How do incorrect results change the processing of arithmetic information? Evidence from a divided visual field experiment

Running head: Arithmetic information processing

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Abstract

Despite several recent important developments in understanding numerical processing of both isolated numbers and numbers in the context of arithmetic equations, the relative impact of congruency on high, compared to low, level processing remains unclear. The current study investigated hemispheric differences in the processing of arithmetic material, as a function of semantic and perceptual congruency, using a delayed answer verification task and divided visual field paradigm. A total of 37 participants (22 females and 15 males, mean age 30.06, SD 9.78) were presented unilaterally or bilaterally with equation results that were either correct or incorrect and had a consistent or inconsistent numerical notation. Statistical analyses showed no visual field differences in a notation consistency task, whereas when judgements had to be made on mathematical accuracy there was a right visual field advantage for incorrect equations that were notation consistent. These results reveal a clear differential processing of arithmetic information by the two cerebral hemispheres with a special emphasis on erroneous calculations. Faced with incorrect results and with a consistent numerical notation, the left hemisphere outperforms its right counterpart in making mathematical accuracy decisions.

Keywords: Hemispheric specialisation, mathematical cognition, number notation, accuracy, divided visual field

As a general rule, maths and language have been demonstrated to share specialisation in the same cerebral hemisphere (Semenza at al., 2006). The left hemisphere, for instance, has been found to be superior to the right for mathematical processing under a split-brain clinical condition (Funnell, Colvin, & Gazzaniga, 2007). This is consistent with Sperry, Gazzaniga, and Bogen’s (1969) seminal work on commissurotomized patients using lateralized presentation and underlines a left hemisphere specialisation for calculation. The lateralized presentation is achieved, even in neurologically intact participants, by means of the divided visual field methodology (Bourne, 2006). However, it is not the case that the left hemisphere outperforms its right counterpart whatever the numerical task, and the lateralisation of some numeric processes remains unclear.

Number comparison, based on notation, i.e. where the number is presented as an arabic digit or word, has generally been found to produce no hemispheric differences (e.g., Ratinckx, Brysbaert, & Reynvoet, 2001). This equivalent bilateral representation of number magnitude (Reynvoet & Ratinckx, 2004) can be interpreted as suggesting that an analogical quantity representation exists in both hemispheres, which would be in agreement with Dehaene’s (1992) triple-code model. According to this theoretical framework of number processing (Dehaene & Cohen, 1997; Dehaene, Piazza, & Pinel, 2003), numbers can be mentally manipulated in an arabic, verbal or analogical magnitude form. The visual arabic code represents numbers as strings of digits. In the verbal/auditory code, numbers are represented as words. The analogue magnitude code, on the other hand, is modality independent and represents numerical quantities over an analogical number line. Additionally, due to the relevance of spatial position in certain calculation tasks (e.g., where operands have two or more digits) as well as other stimulus characteristics (e.g., verbal vs. non-verbal numerical indicators), a right hemisphere advantage has been reported (Troup, Bradshaw, & Nettleton, 1983). Thus, evidence indicates that not only the format of the numerical information is important in visual field experiments (Boles, 1986), but also the task requirements, as suggested by Ratinckx and collaborators (2001). Moreover, the use of mathematical equations and their semantic processing has allowed for the possibility of the analysis of cognitive processes that go beyond those explored in previous number comparison studies where only two externally presented figures had to be compared.

In tasks that require a decision on the veracity of equations, participants tend to take longer to recognize incorrect equations as incorrect than they do to recognize correct equations as correct (Zbrodoff & Logan, 2000). The processing of incorrect problems in this context may require resolving the interference between the internally computed and externally presented incorrect answer after the incorrect result had been detected (Menon, Mackenzie, Rivera, & Reiss, 2002). This, therefore, could be interpreted as an arithmetic Stroop(-like) effect in which the presentation of a semantically incongruent answer interfered with the participants' ability to produce the correct response (Zbrodoff & Logan, 2000).

