to healthy controls (OR = 0.27, 95% CrI =[0.05; 0.74]). A model summary is provided in *Table 2*.

In light of the slower response times of patients in the Stroop task, we conducted an additional analysis for the **math achievement test**. We added the median response time per subject as a marker of individual number processing speed to the Bayesian GLMM. Using this

Accepted manuscript

ACCEPTED MANUSCRIPT

approach, we aimed at controlling for the effect of (low level) number processing speed on performance in the time-restricted arithmetic test. However, the Bayesian GLMM revealed that even after controlling for individual processing speed, the odds of providing a correct answer were substantially lower for patients with PVD vs. controls (*OR* = 0.28, 95% CrI = [0.05; 0.84]).

---------- Insert Table 2 about here ----------

Discussion

In order to examine the effect of vestibular information on numerical cognition, we compared patients with unilateral PVD and healthy controls by means of two tasks that differed with respect to their complexity. By using a low level numerical cognition task (number Stroop), we were interested whether patients and healthy controls differ with respect to automatic and intentional magnitude processing. A higher level of processing was examined in order to assess whether PVD affects the efficient manipulation of numbers. We found that patients with PVD performed worse in a **math achievement test**. Considering the number Stroop task, patients with PVD showed slower reaction times compared to healthy controls. However, we found no evidence of impaired automatic or intentional magnitude processing, which is inconsistent with the hypothesis of a specific number deficit (i.e., dyscalculia). Patients with PVD did not differ from healthy controls in terms of facilitation or interference from neither the task-irrelevant numerical value in the *physical* subtest nor the task-irrelevant physical size in the *numerical* subtest. Furthermore, there was no difference between patients and controls in the number distance effect, which further corroborated the evidence in favor of normal magnitude processing in PVD.

Accepted manuscript

ACCEPTED MANUSCRIPT

Our findings of impaired **math performance** are consistent with the frequent subjective complaints of patients with PVD (Harun et al., 2015). They are also in line with the existing, yet scarce empirical evidence of impaired numerical cognition in vestibular patients (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2003; Bessot, Denise, Toupet, Van Nechel, & Chavoix, 2012; Risey & Briner, 1990; Yardley et al., 2002). Unlike previous studies, we demonstrated impaired arithmetic performance under static conditions. Thus, we provide evidence that previously reported numerical deficits cannot be exclusively attributed to dual-task interference (i.e., impaired cognitive performance due to prioritization of an ongoing postural challenge). This idea is supported by other studies showing various cognitive deficits in PVD in static conditions even though the deficits were more pronounced with an ongoing postural challenge (Redfern et al., 2004; Talkowski et al., 2005; Yardley et al., 2001).

We hypothesize that the observed pattern of arithmetic deficits and normal magnitude processing might be a consequence of metabolic changes in parietal areas during acute PVD. It has been shown that acute PVD leads to a complex activation-deactivation pattern of glucose metabolism. While glucose metabolism is increased in the parieto-insular vestibular cortex, metabolic downregulations are observed in the inferior parietal cortex (Bense et al., 2004; Dieterich & Brandt, 2008). There is a large consensus that parietal areas are crucial for numerical cognition (Ansari, 2008; Arsalidou & Taylor, 2011; Dehaene, Piazza, Pinel, & Cohen, 2003; Hubbard, Piazza, Pinel, & Dehaene, 2005) and play an important role in impaired numerical cognition (Ashkenazi et al., 2008; Butterworth et al., 2011; Delazer & Benke, 1997; Kadosh et al., 2007; Mussolin et al., 2010; Price et al., 2007). While the intraparietal sulcus is mainly involved in magnitude processing, inferior parietal areas such as the angular gyrus have repeatedly been shown to support arithmetic fact retrieval (Delazer, Girelli, Grana, & Domahs,

Accepted manuscript

ACCEPTED MANUSCRIPT

2003; Göbel, Rushworth, & Walsh, 2006; Grabner et al., 2007, 2009; Zamarian, Ischebeck, & Delazer, 2009). In this light, it is conceivable that PVD leads to transient metabolic downregulations in inferior parietal areas, and this in turn affects arithmetic performance in PVD.

In contrast to evidence in favor of impaired **math achievement**, normal SCE and distance effects in patients with PVD point to intact automatic and intentional magnitude processing. In this light, our clinical sample clearly differed from the number Stroop performance in individuals with dyscalculia (Ashkenazi et al., 2008, 2009; Kadosh et al., 2007; Rubinsten & Henik, 2005, 2009; Rubinsten et al., 2002). Furthermore, the lack of group differences in terms of the distance effect is inconsistent with the idea of impaired number-space associations in vestibular patients (Smith, 2012). The distance effect is usually interpreted as an indicator for the preciseness of spatial representations of numbers on the internal mental number line (Bugden & Ansari, 2011; De Smedt et al., 2009; Heine et al., 2010; Holloway & Ansari, 2009; Noël, Rousselle, & Mussolin, 2005). In the same vein, it is important to note that we were able to demonstrate that unilateral vestibular deficit does not affect the mental representation of numbers in a random number generation task (Moser et al., 2016). Consistently, unilateral galvanic vestibular stimulation did not induce a bias on the mental number line in healthy participants (Ferrè, Vagnoni, & Haggard, 2013). Our current data adds important evidence that arithmetic difficulties in PVD are not caused by impaired mental representation of numbers.

Taken together, the results from this study suggest that the observed arithmetic deficits are due to impaired arithmetic fact retrieval rather than by abnormal magnitude processing. However, it cannot be excluded that the arithmetic deficit in PVD might – at least partly – reflect a domain-general cognitive deficit rather than a number-specific deficit. In fact, the growing

Accepted manuscript

ACCEPTED MANUSCRIPT

literature on the cognitive consequences of PVD has found deficits in many cognitive domains (see Bigelow & Agrawal, 2015; Hanes & McCollum, 2006; Mast et al., 2014; Smith et al., 2005). If the observed arithmetic deficit is caused by metabolic changes in the inferior parietal cortex – as hypothesized above – it is noteworthy that those structures (e.g., the angular gyrus) do not only support arithmetic fact retrieval but are associated with a general language system that mediates the retrieval of verbally stored facts by phonological processing (Binder, Frost, Hammeke, Rao, & Cox, 1996; Paulesu, Frith, & Frackowiak, 1993; Price, 1998, 2000; Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002).

Importantly, it is possible that the cause of arithmetic deficits goes beyond the role of impaired fact-retrieval. For example, weak arithmetic performance of PVD patients could be a consequence of the time-restricted nature of the arithmetic test. In fact, despite normal SCE and distance effects, the patients showed slower response times in both number Stroop subtests. **Slower response times might reflect an indirect effect of decreased alertness due to disruption of the circadian rhythm, which has been reported in rodents and humans with vestibular loss (Martin et al., 2015, 2016). Thus,** the **observed** arithmetic deficit could be attributable to general slower processing speed in PVD. **Nevertheless**, we consider this possible interpretation unlikely since additional analysis showed that the patients with PVD still performed worse in the arithmetic test if the effect of individual processing speed from the number Stroop task was controlled for.

