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Brederoo, Sanne G.; Nieuwenstein, Mark R.; Lorist, Monicque M.; Cornelissen, Frans W.

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# Hemispheric specialization for global and local processing: A direct comparison of linguistic and non-linguistic stimuli

Sanne G. Brederoo<sup>a,b,d,\*</sup>, Mark R. Nieuwenstein<sup>a,d</sup>, Monicque M. Lorst<sup>a,b,d</sup>,  
Frans W. Cornelissen<sup>b,c,d</sup>

<sup>a</sup> Experimental Psychology, Faculty of Behavioural and Social Sciences, University of Groningen, The Netherlands

<sup>b</sup> Neuroimaging Center Groningen, University Medical Center Groningen, University of Groningen, The Netherlands

<sup>c</sup> Laboratory of Experimental Ophthalmology, University Medical Center Groningen, University of Groningen, The Netherlands

<sup>d</sup> Research School Behavioural and Cognitive Neurosciences, University of Groningen, The Netherlands

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## ABSTRACT

It is often assumed that the human brain processes the global and local properties of visual stimuli in a lateralized fashion, with a left hemisphere (LH) specialization for local detail, and a right hemisphere (RH) specialization for global form. However, the evidence for such global-local lateralization stems predominantly from studies using linguistic stimuli, the processing of which has shown to be LH lateralized in itself. In addition, some studies have reported a reversal of global-local lateralization when using non-linguistic stimuli. Accordingly, it remains unclear whether global-local lateralization may in fact be stimulus-specific. To address this issue, we asked participants to respond to linguistic and non-linguistic stimuli that were presented in the right and left visual fields, allowing for first access by the LH and RH, respectively. The results showed global-RH and local-LH advantages for both stimulus types, but the global lateralization effect was larger for linguistic stimuli. Furthermore, this pattern of results was found to be robust, as it was observed regardless of two other task manipulations. We conclude that the instantiation and direction of global and local lateralization is not stimulus-specific. However, the magnitude of global,—but not local,—lateralization is dependent on stimulus type.

## 1. Introduction

Functional hemispheric asymmetry, or *lateralization*, is a particular instance of cortical specialization that enables the brain to use dedicated or optimized processing routines, promoting efficiency in processing of different types of information. The left hemisphere's (LH) dominance for language-related processes and the right hemisphere's (RH) dominance for visuospatial processes are well-known examples of lateralization of the human brain (Cai, Van der Haegen, & Brysbaert, 2013; Hervé, Zago, Petit, Mazoyer, & Tzourio-Mazoyer, 2013; Stephan et al., 2003). In addition, lateralization has been argued to exist for the processing of different aspects of visual information (Hellige, Laeng, & Michimata, 2010). Specifically, studies on patients with unilateral brain lesions (e.g. Delis, Robertson, & Efron, 1986; Robertson, Lamb, & Knight, 1988), and neuroimaging studies with neurologically intact adults (e.g. Fink et al., 1996; Han et al., 2002) suggest that the LH may be specialized in identifying the local elements of visual stimuli, while the RH may be specialized in identifying their global form. These findings have been corroborated by behavioral studies, showing a left

visual field (LVF) superiority for global processing and a right visual field (RVF) superiority for local processing, congruent with RH and LH lateralization, respectively (e.g. Hübner, 1998; Van Kleeck, 1989; Yovel, Yovel, & Levy, 2001).

A potential caveat to the interpretation of these findings lies in the fact that a preponderance of global-local studies used linguistic stimuli, modeled after the classical hierarchical Navon letters (Navon, 1977). As letters themselves have been shown to induce predominantly LH fusiform gyrus activity (Callan, Callan, & Masaki, 2005; Flowers et al., 2004; Polk et al., 2002), the use of hierarchical letter stimuli to study global-local lateralization introduces a confounding factor. Consequently, results derived using letter stimuli can be interpreted in more than one way. On the one hand, the classic interpretation of local-LH/RVF and global-RH/LVF advantages can be made. This interpretation requires the underlying assumption that global-local lateralization is content-neutral, and as such is not affected by the linguistic nature of the stimuli. Alternatively, the pattern of results can be explained in terms of stimulus-specific lateralization, with linguistic-LH/RVF and visuospatial-RH/LVF advantages. This interpretation assumes that the