It is also well established that the perception of specific number information, such as verbal or visuospatial information, is deemphasized in magnitude judgment in contrast to number recognition tasks (Boles, 1986; Ratinckx & Brysbaert, 2002). Consequently, how numbers are mentally represented has been hypothesized to be influenced by the processing level of the task (Liang et al., 2012). Those tasks for which a low-level processing is sufficient have exhibited a numerical notation-dependent effect, whereas tasks that rely on a deeper magnitude processing utilize an abstract numerical representation. It is currently unclear, however, how level of processing (perceptual or notation) might mediate mathematical accuracy resolution or semantic processing in a number comparison task where information relevance is decided in a top-down fashion.

Generally, it has been demonstrated that number comparison tasks produce no hemispheric difference (Ratinckx, Brysbaert, & Reynvoet, 2001). This could be due to the simplicity of the tasks as when greater arithmetic resources are required there tends to be a left hemisphere bias (Funnell, Colvin, & Gazzaniga, 2007). Moreover, consistent with Zbrodoff and Logan (2000), the present study hypothesized that under relevant and demanding mathematical conditions incorrect equations would take longer to resolve but that accuracy rates would also be greater. It was anticipated that mathematical accuracy resolution would be further influenced by notation consistency (Liang et al., 2012), in a way that is dependent on hemispheric processing. Such an interaction would be expected if greater complexity is indeed required to tease apart the hemispheric functional asymmetry of arithmetic processing. Apart from the specific profile in terms of accuracy and notation, the left hemisphere could act just as well as both hemispheres together (Marks & Hellige, 2003), or the bilateral redundancy gain that results from projecting the same information on both visual fields could surpass not just right- but also left hemisphere performance.

METHOD

Participants

Participants were 22 female and 15 male volunteers, recruited by internal institutional advertisement, and aged between 20 and 54 years old (mean 30.06, SD 9.78). All of them were right-handed (Oldfield, 1971), had normal or corrected-to-normal vision and their first language was English. There was no self-reported history of neurological dysfunction, psychological disorder, language difficulty or mathematical impairment. In addition, they all gave written informed consent and every aspect of the research adhered to ethical clearance granted by the university where the work was conducted.

Materials

A total of 180 arithmetic equations were created attending to notation consistency and mathematical accuracy. In terms of numerical notation (verbal or arabic) consistency, that used for the first part of the equation could match or not the notation used for the equation result. In terms of mathematical accuracy, the equation result, or target stimulus, could be either correct or incorrect. There were as many correct equation results as incorrect equation results and as many notation consistent equations as notation inconsistent equations. Specifically, equation results could be correct and consistent in notation (e.g., 3+4=7), correct but inconsistent in notation (e.g., 3x2=six), incorrect but notation consistent (e.g., 9-6=4), and incorrect and notation inconsistent (e.g., 8÷4=three). They could also be presented on either the left-, right- or both visual fields. This was done according to an experimental design with 12 cells, where each cell had 15 equations: 4 additions, 4 subtractions, 4 multiplications, and 3 divisions.

All stimuli were presented in black colour over a white background. The first part of the equation, or problem, was displayed horizontally in the centre of the screen, extending a maximum of 10.6 degrees of visual angle by 1.1 degrees of visual angle horizontally and vertically. Equation results, also shown horizontally, were presented after each problem at 6.5 degrees of visual angle left and/or right of the fixation mark, measured from the centre of the stimulus to the centre of the fixation mark. Equation length was matched across conditions in terms of number of characters, for the first part of the equation as well as for the equation result.

The minimum result for correct equations was 2 and the maximum was 20, while incorrect answers could be -1/+1 or -3/+3 from the correct solution. As problems with 0 and 1 operands (e.g., 0+4, 1x6) are rule-based arithmetic facts (LeFevre and Liu, 1997), they were not utilized. Repeated-operand or “tie” problems (e.g., 7+7, 2x2) were not included either because they differ in operand encoding from non-tie problems (Blankenberger, 2001).

Procedure

The session started by explaining to participants what was meant by “mathematical accuracy” and “notation consistency”, providing them with a few examples of each and instructing them on how to complete the following test. Although equations could be either accurate or inaccurate and consistent or inconsistent, instructions in the mathematical accuracy task required participants to respond only according to whether the equation result was accurate or inaccurate. Likewise, in the notation consistency task participants had to respond only according to whether or not the same notation was used in the first and second parts of the equation.