As another domain-general mechanism that is implicated in **mathematical tasks**, it is important to consider the role of executive functions. By definition, executive functions are responsible for the control and regulation of cognitive processes during performance in complex tasks (Miyake et al., 2000). In fact, a closer look at the previous studies that found numerical

Accepted manuscript

ACCEPTED MANUSCRIPT

deficits in vestibular patients reveals that those deficits cannot be explained independently of executive functions. Yardley et al. (2002) found deficits in counting backwards while patients with PVD were seated on an oscillatory chair and performed a body orientation monitoring task. Performance in dual-tasks relies on intact executive functions in order to constantly allocate attention between concurrent tasks (Logie, Cocchini, Delia Sala, & Baddeley, 2004). Moreover, counting backwards requires monitoring and dynamically manipulating the contents in working memory. As such, the counting process is dependent on the updating component of executive functions (Logie & Baddeley, 1987; Miyake et al., 2000). Similarly, in the first study that claimed dyscalculia in vestibular patients (Risey & Briner, 1990), patients with central vestibular disorders performed worse in counting backwards and in the backward digit span. In our view, these results demonstrate primarily impaired updating and do not allow for direct conclusions regarding an arithmetic deficit.

Consequently, we argue that impaired executive functions play a crucial role in the arithmetic deficit of patients with PVD. It is broadly accepted that executive functions (primarily updating) do not only support counting but also exert dominant influence on arithmetic performance (Andersson, 2008; Bull & Scerif, 2001; Deschuyteneer, Vandierendonck, & Muyllaert, 2006; DeStefano & LeFevre, 2004; Jarvis & Gathercole, 2003; Logie, Gilhooly, & Wynn, 1994; Passolunghi & Pazzaglia, 2004; St Clair-Thompson & Gathercole, 2006; van der Sluis et al., 2007; van der Ven, Kroesbergen, Boom, & Leseman, 2012). In complex arithmetic problems, updating is needed to replace items held in working memory with newer, more relevant information for the solution of a given (arithmetic) problem (Hitch, 1978; Morris & Jones, 1990). Moreover, it has been proposed that updating also influences performance in

Accepted manuscript

ACCEPTED MANUSCRIPT

simple arithmetic problems where the result can be retrieved a from long-term memory (Deschuyteneer et al., 2006).

Furthermore, it is important to point out that executive deficits were found in patients suffering from PVD. Grimm et al. (1989) reported executive deficits in patients with perilymph fistula syndrome. Black et al. (2004) found difficulties in prioritizing tasks in patients with complete vestibular loss. Moreover, we recently showed that patients with PVD produce more redundant sequences in a random number generation task, which is indicative of impaired updating (Moser et al., 2016). Considering the essential role of executive functions in **mathematical tasks**, there is strong evidence that an executive deficit is causally relevant for impaired **math achievement** in patients with PVD. **Identifying the pathways through which lack of vestibular input might affect executive functions requires further investigation. For example, Hitier et al. (2014) have discussed a pathway that might transmit vestibular information via the cerebellum and the ventral lateral nucleus to the parietal cortex. Intriguingly, both the cerebellum and the parietal cortex play an important role for executive functions (Jahanshahi, Dirnberger, Fuller, & Frith, 2000; Koziol, Budding, & Chidekel, 2012).**

Accepted manuscript

Conclusions

We were able to empirically support anecdotal evidence of impaired **math performance** in PVD. Patients with PVD performed worse in **a math achievement test** but showed normal number magnitude processing. Our findings are inconsistent with the hypothesis of a specific number processing deficit in PVD (i.e., dyscalculia). We argue that impaired executive functions are – at least partly – responsible for the observed arithmetic deficit. Poor **math performance**

ACCEPTED MANUSCRIPT

can have severe consequences for activities of daily living such as handling finances (Harun et al., 2015). Moreover, it might also substantially impair performance at the workplace (Parsons & Bynner, 2005). **Thus, it is crucial to follow-up on the mechanisms that cause mathematical deficits in PVD. A relatively large body of experimental evidence can be used to design adequate tools for the diagnosis and rehabilitation of patients with PVD suffering from arithmetic or other cognitive deficits.**

Acknowledgements

This research was supported by the Swiss National Science Foundation.

Accepted manuscript

ACCEPTED MANUSCRIPT

References

Algom, D., Dekel, A., & Pansky, A. (1996). The perception of number from the separability of the stimulus: The Stroop effect revisited. *Memory and Cognition*, *24*(5), 557–572. https://doi.org/10.3758/Bf03201083

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2003). Dual-task study of cognitive and postural interference in patients with vestibular disorders. *Otology & Neurotology*, *24*(2), 289–293. https://doi.org/10.1097/00129492-200303000-00026

Andersson, U. (2008). Working memory as a predictor of written arithmetical skills in children: The importance of central executive functions. *British Journal of Educational Psychology*, *78*(2), 181–203. https://doi.org/10.1348/000709907X209854

Angelaki, D. E., & Cullen, K. E. (2008). Vestibular System: The Many Facets of a Multimodal Sense. *Annual Review of Neuroscience*, *31*(1), 125–150. https://doi.org/10.1146/annurev.neuro.31.060407.125555

Ansari, D. (2008). Effects of development and enculturation on number representation in the brain. *Nature Reviews Neuroscience*, *9*(4), 278–91. https://doi.org/10.1038/nrn2334

Arsalidou, M., & Taylor, M. J. (2011). Is 2+2=4? Meta-analyses of brain areas needed for numbers and calculations. *Neuroimage*, *54*(3), 2382–2393. https://doi.org/10.1016/j.neuroimage.2010.10.009

Ashkenazi, S., Henik, A., Ifergane, G., & Shelef, I. (2008). Basic numerical processing in left intraparietal sulcus (IPS) acalculia. *Cortex*, *44*(4), 439–448. https://doi.org/10.1016/j.cortex.2007.08.008

Ashkenazi, S., Rubinsten, O., & Henik, A. (2009). Attention, Automaticity, and Developmental Dyscalculia. *Neuropsychology*, *23*(4), 535–540. https://doi.org/10.1037/a0015347

Bense, S., Bartenstein, P., Lochmann, M., Schlindwein, P., Brandt, T., & Dieterich, M. (2004). Metabolic changes in vestibular and visual cortices in acute vestibular neuritis. *Annals of Neurology*, *56*(5), 624–630. https://doi.org/10.1002/ana.20244

Bessot, N., Denise, P., Toupet, M., Van Nechel, C., & Chavoix, C. (2012). Interference between walking and a cognitive task is increased in patients with bilateral vestibular loss. *Gait & Posture*, *36*(2), 319–321. https://doi.org/10.1016/j.gaitpost.2012.02.021

Bigelow, R. T., & Agrawal, Y. (2015). Vestibular involvement in cognition: Visuospatial ability, attention, executive function, and memory. *Journal of Vestibular Research-Equilibrium & Orientation*, *25*(2), 73–89. https://doi.org/10.3233/VES-150544

Bigelow, R. T., Semenov, Y. R., du Lac, S., Hoffman, H. J., & Agrawal, Y. (2015). Vestibular vertigo and comorbid cognitive and psychiatric impairment: the 2008 National Health Interview Survey. *Journal of Neurology Neurosurgery and Psychiatry*. https://doi.org/10.1136/jnnp-2015-310319

Bigelow, R. T., Semenov, Y. R., Trevino, C., Ferrucci, L., Resnick, S. M., Simonsick, E. M., … Agrawal, Y. (2015). Association Between Visuospatial Ability and Vestibular Function in the Baltimore Longitudinal Study of Aging. *Journal of the American Geriatrics Society*, *63*(9). https://doi.org/10.1111/jgs.13609

Binder, J. R., Frost, J. A., Hammeke, T. A., Rao, S. M., & Cox, R. W. (1996). Function of the left planum temporale in auditory and linguistic processing. *Brain : A Journal of Neurology*, *119*, 1239–1247.