\* Corresponding author at: Dept. of Experimental Psychology, Grote Kruisstraat 2/1, 9712 TS Groningen, The Netherlands.  
E-mail address: [sannebrederoo@gmail.com](mailto:sannebrederoo@gmail.com) (S.G. Brederoo).

more taxing local level (as shown by the *global precedence effect*, Navon, 1977) is processed by the hemisphere that is specialized for that stimulus type, predicting local-LH/RVF advantages for linguistic stimuli, but local-RH/LVF advantages for visuospatial stimuli (Fink et al., 1997a, 1997b; Kinsbourne, 1970). In addition, Fink et al. propose that the non-specialized hemisphere processes the global level, as this is the level that is processed by default, resulting in global-RH/LVF advantages for linguistic stimuli, but global-LH/RVF advantages for visuospatial stimuli (Fink et al., 1997a, 1997b).

Whether a content-neutral or stimulus-specific interpretation best explains global-local lateralization cannot be determined based on the available literature. The current study aims to resolve this issue by directly comparing global-local lateralization for linguistic (i.e. letter) and non-linguistic (i.e. figure) stimuli. Before we turn to the present study, we will shortly review the existing theoretical and empirical support for each of the accounts.

### 1.1. Support for content-neutral global-local lateralization

The content-neutral account of global-local lateralization finds support in the theory that perceptual lateralization is the result of hemispheric differences in spatial frequency processing (e.g. Christman, 1989; Han et al., 2002; Kitterle, Hellige, & Christman, 1992; Musel et al., 2014; Sergent, 1982). This hypothesis forms the basis of the Double Filtering by Frequency (DFF) theory (Flevaris & Robertson, 2016; Ivry & Robertson, 1998). According to the DFF theory, when confronted with visual input, first a spatial frequency range is selected from the incoming spectrum, during which no hemispheric asymmetries are present. Next, this selection is fed forward to each of the hemispheres, where the LH amplifies the high spatial frequency (HSF) range, and the RH amplifies the low spatial frequency (LSF) range of this pre-selection. As a consequence, the HSF amplification in the LH causes a local-LH advantage, and the LSF amplification in the RH causes a global-RH advantage. Thus, the DFF theory predicts that global-local lateralization can be observed for different stimulus types as long as these have similar spatial frequency spectra (for an overview, see Dien, 2008).

Another line of support for the content-neutral account can be found in studies that report the classical global-local lateralization pattern when using non-linguistic stimuli. In such a study, using functional magnetic resonance imaging (fMRI), Martinez et al. (1997) found enhanced activity over the LH occipito-temporal junction during local processing, and enhanced activation of the RH occipito-temporal junction during global processing. Similarly, the classical local-RVF and global-LVF effects have been found in behavioral studies using non-linguistic stimuli (e.g. Hübner & Studer, 2009; Kimchi & Merhav, 1991).

In further support for the content-neutral account, a study that compared global-local lateralization for linguistic and non-linguistic stimuli found the classical pattern of results for both types of stimuli (Bedson & Turnbull, 2002). Using a change detection paradigm, they showed that participants more accurately detected global changes in the LVF, regardless of the nature of the stimuli.

### 1.2. Support for stimulus-specific global-local lateralization

The strongest support for a stimulus-specific account of global-local lateralization comes from two contrasting studies by Fink et al., 1996, 1997a, 1997b. In a positron emission tomography (PET) experiment using linguistic stimuli, they found the LH inferior cortex to be more involved in processing of the local level, and the RH lingual gyrus in processing of the global level (Fink et al., 1996, 1997b). In contrast, when using non-linguistic stimuli in the same paradigm, they found these effects to be reversed to enhanced RH lingual gyrus activity for local processing, and enhanced LH inferior occipital activity for global processing (Fink et al., 1997a, 1997b). In accounting for these results, Fink et al. proposed that processing of the local level of a stimulus is

managed by the hemisphere that is specialized for the presented stimulus type. For linguistic stimuli this would entail the LH, and for non-linguistic stimuli the RH. They further proposed that the other, non-specialized hemisphere engages in processing of the global level of the stimulus, this being the default processing mode (Fink et al., 1997a, 1997b).