The test was run on SuperLab® software beginning with a practice session consisting of 24 trials for “notation consistency” and another 24 for “mathematical accuracy”. Trial feedback was provided and instruction reminders were displayed after every 8 trials. The main experiment consisted of 180 randomized equations presented twice, once for “mathematical accuracy” and once for “notation consistency” in blocks that were counterbalanced. In addition, no performance feedback was provided at this stage and there was an optional 5 minute break between tasks. Throughout the experiment, participants were seated 57cm from the computer screen with their head supported by a chin rest.

Each trial began with the first part of an equation being shown in the centre of the screen for 1000ms. This was followed by a central cross-hair displayed for another 1000ms on which fixation was required. The equation answer was then presented for 150ms to either the left, right, or both visual fields. After that, a backward mask in the form of a random dot array followed for up to 5000ms when participants had to respond as quickly and as accurately as possible by indicating whether the solution displayed was correct or incorrect in one of the blocks of stimuli, or whether the number notation was consistent or inconsistent in the other block of stimuli. Once participants had responded, the screen became blank for 1500ms, before the first part of the next equation was presented and with it the next trial began.

When the response was based on mathematical accuracy, using a colour-coded response pad, participants had to respond by pressing a green key if the correct answer of the equation was displayed, or by pressing a red key if the incorrect answer was displayed. When the response was based on notation consistency, participants had to press the green key if the equation and answer were notation consistent, and the red key otherwise. Response hand and key on which the index and middle finger rested were counterbalanced between participants. The two measures taken throughout were reaction time and accuracy. An overall acceptable accuracy proportion was considered to be 0.75 or higher and all reaction times from correct responses that fell between 300ms and 4000ms were used in the statistical analysis.

RESULTS

Data were analysed using four repeated-measures factorial ANOVAs (notation [consistent, inconsistent] x accuracy [correct, incorrect] x visual field [left, right, both]); one for each of the two dependent variables (accuracy and reaction time) in the two experimental tasks. One of the tasks required participants to answer according to notation consistency, the other according to mathematical accuracy. Significant main and interaction effects were further investigated using lower order ANOVA and paired-samples t-tests. Greenhouse–Geisser corrections are reported whenever the assumption of sphericity was violated.

When completing the notation consistency task (Table 1), responses were significantly faster [$F(1, 36) = 27.17$, $MSE = 15325$, $p = .001$] in the notation consistent condition (mean = 849, SD = 289) than in the notation inconsistent condition (mean = 910, SD = 276). In terms of proportion of correct responses, there was a significant interaction between notation consistency and mathematical accuracy [$F(1, 36) = 4.75$, $MSE = 0.007$, $p = .036$, see Fig. 1]. There was a higher proportion of correct responses for notation consistent compared to inconsistent conditions, when equations were mathematically accurate [$t(36) = 3.57$, $p = .001$], than when they were not [$t(36) = 0.30$, $p = .765$]. Mathematical accuracy, in turn, only increased the proportion of correct responses when numerical notation was consistent [$t(36) = 2.04$, $p = .049$], not when it was inconsistent [$t(36) = 0.97$, $p = .338$].

(Please insert Table 1 about here.)

(Please insert Fig. 1 about here.)

In the mathematical accuracy task (Table 2), the proportion of correct responses was significantly greater [$F(1, 36) = 8.06$, $MSE = 0.005$, $p = .007$] when the result being reported by the equation was incorrect (mean = 0.948, SD = 0.047) than when it was correct (mean = 0.929, SD = 0.061). This superior accuracy came at a reaction time cost, as participants were significantly slower [$F(1, 36) = 40.23$, $MSE = 31778$, $p = .001$] at responding accurately to incorrect equations (mean = 856, SD = 283) than to correct ones (mean = 749, SD = 223).

Performance did not vary across visual field conditions in terms of accuracy [$F(2, 72) = 0.55$, $MSE = 0.002$, $p = .582$]; however, it did vary in terms of reaction time [$F(1.69, 60.67) = 3.49$, $MSE = 14751$, $p = .044$]. Correct responses were significantly faster [$t(36) = 3.16$, $p = .003$] when the stimuli were shown to both visual fields (mean = 789, SD = 252) than to just the left visual field (mean = 822, SD = 269). There were no significant differences between presenting the stimuli on both visual fields compared to just the right visual field regardless of notation consistency and mathematical accuracy [$t(36) = 0.68$, $p = .503$] or showing the response on the left visual field vs. on its right counterpart [$t(36) = 1.60$, $p = .119$].