Black, F. O., Pesznecker, S., & Stallings, V. (2004). Permanent gentamicin vestibulotoxicity. *Otology & Neurotology*, *25*(4), 559–69. https://doi.org/10.1097/00129492-200407000-

Accepted Manuscript

ACCEPTED MANUSCRIPT

00025

Borel, L., Harlay, F., Lopez, C., Magnan, J., Chays, A., & Lacour, M. (2004). Walking performance of vestibular-defective patients before and after unilateral vestibular neurotomy. *Behavioural Brain Research*, *150*(1), 191–200. https://doi.org/10.1016/S0166-4328(03)00257-2

Borel, L., Lopez, C., Péruch, P., & Lacour, M. (2008). Vestibular syndrome: a change in internal spatial representation. *Clinical Neurophysiology*, *38*(6), 375–389. https://doi.org/10.1016/j.neucli.2008.09.002

Brandt, T. (2003). *Vertigo: its multisensory syndromes*. London: Springer.

Brandt, T., Schautzer, F., Hamilton, D., Brüning, R., Markowitsch, H. J., Kalla, R., … Strupp, M. (2005). Vestibular loss causes hippocampal atrophy and impaired spatial memory in humans. *Brain*, *128*(11), 2732–2741. https://doi.org/10.1093/brain/awh617

Bugden, S., & Ansari, D. (2011). Individual differences in children's mathematical competence are related to the intentional but not automatic processing of Arabic numerals. *Cognition*, *118*(1), 32–44. https://doi.org/10.1016/j.cognition.2010.09.005

Bull, R., & Scerif, G. (2001). Executive functioning as a predictor of children's mathematics ability: Inhibition, switching, and working memory. *Developmental Neuropsychology*, *19*(3), 273–293. https://doi.org/10.1207/S15326942DN1903_3

Bürkner, P.-C. (n.d.). brms : An R package for bayesian generalized linear mixed models using Stan. *Journal of Statistic Software*.

Butterworth, B. (2005). Developmental Dyscalculia. In J. I. D. Campbell (Ed.), *Handbook of Mathematical Cognition* (pp. 455–467). Hove, UK: Psychology Press.

Butterworth, B., Varma, S., & Laurillard, D. (2011). Dyscalculia: From Brain to Education. *Science*, *332*(6033), 1049–1053. https://doi.org/10.1126/science.1201536

Candidi, M., Micarelli, A., Viziano, A., Aglioti, S. M., Minio-Paluello, I., & Alessandrini, M. (2013). Impaired mental rotation in benign paroxysmal positional vertigo and acute vestibular neuritis. *Frontiers in Human Neuroscience*, *7*. https://doi.org/10.3389/fnhum.2013.00783

Cohen, H. S. (2000). Vestibular disorders and impaired path integration along a linear trajectory. *Journal of Vestibular Research-Equilibrium & Orientation*, *10*(1), 7–15.

Cohen Kadosh, R., & Walsh, V. (2007). Dyscalculia. *Current Biology*, *17*(22), R946–R947. https://doi.org/10.1016/j.cub.2007.08.038

De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (1999). The contribution of working memory resources in the verification of simple mental arithmetic sums. *Psychological Research-Psychologische Forschung*, *62*(1), 72–77. https://doi.org/10.1007/S004260050041

De Smedt, B., Janssen, R., Bouwens, K., Verschaffel, L., Boets, B., & Ghesquière, P. (2009). Working memory and individual differences in mathematics achievement: A longitudinal study from first grade to second grade. *Journal of Experimental Child Psychology*, *103*(2), 186–201. https://doi.org/10.1016/j.jecp.2009.01.004

Dehaene, S., Bossini, S., & Giraux, P. (1993). The mental representation of parity and number magnitude. *Journal of Experimental Psychology: General*, *122*(3), 371–396. https://doi.org/10.1037/0096-3445.122.3.371

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology*, *20*(3–6), 487–506. https://doi.org/10.1080/02643290244000239

Accepted manuscript

ACCEPTED MANUSCRIPT

Delazer, M., & Benke, T. (1997). Arithmetic facts without meaning. *Cortex*, *33*(4), 697–710. https://doi.org/10.1016/S0010-9452(08)70727-5

Delazer, M., Girelli, L., Grana, A., & Domahs, F. (2003). Number processing and calculation - Normative data from healthy adults. *Clinical Neuropsychologist*, *17*(3), 331–350. https://doi.org/10.1076/clin.17.3.331.18092

Deroualle, D., Toupet, M., van Nechel, C., Duquesne, U., Hautefort, C., & Lopez, C. (2017). Anchoring the Self to the Body in Bilateral Vestibular Failure. *PLOS ONE*, *12*(1), 1–21. https://doi.org/10.1371/journal.pone.0170488

Deschuyteneer, M., Vandierendonck, A., & Muyllaert, I. (2006). Does solution of mental arithmetic problems such as 2+ 6 and 3× 8 rely on the process of "memory updating"? *Experimental Psychology*, *53*(3), 198–208. https://doi.org/10.1027/1618-3169.53.3.198

DeStefano, D., & LeFevre, J. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology*, *16*(3), 353–386. https://doi.org/10.1080/09541440244000328

Dieterich, M., & Brandt, T. (2008). Functional brain imaging of peripheral and central vestibular disorders. *Brain*, *131*(10), 2538–2552. https://doi.org/10.1093/brain/awn042

Ferrè, E. R., Vagnoni, E., & Haggard, P. (2013). Galvanic vestibular stimulation influences randomness of number generation. *Experimental Brain Research*, *224*(2), 233–241. https://doi.org/10.1007/S00221-012-3302-6

Frank, S. L., Trompenaars, T., & Vasishth, S. (2016). Cross-Linguistic Differences in Processing Double-Embedded Relative Clauses: Working-Memory Constraints or Language Statistics? *Cognitive Science*, *40*(3), 554–578. https://doi.org/10.1111/cogs.12247

Gelman, A., & Rubin, D. B. (1992). Inference from Iterative Simulation Using Multiple Sequences. *Statistical Science*, *7*(4), 457–511. https://doi.org/10.1214/ss/1177011136

Girelli, L., Lucangeli, D., & Butterworth, B. (2000). The development of automaticity in accessing number magnitude. *Journal of Experimental Child Psychology*, *76*(2), 104–122. https://doi.org/10.1006/Jecp.2000.2564

Göbel, S. M., Rushworth, M. F., & Walsh, V. (2006). Inferior parietal rTMS affects performance in an addition task. *Cortex*, *42*(5), 774–781. https://doi.org/10.1016/S0010-9452(08)70416-7

Grabherr, L., Cuffel, C., Guyot, J.-P., & Mast, F. W. (2011). Mental transformation abilities in patients with unilateral and bilateral vestibular loss. *Experimental Brain Research*, *209*(2), 205–214. https://doi.org/10.1007/s00221-011-2535-0