Also favoring a stimulus-specific account are some of the results of studies by Kéïta and colleagues. In a series of behavioral experiments, they found a local-RVF advantage for linguistic stimuli that was absent (Kéïta, Bedoin, Burack, & Lepore, 2014), or reversed to a local-LVF advantage (Kéïta & Bedoin, 2011, Experiment 2) when non-linguistic were used.

While the complete reversal of global-local lateralization is, to our knowledge, limited to the experiments by Fink et al. (1997a, 1997b) and Kéïta and Bedoin (2011, Experiment 2), there are also a number of studies that used non-linguistic stimuli and found no lateralization effects. For example, in the behavioral studies by Polich and Aguilar (1990) and Blanca and López-Montiel (2009), no significant global-local lateralization effects were found. However, it must be noted that there also exist studies using linguistic stimuli that failed to find global-local lateralization effects (Boles, 1984; Van Kleeck, 1989), and even one reporting a reversed local-LVF advantage, when stimulus duration was limited (Boles & Karner, 1996).

### 1.3. Confounding factors in letter-figure comparison studies

Aside from presenting mixed results, another problem in interpreting the results from previous studies is that the results might have been suboptimal due to potential confounding factors. Most notably, in the studies that found reversed lateralization for non-linguistic stimuli, the used letter and figure stimuli differed substantially on a number of crucial aspects.

Firstly, the number of local elements that made out one global stimulus was much higher for figures than for letters. The studies by Fink et al. used global letters that were made out of 9 or 15 (example stimuli in Fink et al., 1996), or 11 or 18 (example stimuli Fink et al., 1997b) local letters, while their figure stimuli were made out of 48 local elements (example stimuli Fink et al., 1997a, 1997b). Likewise, Kéïta et al. used letter stimuli that were made out of 16–26 elements, while their figure stimuli consisted of 24–32 elements (Kéïta & Bedoin, 2011; Kéïta et al., 2014). This might be problematic for the interpretation of their letter-figure comparison, because it has been shown that the number of local elements that a global stimulus is made out of has an effect on lateralization effects. More precisely, stimuli consisting of fewer local elements are more likely to produce local-RVF effects than those consisting of many local elements, and this may be due to the fact that local elements will be perceived as texture, rather than as individual stimuli, when their numbers increase (Christman & Weiner, 1997; Kimchi & Merhav, 1991).

Secondly, the global/local size ratio differed between letters and figures. Letter stimuli in Fink et al.'s studies, for example, had a size ratio of 1/6 or 1/5, whereas it was 1/16 for their figure stimuli. These differences in global/local size ratio might be problematic because it has been shown that lateralization effects are less robust when a smaller global/local ratio is used (Yovel et al., 2001).

Lastly, as explicitly stated by Kéïta and Bedoin (2011), their figure stimuli were more complex than their letter stimuli. This forms a third confounding factor that might play a role in the observed differences in lateralization, as a shift in visual field asymmetries has been shown to be the result of increasing the complexity of stimuli (Fontenot, 1973). In this study by Fontenot, an RVF advantage was apparent for 3-letter nonsense words. In contrast, an LVF advantage was found for figures, but only when these were high in complexity.

In sum, reversals of the classic lateralization pattern might be related to a number of confounding factors, rather than by the modulation of stimulus type.

#### 1.4. Present study

In the present study, we set out to provide a more conclusive test of content-neutral versus stimulus-specific global-local lateralization, by avoiding inconsistencies in stimulus material. To this end, we compared global-local processing of linguistic and non-linguistic stimuli in a behavioral experiment, in a within-subjects design. We controlled for potential confounds by using letter and figure stimuli that are comparable in their number of local elements, global/local size ratio, and complexity. Furthermore, we compared lateralization for these letter and figure stimuli across different presentation conditions and tasks, so as to determine the robustness of any possible difference between lateralization for linguistic and non-linguistic stimuli. If global-local lateralization indeed is content-neutral, we predict local-RVF and global-LVF advantages for both letter and figure stimuli. If, alternatively, stimulus-specific lateralization drives the observed global-local lateralization effects, we predict a local-RVF for letters and a local-LVF advantage for figures.