There was a significant notation consistency by visual field interaction in terms of proportion of correct responses [$F(2, 72) = 4.89$, $MSE = 0.003$, $p = .010$], which as depicted in Fig. 2 was qualified by the mathematical accuracy of the equation result being reported [$F(1.62, 58.26) = 3.55$, $MSE = 0.005$, $p = .044$]. There were no significant differences in terms of the proportion of correct responses between the 3 levels of visual field when mathematical accuracy was correct and the numerical notation was consistent [$F(2, 72) = 0.07$, $MSE = 0.003$, $p = .933$] or inconsistent [$F(2, 72) = 0.89$, $MSE = 0.004$, $p = .417$]. This was also the case when the equation reported an incorrect result in the notation inconsistent condition [$F(2, 72) = 2.50$, $MSE = 0.002$, $p = .090$], but changed for the notation consistent condition [$F(2, 72) = 6.95$, $MSE = 0.003$, $p = .002$].

When mathematical accuracy was incorrect and numerical notation was consistent, the proportion of correct responses was higher on the right visual field than on the left visual field [$t(36) = 3.30$, $p = .002$] and on both visual fields than on the left visual field [$t(36) = 2.87$, $p = .007$]. There were no significant differences between the right visual field and both visual fields [$t(36) = 0.31$, $p = .755$]. In addition when mathematical accuracy was incorrect, performance on both visual fields was better in the case of numerical notation consistency than on numerical notation inconsistency [$t(36) = 2.05$, $p = .047$]. A similar trend was shown on the right visual field [$t(36) = 1.95$, $p = .060$], whereas the opposite pattern of results was found on the left visual field [$t(36) = 3.57$, $p = .001$].

(Please insert Table 2 about here.)

(Please insert Fig. 2 about here.)

The above 3 way interaction for accuracy data was also significant [$F(2, 72) = 5.37$, $MSE = 8727$, $p = .007$] in the analysis of reaction times as illustrated in Fig. 3. There were no significant differences across the 3 visual field conditions when the equation reported a correct result and numerical notation was either consistent [$F(2, 72) = 0.12$, $MSE = 8802$, $p = .885$] or inconsistent [$F(2, 72) = .90$, $MSE = 11313$, $p = .410$], or even when the equation result was incorrect and numerical notation was inconsistent [$F(2, 72) = 0.86$, $MSE = 10147$, $p = .427$]. These findings matched those encountered in the analysis of proportion of correct responses. However, results differed when the equation result was incorrect and the numerical notation was consistent [$F(2, 72) = 9.29$, $MSE = 10310$, $p = .001$]. In this case, correct responses were significantly faster when the equation result was shown bilaterally than either on the right visual field [$t(36) = 2.26$, $p = .030$] or on the left visual field [$t(36) = 4.29$, $p = .001$]. Under these conditions, it also took participants less time to respond correctly when the equation result was shown on the right visual field than on the left visual field [$t(36) = 2.09$, $p = .044$]. Additionally, when incorrect equation results were presented bilaterally, reaction times were faster if the numerical notation was consistent [$t(36) = 2.81$, $p = .008$]. Results from other comparisons were not significant.

(Please insert Fig. 3 about here.)

DISCUSSION

This study has shown that in a mathematical accuracy task, where a deeper level of processing is required, the left hemisphere performs better and there is a bilateral redundancy gain, but only when numerical notation is consistent and mathematical accuracy is incorrect.

In a notation consistency task, where there is no hemispheric modulation, notation consistency increases the proportion of correct responses when mathematical accuracy is correct but not when it is incorrect. These results reveal clear differential processing of arithmetic information by the two cerebral hemispheres that is both task and stimulus dependent. When an incongruent amount with consistent numerical notation is presented, the left hemisphere outperforms its right counterpart in mathematical accuracy judgements.