Grabner, R. H., Ansari, D., Koschutnig, K., Reishofer, G., Ebner, F., & Neuper, C. (2009). To retrieve or to calculate? Left angular gyrus mediates the retrieval of arithmetic facts during problem solving. *Neuropsychologia*, *47*(2), 604–608. https://doi.org/10.1016/j.neuropsychologia.2008.10.013

Grabner, R. H., Ansari, D., Reishofer, G., Stern, E., Ebner, F., & Neuper, C. (2007). Individual differences in mathematical competence predict parietal brain activation during mental calculation. *NeuroImage*, *38*(2), 346–356. https://doi.org/10.1016/j.neuroimage.2007.07.041

Grimm, R. J., Hemenway, W. G., Lebray, P. R., & Black, F. O. (1989). The Perilymph Fistula Syndrome Defined in Mild Head Trauma. *Acta Oto-Laryngologica*, 1–40. https://doi.org/10.3109/00016488909138632

Gu, S. L., Gau, S. S. F., Tzang, S. W., & Hsu, W. Y. (2013). The ex-Gaussian distribution of reaction times in adolescents with attention-deficit/hyperactivity disorder. *Research in Developmental Disabilities*, *34*(11), 3709–3719. https://doi.org/10.1016/j.ridd.2013.07.025

Accepted manuscript

ACCEPTED MANUSCRIPT

Guidetti, G., Monzani, D., Trebbi, M., & Rovatti, V. (2008). Impaired navigation skills in patients with psychological distress and chronic peripheral vestibular hypofunction without vertigo. *Acta Otorhinolaryngologica Italica*, *28*(1), 21–25.

Hanes, D. A., & McCollum, G. (2006). Cognitive-vestibular interactions: a review of patient difficulties and possible mechanisms. *Journal of Vestibular Research*, *16*(3), 75–91.

Hartmann, M., Grabherr, L., & Mast, F. W. (2012). Moving along the mental number line: Interactions between whole-body motion and numerical cognition. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(6), 1416–1427. https://doi.org/10.1037/a0026706

Harun, A., Semenov, Y. R., & Agrawal, Y. (2015). Vestibular Function and Activities of Daily Living Analysis of the 1999 to 2004 National Health and Nutrition Examination Surveys. *Gerontology and Geriatric Medicine*, *1*, 2333721415607124. https://doi.org/10.1177/2333721415607124

Heathcote, A., Popiel, S. J., & Mewhort, D. J. (1991). Analysis of response time distributions: An example using the Stroop task. *Psychological Bulletin*, *109*(2), 340–347. https://doi.org/10.1037/0033-2909.109.2.340

Heine, A., Tamm, S., De Smedt, B., Schneider, M., Thaler, V., Torbeyns, J., … Jacobs, A. (2010). The Numerical Stroop Effect in Primary School Children: A Comparison of Low, Normal, and High Achievers. *Child Neuropsychology*, *16*(5), 461–477. https://doi.org/10.1080/09297041003689780

Hervey, A. S., Epstein, J. N., Curry, J. F., Tonev, S., Eugene Arnold, L., Keith Conners, C., … Hechtman, L. (2006). Reaction time distribution analysis of neuropsychological performance in an ADHD sample. *Child Neuropsychology*, *12*(2), 125–140. https://doi.org/10.1080/09297040500499081

Hitch, G. J. (1978). The role of short-term working memory in mental arithmetic. *Cognitive Psychology*, *10*(3), 302–323. https://doi.org/10.1016/0010-0285(78)90002-6

Hitier, M., Besnard, S., & Smith, P. F. (2014). Vestibular pathways involved in cognition. *Frontiers in Integrative Neuroscience*, *8*, 59. https://doi.org/10.3389/fnint.2014.00059

Hoekstra, R., Morey, R. D., Rouder, J. N., & Wagenmakers, E.-J. (2014). Robust misinterpretation of confidence intervals. *Psychonomic Bulletin & Review*, *21*(5), 1157–1164. https://doi.org/10.3758/s13423-013-0572-3

Hofmeister, P., & Vasishth, S. (2014). Distinctiveness and encoding effects in online sentence comprehension. *Frontiers in Psychology*, *5*, 1237. https://doi.org/10.3389/fpsyg.2014.01237

Holloway, I. D., & Ansari, D. (2009). Mapping numerical magnitudes onto symbols: The numerical distance effect and individual differences in children's mathematics achievement. *Journal of Experimental Child Psychology*, *103*(1), 17–29. https://doi.org/10.1016/j.jecp.2008.04.001

Hubbard, E. M., Piazza, M., Pinel, P., & Dehaene, S. (2005). Interactions between number and space in parietal cortex. *Nature Reviews Neuroscience*, *6*(6), 435–448. https://doi.org/10.1038/Nrn1684

Hufner, K., Hamilton, D. A., Kalla, R., Stephan, T., Glasauer, S., Ma, J., … Brandt, T. (2007). Spatial memory and hippocampal volume in humans with unilateral vestibular deafferentation. *Hippocampus*, *17*(6), 471–485. https://doi.org/10.1002/hipo.20283

Husain, S., Vasishth, S., & Srinivasan, N. (2014). Strong expectations cancel locality effects: Evidence from Hindi. *PLoS ONE*, *9*(7). https://doi.org/10.1371/journal.pone.0100986

Accepted manuscript

ACCEPTED MANUSCRIPT

Isaacs, E. B., Edmonds, C. J., Lucas, A., & Gadian, D. G. (2001). Calculation difficulties in children of very low birthweight: a neural correlate. *Brain*, *124*(9), 1701–1707. https://doi.org/10.1093/brain/124.9.1701

Jahanshahi, M., Dirnberger, G., Fuller, R., & Frith, C. D. (2000). The role of the dorsolateral prefrontal cortex in random number generation: A study with positron emission tomography. *Neuroimage*, *12*(6), 713–725. https://doi.org/10.1006/nimg.2000.0647

Jarvis, H. L., & Gathercole, S. E. (2003). Verbal and non-verbal working memory and achievements on national curriculum tests at 11 and 14 years of age. *Educational and Child Psychology*, *20*(3), 123–140.

Kadosh, R. C., Kadosh, K. C., Schuhmann, T., Kaas, A., Goebel, R., Henik, A., & Sack, A. T. (2007). Virtual dyscalculia induced by parietal-lobe TMS impairs automatic magnitude processing. *Current Biology*, *17*(8), 689–693. https://doi.org/10.1016/j.cub.2007.02.056

Koziol, L. F., Budding, D. E., & Chidekel, D. (2012). From movement to thought: Executive function, embodied cognition, and the cerebellum. In *Cerebellum* (Vol. 11, pp. 505–525). https://doi.org/10.1007/s12311-011-0321-y

Kremmyda, O., Hüfner, K., Flanagin, V. L., Hamilton, D. A., Linn, J., Strupp, M., … Brandt, T. (2016). Beyond Dizziness: Virtual Navigation, Spatial Anxiety and Hippocampal Volume in Bilateral Vestibulopathy. *Frontiers in Human Neuroscience*, *10*. https://doi.org/10.3389/fnhum.2016.00139

Kruschke, J. K. (2012). Bayesian estimation supersedes the t test. *Journal of Experimental Psychology: General*, *142*(2), 573–603. https://doi.org/10.1037/a0029146

Kucian, K., Loenneker, T., Dietrich, T., Dosch, M., Martin, E., & von Aster, M. (2006). Impaired neural networks for approximate calculation in dyscalculic children: a functional MRI study. *Behavioral and Brain Functions*, *2*, 31. https://doi.org/10.1186/1744-9081-2-31

Lee, M. D., & Wagenmakers, E.-J. (2005). Bayesian Statistical Inference in Psychology: Comment on Trafimow (2003). *Psychological Review*, *112*(3), 662–668. https://doi.org/10.1037/0033-295X.112.3.662

Loetscher, T., Schwarz, U., Schubiger, M., & Brugger, P. (2008). Head turns bias the brain's internal random generator. *Current Biology*, *18*(2), R60–R62. https://doi.org/10.1016/J.Cub.2007.11.015

Logie, R. H., & Baddeley, A. D. (1987). Cognitive processes in counting. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*(2), 310.