## 2. Material and methods

### 2.1. Participants

Seventeen students (7 women, 10 men) from the University of Groningen took part in the experiment for course credits.<sup>1</sup> Mean age was 19.5 years (range 18–23). All participants were right-handed with a mean of 9.6 (range 7–10) on the Flinders handedness survey (Nicholls, Thomas, Loetscher, & Grimshaw, 2013). All participants reported to have normal or corrected-to-normal vision, which was verified using a Snellen chart. The ethical committee of the Psychology Department of the University of Groningen approved the experiment, and participants gave written consent before the test session began.

### 2.2. Stimuli and apparatus

In half of the trials, hierarchical letters were presented, while in the other half hierarchical figures were presented. Stimulus letters were T and H (targets), and Y and N (distractors). Stimulus figures were a diamond and a plus sign (targets) and a rectangle and a cross (distractors). These stimuli were chosen because the amount of information they convey on the nasal or temporal side does not depend on the visual field of presentation (they are largely symmetrical around the midline). All stimuli were incongruent, that is, the identity of the letters or figures presented at the global level always differed from that of the local level, because such stimuli have been shown to produce visual field effects more reliably (Hübner & Volberg, 2005; Martens & Hübner, 2013).

As directing attention toward and away from salient stimulus attributes has been shown to be a lateralized process itself (Mevorach, Humphreys, & Shalev, 2006a, 2006b), we aimed to ensure that local and global levels of our stimuli were equally salient. As starting point for construction of the stimuli, we used those from the ‘equal salience’ condition of Yovel et al.’s study in which they compared stimulus and task factors (2001). With this study, Yovel et al. showed that lateralization effects were more robust when using stimuli that have equally salient levels, compared to stimuli that have a more salient global than local level. For both letter and figure stimuli, a global stimulus was comprised of local stimuli placed within a 5 × 5 grid, with a global/local ratio of 0.14. The global letters consisted of 7–13 local letters (mean 10.5), and the global figures consisted of 8–12 local figures (mean 9.5). Fig. 1 shows example stimuli.

<sup>1</sup> In total, 28 participants were tested, but the data of 11 participants were not included in the analyses because they failed to follow the instructions during part of the experiment. Analyses including the data of these participants did not alter the results of interest as reported in the main text, and the results of these additional analyses are presented in the Appendix A. Supplementary materials II.

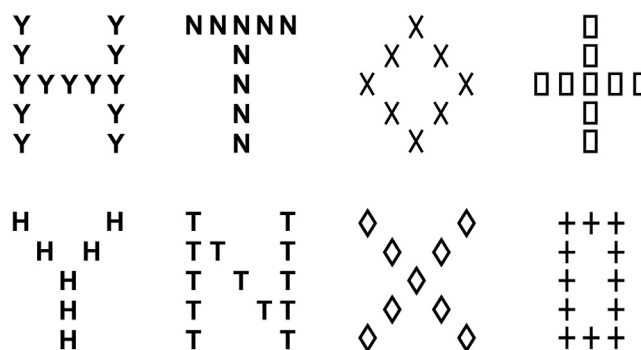


Fig. 1. Examples of four letter stimuli (left) and four figure stimuli (right), showing targets at the global level (upper), and local level (lower).

The hierarchical stimuli were presented in black on a white background, and subtending 3.5° of visual angle, with their inner edges at 0.5° from the central fixation point. Stimuli were displayed on a 22" CRT monitor (1280 × 1024, 100 Hz, Iiyama Vision Master Pro 513) and viewed from a distance of 57 cm, which was kept fixed using a chin rest. The experimental session took place in a dimly lit and sound attenuating room. The experiment ran in E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA), on a Windows 7 operating system. Responses were collected using an in-house manufactured button box.

### 2.3. Procedure

At the start of the session, participants completed a handedness survey and a visual acuity test. The experiment was divided into two parts, each comprising four blocks that differed in terms of the task and stimuli used. In one of the parts, the stimuli were hierarchical letters while in the other these were hierarchical figures. Nine participants started with the figure stimuli, and eight participants started with the letter stimuli. For each stimulus type, participants first did a target identification task ('target task'), with stimuli displayed unilaterally. Next, they did the same task but with bilaterally presented stimuli. After that, the participants performed a level identification task ('level task'), first with unilateral and next with bilateral stimuli.