As expected (Gebuis et al., 2010), responses were significantly faster in the notation consistent than in the notation inconsistent condition when completing the notation consistency task. The influence of notation consistency on proportion of correct responses also differed for correct and incorrect equations. This means that not only is there a numerical notation-dependent effect for low-level processing tasks (Liang et al., 2012), but that this effect can be modified by high level features. For correct equations, the proportion of correct responses increased with notation consistency, while for incorrect equations it remained unchanged. Contrary to findings in the mathematical accuracy task, visual field had no main or interaction effects either on accuracy or reaction time in the notation task.

In the mathematical accuracy task, where an internally computed equation result had to be compared with an externally presented one, the proportion of correct responses was significantly greater but responses were slower when the result displayed was incorrect than when it was correct. This confirms previous reports of fewer mistakes being made on incorrect equations (e.g., Gonzalez & Kolers, 1982). It is likely that processing incorrect equations involves the resolution of an interference effect (Menon et al., 2002) that stems from the reported equation result not matching the expected solution. This could lead to a recalculation which would explain the effect of improving accuracy, but also of increasing the amount of time required to complete the task. Zbrodoff and Logan (2000) have also found that subjects take longer to produce the result if the presented answer is false, as compared with when it is true. The current study has extended this work by investigating hemispheric functional asymmetry in the context of arithmetic processing. It shows a “bilateral redundancy gain” (Marks & Hellige, 2003; Ratinckx & Fias, 2007), that is, improved performance when identical copies of the stimulus are presented to both visual fields, relative to unilateral (left) single presentations. However, reaction times did not differ significantly between the left and right visual field conditions while completing the mathematical accuracy task.

The effect of notation consistency, while completing the mathematical accuracy task, was shown to depend not only on visual field but also on mathematical accuracy. This was the case for proportion of correct responses as well as reaction time. For correct mathematical accuracy, neither visual field nor notation consistency influenced performance. This result is consistent with the fact that simple number comparison, either with Arabic digits or word numbers, is equally well processed in the left and right hemisphere (Ratinckx & Brysbaert, 2002; Ratinckx, Brysbaert, & Reynvoet, 2001). It also suggests an equivalent bilateral representation of number magnitude in the cerebral hemispheres (Reynvoet & Ratinckx, 2004). However, for incorrect accuracy, visual field becomes relevant in the notation consistent condition. Here, there was a greater proportion of correct responses and shorter reaction times when equation results were displayed on the right visual field than on the left visual field. Under these conditions, the left hemisphere was superior to the right, confirming the previously reported left hemisphere specialization for calculation (Funnell, Colvin, & Gazzaniga, 2007; Zago et al., 2001). This left hemisphere advantage that the authors refer to when notation-consistent, incorrect equation results are being processed is in relation to performance by the right hemisphere. One of the areas in the left hemisphere that may play a special role in number comparison is the intraparietal sulcus (Kadosh et al., 2005). Prefrontal activation during mental calculation has also been shown to be lateralized in a manner similar to that reported during linguistic tasks (Burbaud et al., 1995), specially for processing incorrect equations (Menon et al., 2002). The limited right hemisphere ability to perform simple arithmetic operations (Cohen & Dehaene, 1996) was corroborated by reaction time results.

The interaction between notation consistency and targeted hemisphere, present when mathematical accuracy is violated but absent when mathematical accuracy is present, is not a finding that would be readily predictable by the neuro-anatomical model of number processing (Dehaene, 1992), but could further develop more recent versions of this model (e.g., Dehaene, Piazza, & Pinel, 2003). In addition, for incorrect accuracy and consistent notation, a reaction time bilateral gain was found relative to the right and left visual fields. There was also a greater proportion of correct responses when equation results were shown on both visual fields than on just the left visual field. These results complement the bilateral advantage shown during mental calculation (Hatta & Tsuji, 1993; Hatta & Yoshizaki, 1996) that is characteristic of interhemispheric collaboration. This would suggest that the processing power of the brain is enhanced when interhemispheric collaboration is possible. In addition when mathematical accuracy was incorrect, performance on the right and both visual field conditions was generally better in terms of proportion of correct responses when numerical notation was consistent –the opposite to what happened on the left visual field condition.