Logie, R. H., Cocchini, G., Delia Sala, S., & Baddeley, A. D. (2004). Is there a specific executive capacity for dual task coordination? Evidence from Alzheimer's disease. *Neuropsychology*, *18*(3), 504.

Logie, R. H., Gilhooly, K. J., & Wynn, V. (1994). Counting on working memory in arithmetic problem solving. *Memory and Cognition*, *22*(4), 395–410. https://doi.org/10.3758/BF03200866

Martin, T., Mauvieux, B., Bulla, J., Quarck, G., Davenne, D., Denise, P., … Besnard, S. (2015). Vestibular loss disrupts daily rhythm in rats. *J Appl Physiol (1985)*, *118*(3), 310–318. https://doi.org/10.1152/japplphysiol.00811.2014

Martin, T., Moussay, S., Bulla, I., Bulla, J., Toupet, M., Etard, O., … Quarck, G. (2016). Exploration of Circadian Rhythms in Patients with Bilateral Vestibular Loss. *PLOS ONE*, *11*(6), e0155067. https://doi.org/10.1371/journal.pone.0155067

Accepted Manuscript

ACCEPTED MANUSCRIPT

Mast, F. W., Preuss, N., Hartmann, M., & Grabherr, L. (2014). Spatial cognition, body representation and affective processes: the role of vestibular information beyond ocular reflexes and control of posture. *Frontiers in Integrative Neuroscience*, *8*, 44. https://doi.org/10.3389/fnint.2014.00044

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Morris, N., & Jones, D. M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology*, *81*(2), 111–121. https://doi.org/10.1111/j.2044-8295.1990.tb02349.x

Moser, I., Vibert, D., Caversaccio, M. D., & Mast, F. W. (2016). Acute peripheral vestibular deficit increases redundancy in random number generation. *Experimental Brain Research*, 1–11. https://doi.org/10.1007/s00221-016-4829-8

Mussolin, C., De Volder, A., Grandin, C., Schlögel, X., Nassogne, M.-C., & Noël, M.-P. (2010). Neural correlates of symbolic number comparison in developmental dyscalculia. *Journal of Cognitive Neuroscience*, *22*(5), 860–74. https://doi.org/10.1162/jocn.2009.21237

Nicenboim, B. (2016). (Submitted) Statistical methods for linguistic research : Foundational Ideas -Part II Statistical methods for linguistic research : Foundational Ideas - Part II. *arXiv Preprint arXiv:1602.00245*, *293928448*(April), 591–613. https://doi.org/10.1111/lnc3.12207

Noël, M.-P., Rousselle, L., & Mussolin, C. (2005). Magnitude representation in children: Its development and dysfunction. In J. I. D. Campbell (Ed.), *Handbook of Mathematical Cognition* (pp. 179–195). Hove, UK.

Nuerk, H.-C., Wood, G., & Willmes, K. (2005). The Universal SNARC Effect. *Experimental Psychology*, *52*(3), 187–194. https://doi.org/10.1027/1618-3169.52.3.187

Palmer, E. M., Horowitz, T. S., Torralba, A., & Wolfe, J. M. (2011). What are the shapes of response time distributions in visual search? *Journal of Experimental Psychology: Human Perception and Performance*, *37*(1), 58–71. https://doi.org/10.1037/a0020747

Parsons, S., & Bynner, J. (2005). *Does numeracy matter more?* London: National Research and Development Centre for Adult Literacy and Numeracy.

Passolunghi, M. C., & Pazzaglia, F. (2004). Individual differences in memory updating in relation to arithmetic problem solving. *Learning and Individual Differences*, *14*(4), 219–230. https://doi.org/10.1016/j.lindif.2004.03.001

Paulesu, E., Frith, C. D., & Frackowiak, R. S. J. (1993). The neural correlates of the verbal component of working memory. *Nature*, *362*(6418), 342–345. https://doi.org/10.1038/362342a0

Peirce, J. W. (2007). PsychoPy-Psychophysics software in Python. *Journal of Neuroscience Methods*, *162*(1–2), 8–13. https://doi.org/10.1016/j.jneumeth.2006.11.017

Péruch, P., Borel, L., Gaunet, F., Thinus-Blanc, G., Magnan, J., & Lacour, M. (1999). Spatial performance of unilateral vestibular defective patients in nonvisual versus visual navigation. *Journal of Vestibular Research-Equilibrium & Orientation*, *9*(1), 37–47.

Péruch, P., Borel, L., Magnan, J., & Lacour, M. (2005). Direction and distance deficits in path integration after unilateral vestibular loss depend on task complexity. *Cognitive Brain Research*, *25*(3), 862–872. https://doi.org/10.1016/j.cogbrainres.2005.09.012

Péruch, P., Lopez, C., Redon-Zouiteni, C., Escoffier, G., Zeitoun, A., Sanjuan, M., … Borel, L.

Accepted manuscript

ACCEPTED MANUSCRIPT

(2011). Vestibular information is necessary for maintaining metric properties of representational space: Evidence from mental imagery. *Neuropsychologia*, *49*(11), 3136–3144. https://doi.org/10.1016/j.neuropsychologia.2011.07.026

Pina, V., Castillo, A., Kadosh, R. C., & Fuentes, L. J. (2015). Intentional and automatic numerical processing as predictors of mathematical abilities in primary school children. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.00375

Price, C. J. (1998). The functional anatomy of word comprehension and production. *Trends in Cognitive Sciences*. https://doi.org/10.1016/S1364-6613(98)01201-7

Price, C. J. (2000). The anatomy of language: contributions from functional neuroimaging. *Journal of Anatomy*, *197*(3), 335–359. https://doi.org/10.1046/j.1469-7580.2000.19730335.x

Price, G. R., Holloway, I. D., Rasanen, P., Vesterinen, M., & Ansari, D. (2007). Impaired parietal magnitude processing in developmental dyscalculia. *Current Biology*, *17*(24), R1042–R1043. https://doi.org/10.1016/j.cub.2007.10.013

R Core Team. (2015). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.r-project.org/.