During the target task, one of the two possible target stimuli would appear at either the global or the local level. Participants were instructed to indicate which of the two targets they saw, regardless of the level, as fast as possible. They did so by pressing one of two buttons using their index or middle finger. When participants performed the level task, they had to determine whether either target appeared at the global or the local level, or not at all. Participants indicated at which level they had seen a target, by pressing one of two buttons using their index or middle finger, as fast as possible. The participants were instructed not to press a button when they had not seen a target. The no-target-present condition constituted 20% of the trials in this task, and was included to prevent participants from being able to complete the task by monitoring either the global or the local level only.

During a unilateral presentation block, the hierarchical stimulus appeared in the LVF and RVF equally often, in a randomized manner. In bilateral presentation blocks, two hierarchical stimuli would appear simultaneously on every trial, with one in each visual field. When a target was present, this was in only one of these two stimuli, on only one level. A target was present in the LVF and RVF stimuli equally often within in one block. The unilateral-bilateral contrast was included because previous research has shown that bilateral presentation of stimuli can result in larger lateralization effects (Boles, 1987; Boles, 1990) (see Appendix A. Supplementary materials I. for a discussion).

Each unique task and presentation block consisted of 160 trials. In target tasks, this lead to 40 trials per combination of visual field and level, and in level tasks (where 20% were non-target trials) to 32 trials per combination. Before each of these blocks started, participants were



instructed about their task and the response mapping to the buttons, and were given 16 practice trials to get familiar with the new task and stimulus presentation. Finger-response mappings were counterbalanced over participants.

In each of the blocks, a trial started with the presentation of a central fixation asterisk for 540–600 ms, followed by the unilateral stimulus or bilateral stimuli for 120 ms. The stimulus was followed by a blank screen, the duration of which depended on the stimulus presentation condition. The duration of the blank screen was 120 ms in unilateral trials, and 220 ms in bilateral trials, to allow equalized processing time in relation to the amount of information (which was doubled, in case of bilateral stimuli). After the blank, one or two  $5 \times 5$  grids of hashtags were presented at the location of the stimuli, lasting 110 ms, to prevent further persistence of their after images (Bourne, 2006). Participants were required to respond as fast as possible, with a maximum of 2 s to make their response. Nine participants responded using their left hand, and eight using their right hand, to control for any effects due to visual field-hand congruency (Hellige & Sergent, 1986; Wendt, Vietze, & Kluwe, 2007).

#### 2.4. Statistical analysis

In analyzing the data, we focused on the results for error rates (ERs), because the use of a short presentation time and masking procedure entailed that ERs were most informative (Hellige & Sergent, 1986).<sup>2</sup> To examine whether there is evidence for lateralization of global and local processing in our participants' data, we performed repeated measures ANOVAs with within-subject factors Level (global, local), Visual Field (LVF, RVF), Stimulus Type (letter, figure), Presentation (unilateral, bilateral) and Task (target task, level task). In case of higher-order interactions, ANOVAs with factors Level (global, local) and Visual Field (LVF, RVF) were performed separately for each of the levels of the modulating factor, to assess the magnitude of lateralization across different conditions. In case of a significant Level  $\times$  Visual Field interaction, these ANOVAs were followed up by one-sided paired samples *t*-tests, to examine whether there was an indication for both global-LVF and local-RVF advantages. We did not perform Bonferroni corrections, since the effects were specified a priori, and follow-up *t*-tests were conducted to assess the nature of the significant expected interaction effect. The effect sizes that we report are partial eta-squared ( $\eta_p^2$ ) for the *F*-tests, and Cohen's  $d_m$  for the *t*-tests (Lakens, 2013).

A global-LVF advantage is defined as a relative reduction in ERs when the global target is presented in the LVF compared to the RVF, while a local-RVF advantage reflects a relative reduction in ERs when the local target is presented in the RVF compared to the LVF.