In conclusion, this study has found that mathematical processing, in terms of both response accuracy and speed, is not only dependent on which cerebral hemisphere first receives the information but also on the accuracy and notation consistency of the information to be processed. Faced with incorrect results and with a consistent numerical notation, the left hemisphere outperforms the right hemisphere in making mathematical accuracy judgements.

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Table 1

ANOVA results for each one of the two dependent variables in the notation consistency task.

	Accuracy					Reaction time				
Effect	*df*		*F*	*MSE*	*p*	*df*		*F*	*MSE*	*p*
NC	1	36	2.31	0.008	0.138	1	36	27.17	15325	**0.001**
MA	1	36	1.54	0.006	0.223	1	36	1.43	23591	0.240
NC x MA	1	36	4.75	0.007	**0.036**	1	36	1.38	13411	0.248
VF	2	72	0.22	0.005	0.801	1.62	58.21	1.86	17160	0.172
NC x VF	2	72	0.01	0.004	0.998	2	72	0.77	13988	0.465
MA x VF	2	72	1.46	0.003	0.238	2	72	1.20	10493	0.308
NC x MA x VF	2	72	0.02	0.006	0.979	2	72	0.51	8831	0.601

NC: notation consistency, MA: mathematical accuracy, VF: visual field.

Table 2

ANOVA results for each one of the two dependent variables in the mathematical accuracy task.

	Accuracy					Reaction time				
Effect	*df*		*F*	*MSE*	*p*	*df*		*F*	*MSE*	*p*
NC	1	36	0.01	0.004	0.918	1	36	0.05	14727	0.832
MA	1	36	8.06	0.005	**0.007**	1	36	40.23	31778	**0.001**
NC x MA	1	36	0.58	0.004	0.450	1	36	0.04	14214	0.839
VF	2	72	0.55	0.002	0.582	1.69	60.67	3.49	14751	**0.044**
NC x VF	2	72	4.89	0.003	**0.010**	2	72	1.52	11822	0.226
MA x VF	2	72	1.03	0.004	0.363	2	72	1.00	7594	0.373
NC x MA x VF	1.62	58.26	3.55	0.005	**0.044**	2	72	5.37	8727	**0.007**

NC: notation consistency, MA: mathematical accuracy, VF: visual field.

Figure captions

Fig. 1. Mean proportion of correct responses for correct and incorrect equations across consistent and inconsistent notations when the task was to report on notation consistency. Bars represent standard error.

Fig. 2. Mean proportion of correct responses for correct (a) and incorrect (b) equation results presented to the left, right and both visual fields using consistent and inconsistent notations. The task was to report on mathematical accuracy and bars represent standard error.

Fig. 3. Mean reaction times for correct (a) and incorrect (b) equation results presented to the left, right and both visual fields using consistent and inconsistent notations. The task was to report on mathematical accuracy and bars represent standard error.