Redfern, M. S., Talkowski, M. E., Jennings, J. R., & Furman, J. M. (2004). Cognitive influences in postural control of patients with unilateral vestibular loss. *Gait & Posture*, *19*(2), 105–114. https://doi.org/10.1016/S0966-6362(03)00032-8

Risey, J., & Briner, W. (1990). Dyscalculia in patients with vertigo. *Journal of Vestibular Research*, *1*(1), 31–37.

Rubinsten, O., & Henik, A. (2005). Automatic activation of internal magnitudes: a study of developmental dyscalculia. *Neuropsychology*, *19*(5), 641–648. https://doi.org/10.1037/0894-4105.19.5.641

Rubinsten, O., & Henik, A. (2009). Developmental Dyscalculia: heterogeneity might not mean different mechanisms. *Trends in Cognitive Sciences*, *13*(2), 92–99. https://doi.org/10.1016/j.tics.2008.11.002

Rubinsten, O., Henik, A., Berger, A., & Shahar-Shalev, S. (2002). The development of internal representations of magnitude and their association with Arabic numerals. *Journal of Experimental Child Psychology*, *81*(1), 74–92. https://doi.org/10.1006/jecp.2001.2645

Russell, N. A., Horii, A., Smith, P. F., Darlington, C. L., & Bilkey, D. K. (2003). Bilateral peripheral vestibular lesions produce long-term changes in spatial learning in the rat. *Journal of Vestibular Research : Equilibrium & Orientation*, *13*(1), 9–16. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/14646020

Schautzer, F., Hamilton, D., Kalla, R., Strupp, M., & Brandt, T. (2003). Spatial memory deficits in patients with chronic bilateral vestibular failure. *Annals of the New York Academy of Sciences*, *1004*(1), 316–324. https://doi.org/10.1196/annals.1303.029

Shaki, S., & Fischer, M. H. (2014). Random walks on the mental number line. *Experimental Brain Research*, *232*(1), 43–49. https://doi.org/10.1007/s00221-013-3718-7

Simon, O., Mangin, J.-F., Cohen, L., Le Bihan, D., & Dehaene, S. (2002). Topographical Layout of Hand, Eye, Calculation, and Language-Related Areas in the Human Parietal Lobe. *Neuron*, *33*(3), 475–487. https://doi.org/10.1016/S0896-6273(02)00575-5

Smith, P. F. (2012). Dyscalculia and vestibular function. *Medical Hypotheses*, *79*(4), 493–496. https://doi.org/10.1016/J.Mehy.2012.06.032

Smith, P. F., Zheng, Y. W., Horii, A., & Darlington, C. L. (2005). Does vestibular damage cause cognitive dysfunction in humans? *Journal of Vestibular Research-Equilibrium &*

Accepted Manuscript

ACCEPTED MANUSCRIPT

Orientation, *15*(1), 1–9.
Stackman, R. W., & Herbert, A. M. (2002). Rats with lesions of the vestibular system require a visual landmark for spatial navigation. *Behav Brain Res*, *128*(1), 27–40. https://doi.org/10.1016/S0166-4328(01)00270-4
St Clair-Thompson, H. L., & Gathercole, S. E. (2006). Executive functions and achievements in school: Shifting, updating, inhibition, and working memory. *The Quarterly Journal of Experimental Psychology*, *59*(4), 745–759. https://doi.org/10.1080/17470210500162854
Steiner, E. T., & Ashcraft, M. H. (2012). Three brief assessments of math achievement. *Behavior Research Methods*, *44*(4), 1101–7. https://doi.org/10.3758/s13428-011-0185-6
Steinhauser, M., & Hübner, R. (2009). Distinguishing response conflict and task conflict in the Stroop task: evidence from ex-Gaussian distribution analysis. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(5), 1398–1412. https://doi.org/10.1037/a0016467
Talkowski, M. E., Redfern, M. S., Jennings, J. R., & Furman, J. M. (2005). Cognitive requirements for vestibular and ocular motor processing in healthy adults and patients with unilateral vestibular lesions. *Journal of Cognitive Neuroscience*, *17*(9), 1432–1441. https://doi.org/10.1162/0898929054985419
Tang, J., Critchley, H. D., Glaser, D. E., Dolan, R. J., & Butterworth, B. (2006). Imaging informational conflict: A functional magnetic resonance imaging study of numerical stroop. *Journal of Cognitive Neuroscience*, *18*(12), 2049–2062. https://doi.org/DOI 10.1162/jocn.2006.18.12.2049
van der Sluis, S., de Jong, P. F., & van der Leij, A. (2007). Executive functioning in children, and its relations with reasoning, reading, and arithmetic. *Intelligence*, *35*(5), 427–449. https://doi.org/10.1016/j.intell.2006.09.001
van der Ven, S. H. G., Kroesbergen, E. H., Boom, J., & Leseman, P. P. M. (2012). The development of executive functions and early mathematics: A dynamic relationship. *British Journal of Educational Psychology*, *82*(1), 100–119. https://doi.org/10.1111/j.2044-8279.2011.02035.x
von Aster, M. G., & Shalev, R. S. (2007). Number development and developmental dyscalculia. *Developmental Medicine and Child Neurology*, *49*(11), 868–873.
Wagenmakers, E.-J. (2007). A practical solution to the pervasive problems of p-values. *Psychonomic Bulletin & Review*, *14*(5), 779–804. https://doi.org/10.3758/BF03194105
Wilkinson, G. S., & Robertson, G. J. (2006). Wide Range Achievement Test (WRAT4). *Psychological Assessment Resources*. Retrieved from http://www.v-psyche.com/doc/MENTAL ABILITY/Wide Range Achievement Test 4 (WRAT-4).doc
Yardley, L., Gardner, M., Bronstein, A., Davies, R., Buckwell, D., & Luxon, L. (2001). Interference between postural control and mental task performance in patients with vestibular disorder and healthy controls. *Journal of Neurology Neurosurgery and Psychiatry*, *71*(1), 48–52. https://doi.org/10.1136/Jnnp.71.1.48
Yardley, L., Papo, D., Bronstein, A., Gresty, M., Gardner, M., Lavie, N., & Luxon, L. (2002). Attentional demands of continuously monitoring orientation using vestibular information. *Neuropsychologia*, *40*(4), 373–383. https://doi.org/10.1016/S0028-3932(01)00113-0
Zamarian, L., Ischebeck, A., & Delazer, M. (2009). Neuroscience of learning arithmetic—Evidence from brain imaging studies. *Neuroscience & Biobehavioral Reviews*, *33*(6), 909–925. https://doi.org/10.1016/j.neubiorev.2009.03.005

Accepted manuscript

ACCEPTED MANUSCRIPT

Table 1

Demographics and clinical data of the patients with peripheral vestibular deficit (PVD) and healthy controls.