### 3. Results

The average ER over all conditions was 25% (SE = 3%). We found lateralization for global and local processing, with a significant Level  $\times$  Visual Field interaction ( $F_{Level \times Visual Field}[1,16] = 28.36$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.64$ ), yielding a significant global-LVF advantage (mean LVF advantage =  $-3.9\%$ , SE = 1.1%,  $t[16] = -3.60$ ,  $p = 0.001$ ,  $d_m = 0.3$ ), and a significant local-RVF advantage (mean RVF advantage =  $2.5\%$ , SE = 0.8%,  $t[16] = 3.38$ ,  $p = 0.002$ ,  $d_m = 0.26$ ) (see Fig. 2). There was no significant difference in the magnitude of the lateralization effects seen for the local-RVF and the global-LVF advantages (mean difference =  $1.7\%$ , SE = 1.1%,  $t[16] = -1.63$ ,  $p = 0.123$ ).

Important to our main question, lateralization was modulated by the type of stimulus ( $F_{Level \times Visual Field \times Stimulus Type}[1,16] = 14.00$ ,

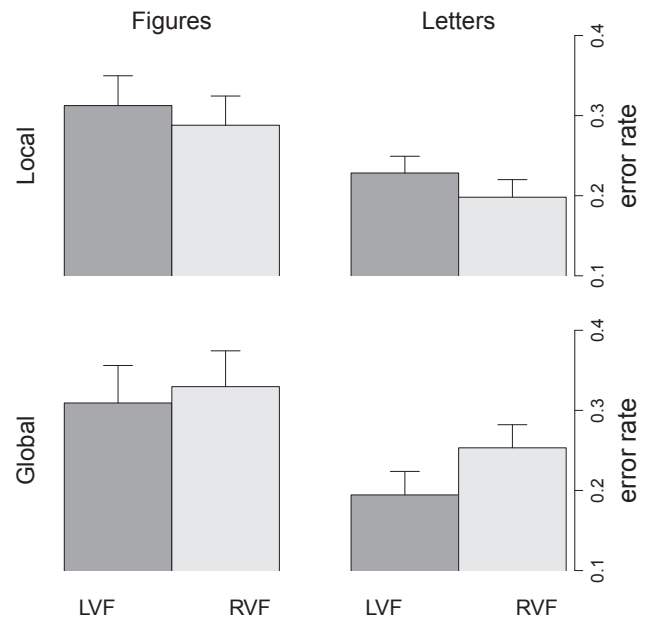


Fig. 2. Mean ERs for local (upper panels) and global (lower panels) stimuli for figures (left panels) and letters (right panels). Dark gray bars depict mean ERs for left visual field trials, light gray bars depict mean ERs for right visual field trials. Error bars represent standard errors of the means.

$p = 0.002$ ,  $\eta_p^2 = 0.47$ ), in the absence of any other modulating effects on lateralization (all *F*'s  $< 3.74$ , all *p*'s  $> 0.07$ ). In separate analyses on letter and figure trials, we found the lateralization effect to be significant for letters ( $F_{Level \times Visual Field}[1,16] = 43.92$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.73$ ), as well as for figures ( $F_{Level \times Visual Field}[1,16] = 9.98$ ,  $p = 0.006$ ,  $\eta_p^2 = 0.38$ ). Each of these lateralization effects consisted of both a global-LVF advantage and a local-RVF advantage (global letters:  $t[16] = -3.71$ ,  $p < 0.001$ ,  $d_m = 0.46$ ; local letters:  $t[16] = 3.06$ ,  $p = 0.004$ ,  $d_m = 0.34$ ; global figures:  $t[16] = -2.29$ ,  $p = 0.018$ ,  $d_m = 0.11$ ; local figures  $t[16] = 2.11$ ,  $p = 0.026$ ,  $d_m = 0.17$ ). The difference between the stimulus types was caused by a significantly larger global-LVF advantage for letters compared to figures ( $t[16] = -3.02$ ,  $p = 0.008$ ). The local-RVF advantage did not significantly differ in magnitude between letters and figures ( $t[16] = 0.78$ ,  $p = 0.448$ ). When comparing the global-local difference of the stimulus types within each of the visual fields, we did not find a difference between letters and figures for the LVF trials ( $t[16] = 1.77$ ,  $p = 0.095$ ), or for the RVF trials ( $t[16] = -0.59$ ,  $p = 0.564$ ).