Fig. 1

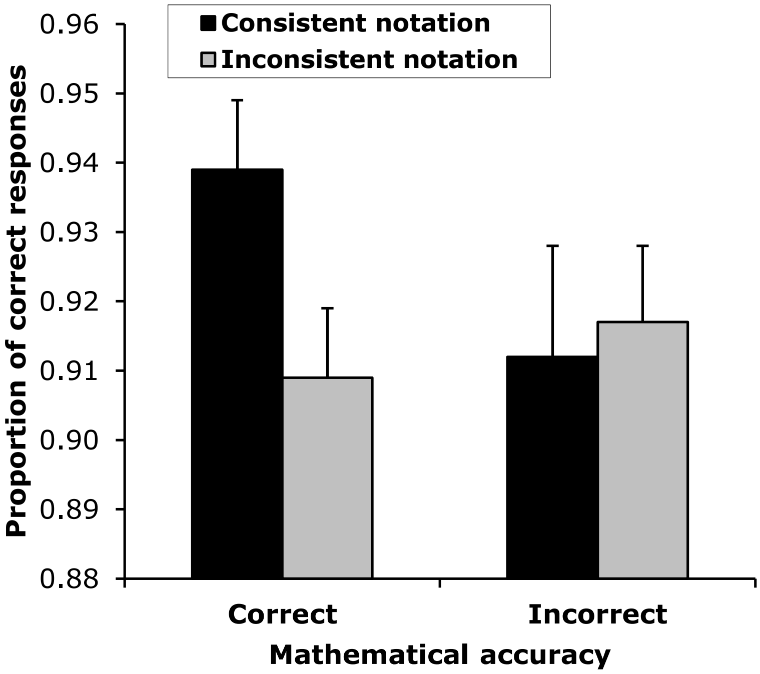
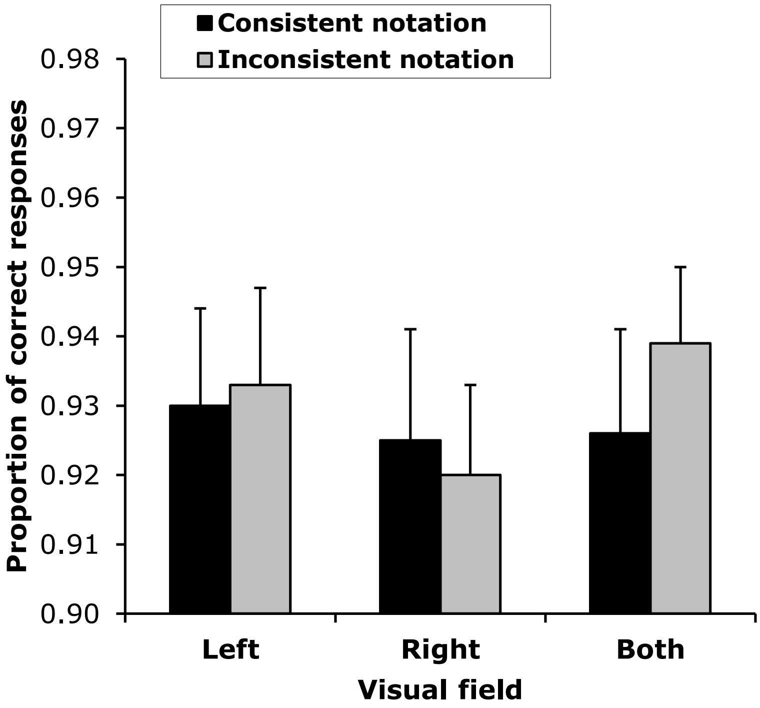

Consistent notation
Inconsistent notation
Proportion of correct responses
0.96
0.95
0.94
0.93
0.92
0.91
0.90
0.89
0.88
Correct
Incorrect
Mathematical accuracy

Fig. 2

a)


Consistent notation
Inconsistent notation
Proportion of correct responses
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.90
Left
Right
Both
Visual field

b)