	Patients with PVD	healthy controls
N	20	21
sex (female / male)	9 / 11	10 / 11
Age (M; SD)	47.11 (13.55)	46.19 (13.75)
Handedness (right /left)	18 / 2	19 / 2
Vertigo onset interval (days)	11.1 (5.48)	-
Neurotological examination (abnormal / normal / n.a)		
- bithermal caloric testing	20 / 0 / 0	-
- pendular rotatory testing	11 / 9 / 0	-
- cervical vestibular evoked myogenic potentials	5 / 14 / 1	-
- video head impulse test	10 / 10 / 0	-
- dynamic visual acuity	5 / 14 / 1	-

Notes.

n.a. not assessed

Accepted manuscript

ACCEPTED MANUSCRIPT

Table 2. *Model summary of the Brief Math Assessment (BMA).*

Parameter	Estimate	CrI	Eff.sample	Rhat
intercept	1.41	[-3.44 ; 6.73]	1070	1
grouppatients	-1.54	[-2.91 ; -0.30]	2742	1
educ3	2.31	[-0.54 ; 5.4]	1955	1
educ4	2.86	[0.09 ; 5.95]	2025	1
educ5	3.56	[0.59 ; 6.67]	2006	1

Accepted manuscript

ACCEPTED MANUSCRIPT

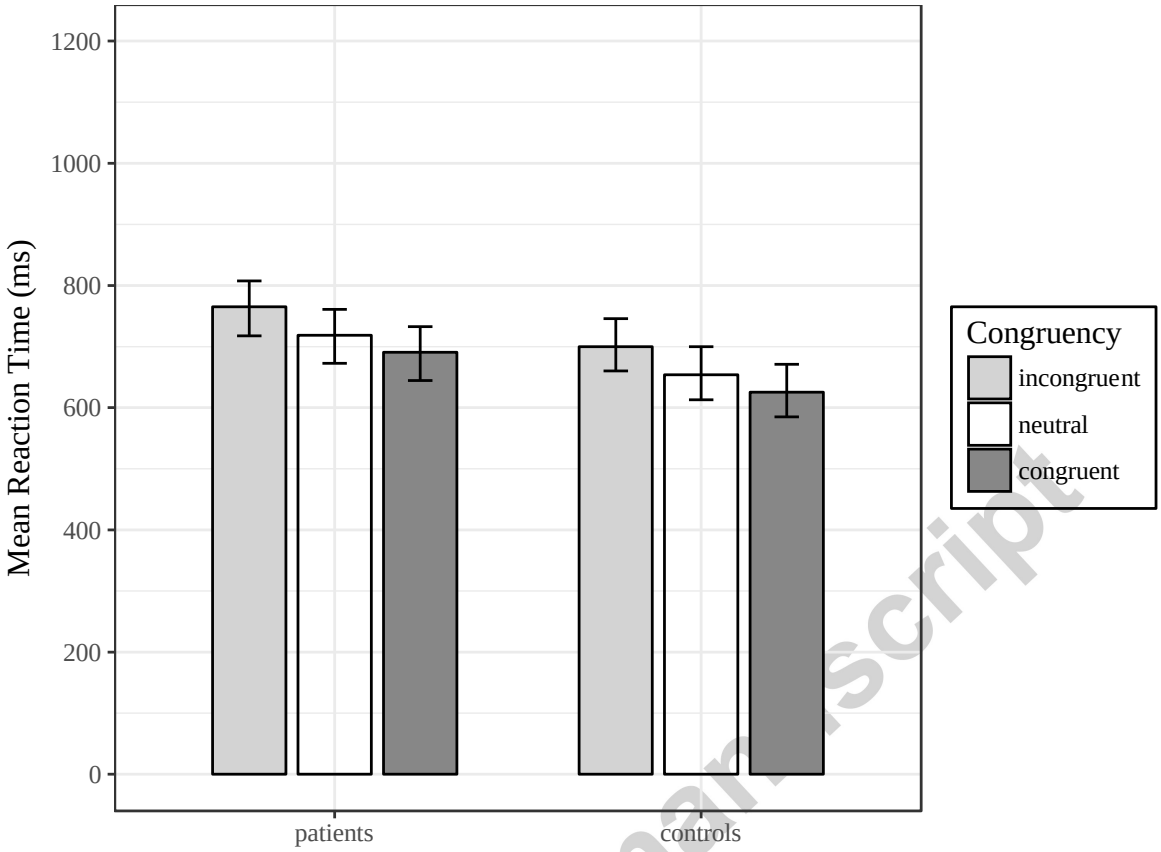


Figure 1. Posterior estimates of mean reaction times and 95 % credible intervals for the congruency effect in the numerical number Stroop task.

Accepted manuscript

ACCEPTED MANUSCRIPT

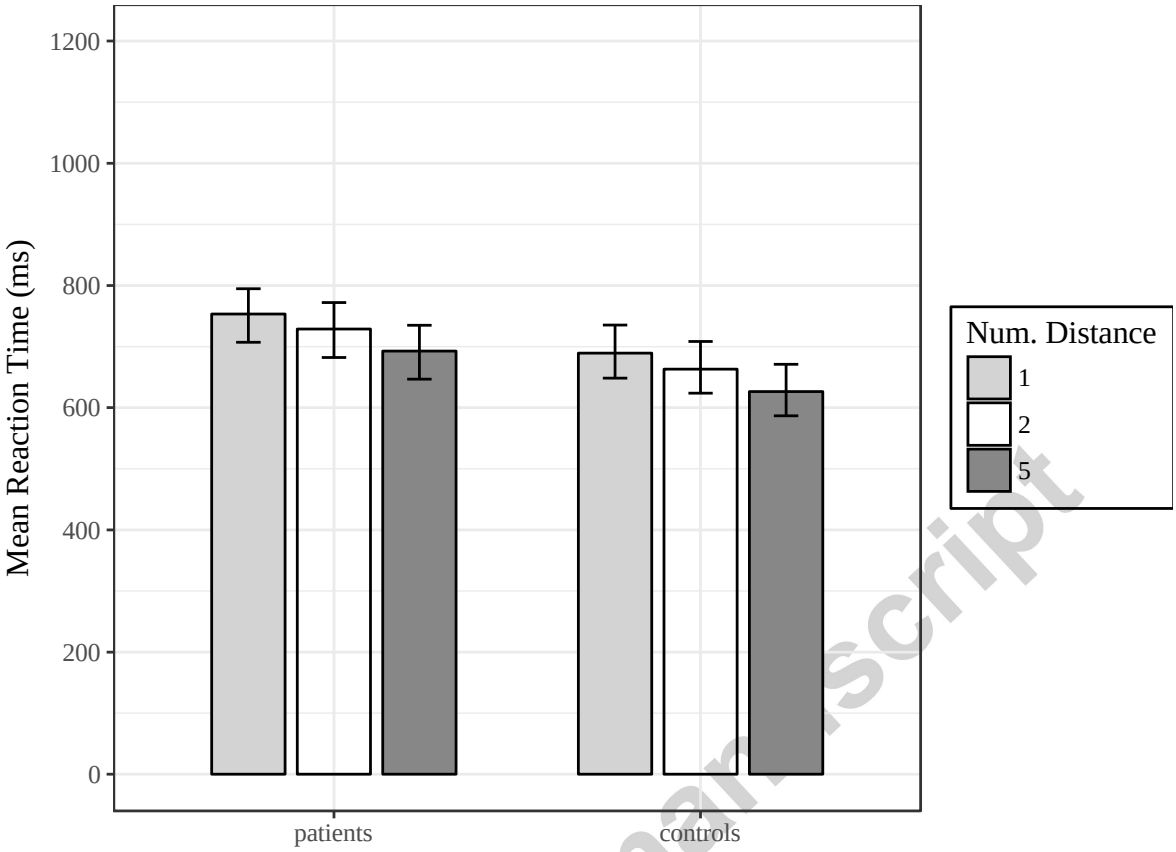


Figure 2. Posterior estimates of mean reaction times and 95 % credible intervals for the number distance effect in the numerical number Stroop task.