We did not observe a general differential lateralization for letters and figures, regardless of level ( $F_{Visual Field \times Stimulus Type}[1,16] = 2.15$ ,  $p = 0.162$ ,  $\eta_p^2 = 0.12$ ), as may have been predicted by theories about linguistic LH- and visuospatial RH-lateralization.

### 4. Discussion

Our main result showed that global-LVF and local-RVF advantages existed for both letters and figures. This indicates that the direction of global-local lateralization does not depend on the stimulus being linguistic or non-linguistic in nature. In addition, we found that the global – but not the local – lateralization effect was larger for letters than for figures. This pattern of results was robust, as it was observed regardless of whether the stimuli were presented unilaterally or bilaterally, and regardless of whether the task required a response relating to the identity of a target or to the level at which a target appeared. Below, we discuss the implications of these results in detail.

<sup>2</sup> The results of analyses on reaction times are in line with the analyses on the ERs, thus ruling out a speed-accuracy trade-off. These results are presented in the Appendix A. Supplementary materials I.

#### 4.1. Global-local lateralization is not stimulus-specific

In finding local-RVF and global-LVF advantages for both letters and figures, our results support the notion that the instantiation and direction of global-local lateralization do not depend on LH-lateralization for linguistic stimuli and RH-lateralization for non-linguistic stimuli. Further support for this lies in the fact that we found no overall visual field differences between the two stimulus types. This is consistent with results from a study involving patients with unilateral lesions, showing that there is no overall performance difference for linguistic and non-linguistic stimuli between patients with LH damage and patients with RH damage (Delis et al., 1986).

Our results do not replicate those of reversed lateralization for non-linguistic stimuli by Fink et al. (1997a, 1997b) and Kéita and Bedoin (2011). A likely explanation for this is that the reversed lateralization effects in those studies are due to differences between their linguistic and non-linguistic stimuli in terms of the number of local elements, the global/local size ratio, or the complexity of the stimuli. The non-linguistic stimuli in Fink et al.'s study (1997a, 1997b) seemed to contain more than double the number of local elements, and have less than half the global/local size ratio compared to their linguistic stimuli (1996, 1997b). Also in Kéita and Bedoin (2011), the number of local elements in the non-linguistic stimuli seemed to far exceed that of the linguistic stimuli, and the non-linguistic stimuli were reported to be more complex than the linguistic stimuli. These are all factors that have been related to the likelihood of finding global-local lateralization effects (Christman & Weiner, 1997; Fontenot, 1973; Kimchi & Merhav, 1991; Yovel et al., 2001). In the current study, we controlled for these confounds; the number of local elements, the global/local size ratio, and the stimulus complexity were similar for letter and figure stimuli, and reversed lateralization for figure stimuli was found to be absent. Therefore, we can conclude that reversals of visual field effects are most likely driven by other factors than stimulus type, and based on the present results we can argue that the instantiation and direction of global-local lateralization do not depend on stimulus type.

#### 4.2. Modulation of global lateralization

Although global-local lateralization is apparent for both stimulus types in the present study, we do see an amplification of the global lateralization effect for letters compared to figures. This finding cannot be explained in terms of the stimulus-specific account of lateralization, since it predicts a reversal of global lateralization, and not a difference in magnitude. We do not have a ready explanation for this modulation of global lateralization, but believe it is worthy of further investigation.

While its cause is not yet clear, our finding of modulation of global lateralization in the absence of modulation of local lateralization suggests that lateralized processing of global information is more susceptible to changes in stimulus characteristics than local lateralized processing. Support for this notion can be found in the fact that a number of previous studies on global-local lateralization report local-RVF advantages in the absence of global-LVF advantages (Boles & Karner, 1996; Christman & Weiner, 1997; Evans, Shedden, Hevenor, & Hahn, 2000; Martinez et al., 1997; Polich & Aguilar, 1990). In contrast, to our knowledge there are no studies reporting global lateralization in the absence of local lateralization.<sup>3</sup> Moreover, in a number of studies that consisted of multiple experiments, local-RVF advantages were more often found than global-LVF advantages (Evert & Kmen, 2003; Kimchi & Merhav, 1991; Kéita & Bedoin, 2011; Yovel et al., 2001). Notably, of the studies just listed, five used non-linguistic stimuli

<sup>3</sup> A study by Hübner, Volberg, and Studer (2007) reports a significant global-LVF advantage but no local-RVF advantage, in accuracy scores. However, in their reaction time data the local-RVF advantage was nearly significant ( $p = 0.054$ ), while the global-LVF advantage was absent, indicating speed-accuracy tradeoffs, rather than global lateralization in the absence of local lateralization.