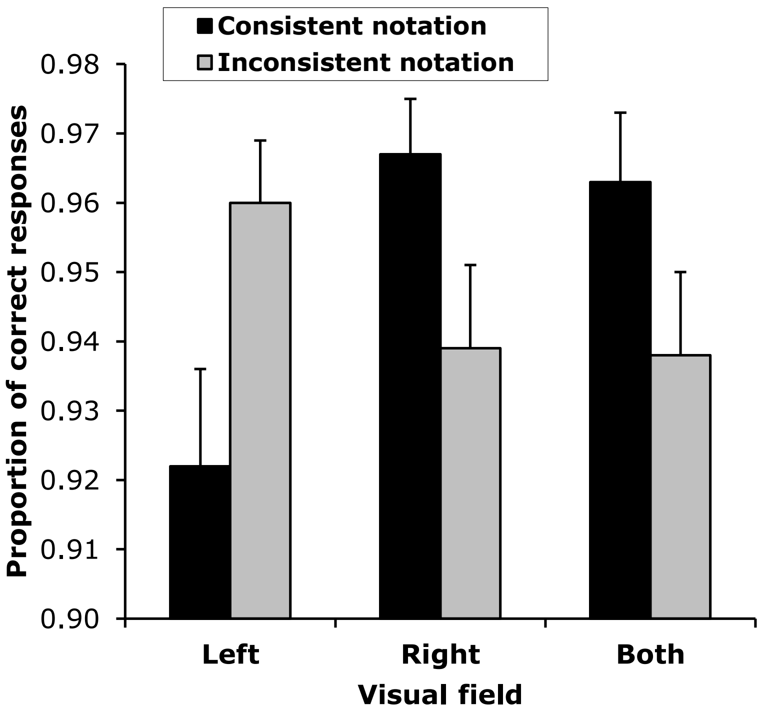
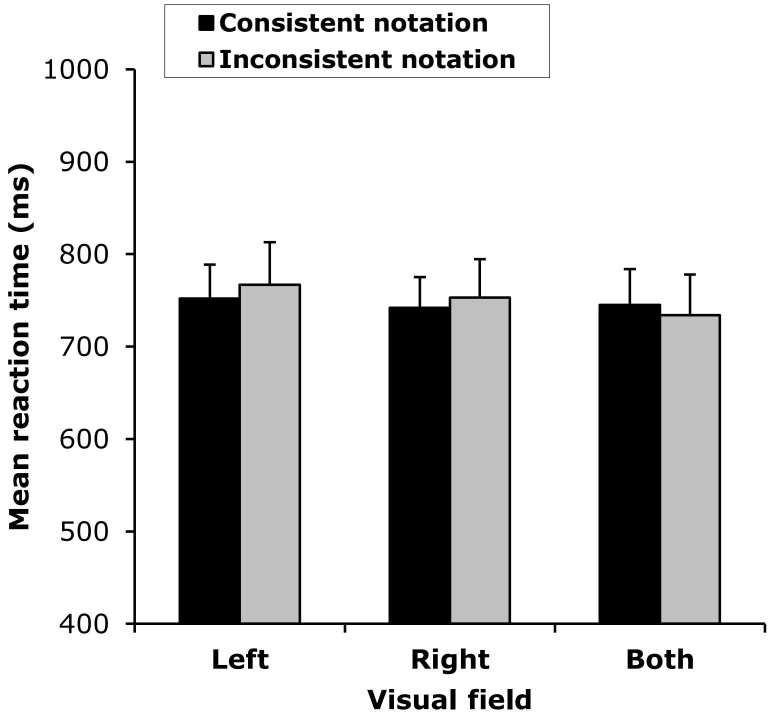
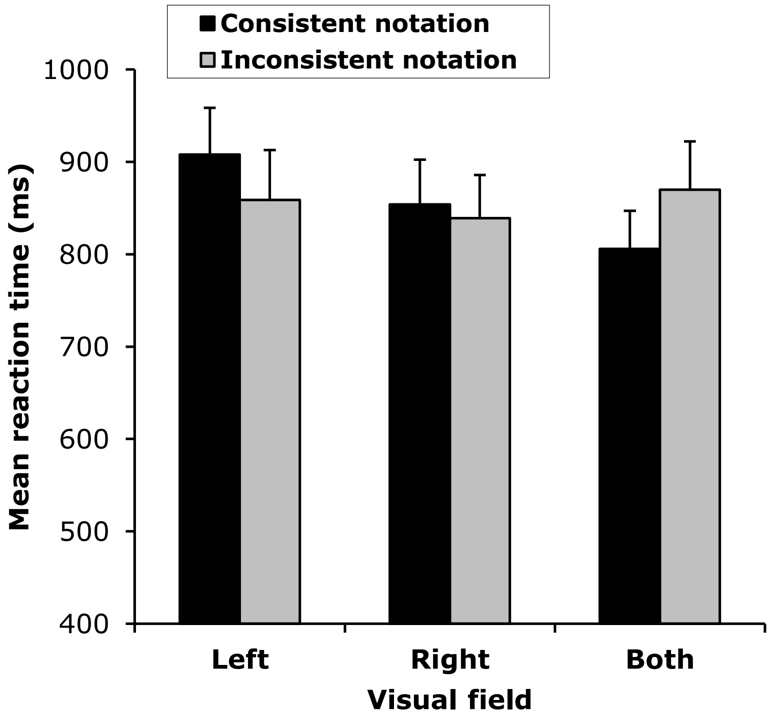

Consistent notation
Inconsistent notation
Proportion of correct responses
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.90
Left
Right
Both
Visual field

Fig. 3

a)


Consistent notation
Inconsistent notation
1000
900
800
700
600
500
400
Mean reaction time (ms)
Left
Right
Both
Visual field

b)


Consistent notation
Inconsistent notation
1000
900
800
700
600
500
400
Mean reaction time (ms)
Left
Right
Both
Visual field