Accepted manuscript

ACCEPTED MANUSCRIPT

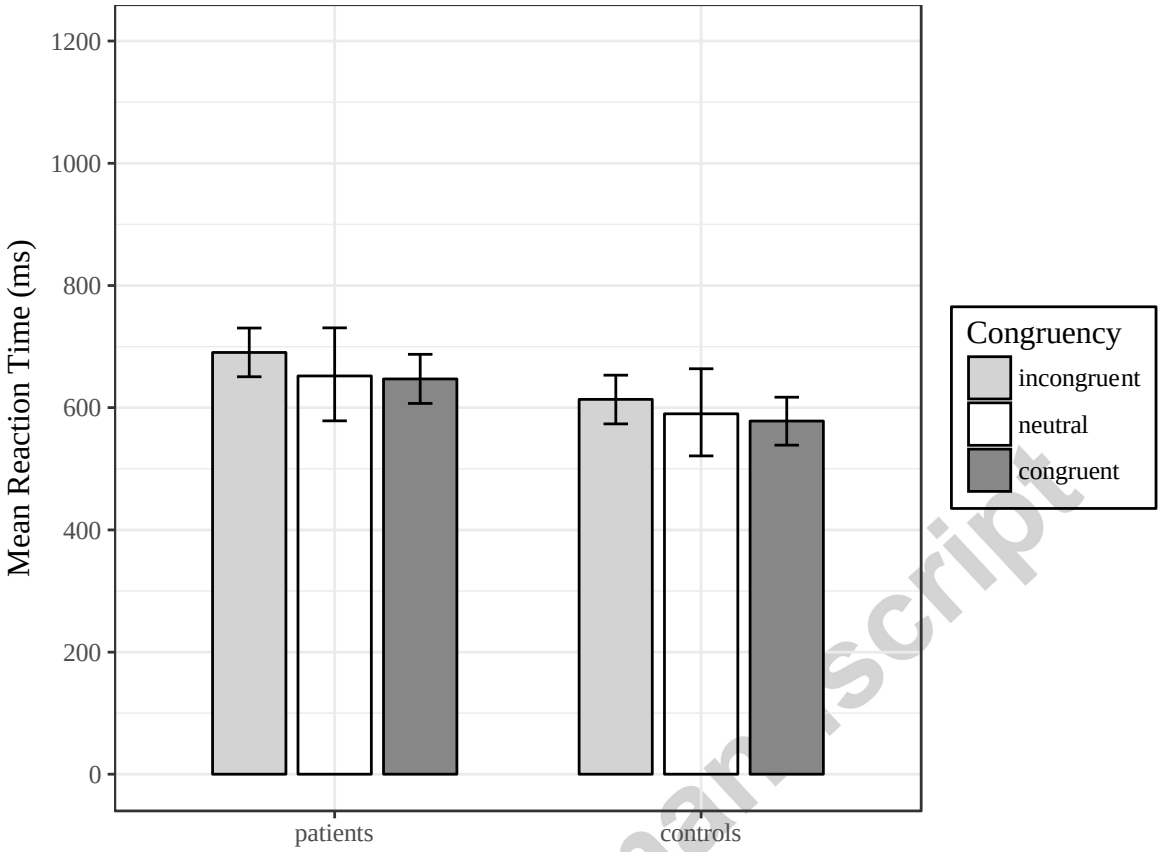


Figure 3. Posterior estimates of mean reaction times and 95 % credible intervals for the congruency effect in the physical number Stroop task.

Accepted manuscript

ACCEPTED MANUSCRIPT

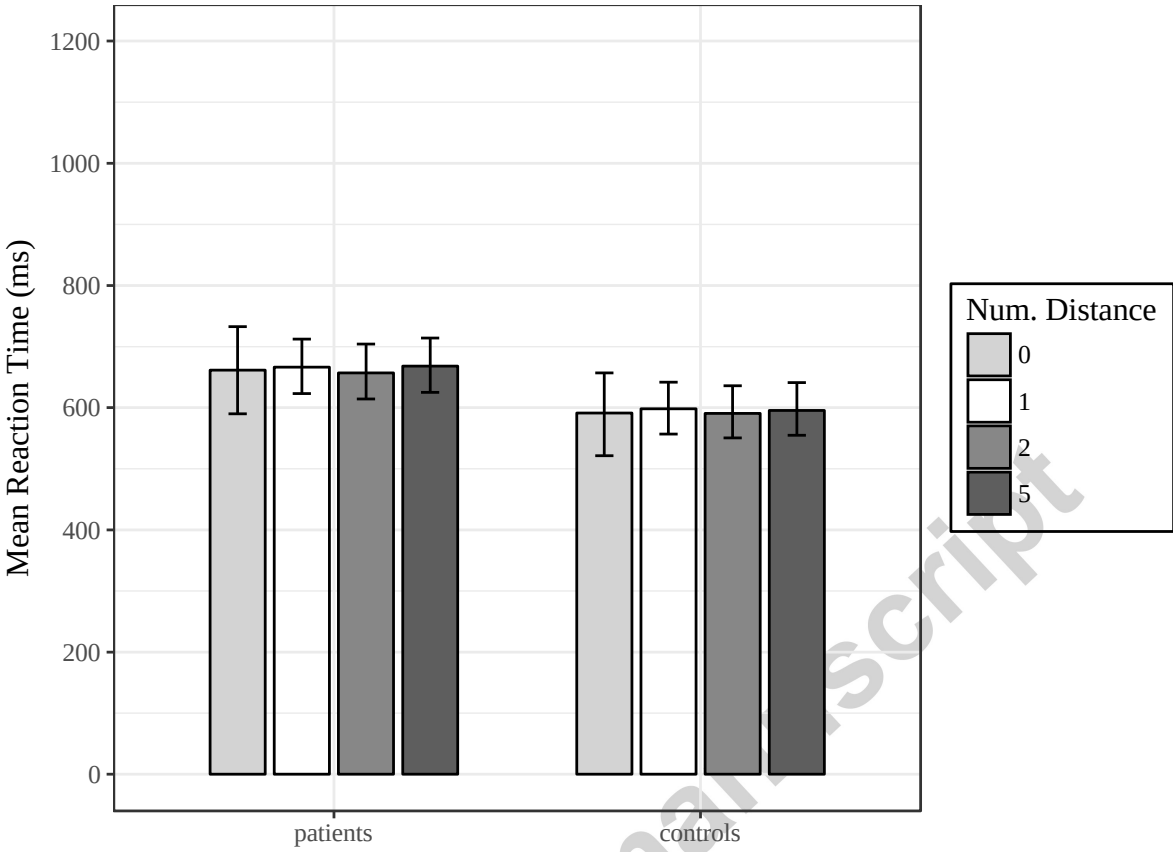


Figure 4. Posterior estimates of mean reaction times and 95 % credible intervals for the number distance effect in the physical number Stroop task.

Accepted manuscript

Highlights

- Patients with acute vestibular neuritis perform show worse math performance.
- No difference in the number stroop task reflects intact number processing.
- Results are inconsistent with a number specific deficit (i.e., dyscalculia)
- Vestibular neuritis leads to a decline in executive functions.