(Christman & Weiner, 1997; Kimchi & Merhav, 1991; Kéita & Bedoin, 2011; Martinez et al., 1997; Polich & Aguilar, 1990), and four used linguistic stimuli (Boles & Karner, 1996; Evans et al., 2000; Evert & Kmen, 2003; Yovel et al., 2001). As the majority of global-local studies use linguistic stimuli, there seems to be an overrepresentation of studies using non-linguistic stimuli among those that report the absence of global-LVF advantages. Taken together, this suggests that local lateralized processing is a robust effect, persisting over all kinds of different stimuli used in these studies, and regardless of the linguistic nature of the stimuli. In contrast, the magnitude of the global-LVF advantage may be influenced by specific stimulus characteristics, of which the linguistic nature of the stimulus is a likely candidate.

Additional support for the notion that global and local lateralization could be independently modulated, comes from neuroimaging and lesion data showing that global and local lateralization do not have the same neural underpinnings. Of the studies reporting local-LH and global-RH processing, the involved LH and RH areas were not found to be homologues, except in one fMRI study using non-linguistic stimuli, that showed the involvement of the occipito-temporal junction in both the LH and RH (Martinez et al., 1997). LH areas found to be involved in local processing are the superior temporal lobe (Delis et al., 1986; Robertson et al., 1988), the posterior temporal lobe (Yamaguchi, Yamagata, & Kobayashi, 2000), and the inferior occipital lobe (Fink et al., 1996; Fink et al., 1997b). RH areas found to be involved in global processing are temporo-parietal areas (Delis et al., 1986; Robertson et al., 1988; Yamaguchi et al., 2000), and the lingual gyrus (Fink et al., 1996; Fink et al., 1997b). These findings highlight the fact that global and local lateralization can be regarded as separate processes, that may, therefore, be independently affected by stimulus characteristics.

In sum, we conclude that local lateralization is a robust phenomenon, while global lateralization can be modulated by stimulus type. A distinction between global and local lateralization is supported by behavioral, neuroimaging, and lesion studies.

#### 4.3. Future studies

We have shown that the use of non-linguistic stimuli does not reverse global and local lateralization, but that it can lead to diminished global lateralization. Future studies are needed to further delineate the cause of this difference between linguistic and non-linguistic stimuli, and why this affects global but not local lateralization.

One known difference between linguistic and non-linguistic stimuli is that in skilled readers, the processing of the former is more automatic than that of the latter (Lachmann, Schmitt, Braet, & Van Leeuwen, 2014). A consequence of the automaticity of letter processing is that it could result in better processing of linguistic than non-linguistic stimuli. While not the focus of the present study, we did indeed find participants to make fewer errors in processing letters than figures ( $p = 0.006$ ). How an increase in global lateralization, and not local lateralization, could follow from automaticity of processing remains a topic for further study.

Further regarding potential differences between linguistic and non-linguistic stimuli, it has been suggested that local figures will presumably be more readily perceived as texture than local letters will, which in turn may affect their lateralized processing (Christman & Weiner, 1997). It is noteworthy that the number of local elements of the current study's stimuli straddled the boundary of being perceived as individual elements or as texture, according to Kimchi (1992) and Christman and Weiner (1997). Following this, if we presume that in our experiment local letters had been perceived as individual elements, but local figures as texture, this may have contributed to their differing lateralized processing. Again, how this then could have affected global lateralization, but not local lateralization, remains unclear. Future studies should consider manipulating the number of local elements, to compare linguistic and non-linguistic stimuli on how this affects global lateralization.

Finally, in addition to the number of local elements, we have listed two more factors that may have contributed to the reversal of global and local lateralization in earlier studies, namely the global/local size ratio and stimulus complexity. To increase our knowledge of lateralization of global and local processing, and of lateralization in general, it is important to assess how such stimulus factors may cause a 'typical' lateralization effect to reverse completely.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.bandc.2017.09.005>.

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