AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology: General

ISSN: 0096-3445

2021, Vol. 150, No. 3, 560–569
http://dx.doi.org/10.1037/xge0000951

The Missing Link: Global-Local Processing Relates to Number-Magnitude Processing in Women

Belinda Pletzer, Andrea Scheuringer, TiAnni Harris, and Thomas Scherndl
University of Salzburg

Number processing and visual hierarchical processing (global-local processing) have much in common. However, the shared aspects of number processing and global-local processing have not been investigated so far. Most visual stimuli are hierarchical with global structures made up of local parts. Processing of global and local aspects occurs in parallel and the global advantage effect indicates faster reactions to global than local aspects. Likewise, multidigit numbers can be represented holistically (whole number magnitudes) or in a decomposed fashion (single digit magnitudes). During comparison of 2-digit numbers, the unit-decade compatibility effect indicates slower responses when the larger number contains the smaller unit digit and has been suggested as a measure of how strongly participants rely on decomposed number representations. However, this interpretation of the compatibility effect is still controversial and a link between global-local processing and the individual tendency to rely on decomposed representations of multidigit numbers remains to be established. To that end we assessed whether the compatibility effect during number comparison was related to various measures of global advantage. To answer this question we drew upon existing data from participants who had completed both, the number comparison task and 2 global-local tasks. Results show that the compatibility effect is indeed negatively related to several measures of global advantage in women, with no evidence for such a relationship in men. These results demonstrate that global-local processing transcends into the numerical domain but also suggest that the compatibility effect reflects different mechanisms in men and women.

Keywords: global-local processing, global advantage, number comparison, compatibility effect

Number processing and visual processing have much in common. Most stimuli in everyday life are hierarchical with global structures made of local parts. Navon (1977) discovered that the processing of global stimulus aspects usually occurs faster than the processing of local stimulus aspects and termed the difference in response times to local and global stimulus aspects *global advantage effect.* It was originally assumed that this response time difference is the result of global processing preceding local processing, and hence the concept was termed *global precedence*. It is now well established that the processing of global structures and local parts occurs in parallel (global-local processing; e.g., Heinze, Johannes, Münte, & Mangun, 1994; Müller-Oehring, Schulte, Raassi, Pfefferbaum, & Sullivan, 2007). Hence, the reaction time (RT) difference may simply be the result of global processing occurring faster than local processing. As global structures comprise lower spatial frequencies than local parts, they are likely processed by different parts of the visual system. While the dorsal visual system processes low spatial frequencies in a coarse but time-efficient manner to enable quick reactions, the ventral visual system processes high spatial frequencies in a fine-grained, but more time-consuming manner, resulting in slower reactions (Milner & Goodale, 2008). However, some studies show that in situations of response conflict between the global and local level, global information interferes more strongly with local responses (global-to-local interference) than vice versa (e.g., Luna, Merino, & Marcos-Ruiz, 1990). It has thus been discussed, if and how global processing inhibits local processing, thus slowing down local processing and contributing to the global advantage effect. In the context of inhibition, some papers speak of a dominance of global processing over local processing (e.g., Luna et al., 1990).

A large number of studies show that global advantage is not constant, but the size and even the directionality of the global advantage effect depend on stimulus characteristics, situational characteristics, and individual characteristics (e.g., Müller-Oehring, Schulte, Raassi, Pfefferbaum, & Sullivan, 2007). For example, the global advantage effect depends on the size or ec-

This article was published Online First September 3, 2020.

Belinda Pletzer, Andrea Scheuringer, and TiAnni Harris, Department of Psychology and Centre for Cognitive Neuroscience, University of Salzburg; Thomas Scherndl, Department of Psychology, University of Salzburg.

Idea & study design: Belinda Pletzer; Selection of tasks: Belinda Pletzer, Andrea Scheuringer; Data acquisition & preprocessing: Andrea Scheuringer, TiAnni Harris; Data analysis: Belinda Pletzer, Thomas Scherndl; Manuscript preparation: Belinda Pletzer. All authors reviewed the manuscript prior to submission. This study was funded by the Austrian Science Fund (P28261). We furthermore thank the students of Belinda Pletzer for their help with data acquisition and all participants for their time and willingness to contribute to this study. The authors state that they have no competing financial interests.

Correspondence concerning this article should be addressed to Belinda Pletzer, Centre for Cognitive Neuroscience, University of Salzburg, Hellbrunnerstrasse 34, 5020 Salzburg, Austria. E-mail: belinda.pletzer@sbg.ac.at

centricity of stimuli (e.g., Navon & Norman, 1983) and the spacing of local stimuli, with larger spacing resulting in a smaller or even reversed global advantage effect (Huberle & Karnath, 2006; Martin, 1979). Hemifield presentation results in stronger global advantage during right-hemispheric compared to left-hemispheric processing (e.g., Fink et al., 1996; Robertson & Lamb, 1991). Even the stimulus material has been shown to affect global advantage with stronger global advantage effects using letters than geometrical shapes (Pletzer, Petasis, & Cahill, 2014).

Furthermore, the global advantage effect is heavily affected by task instructions (Pletzer et al., 2014). A larger global advantage effect is elicited when participants are instructed to focus on either the global or local level (selective attention condition) rather than responding to targets at both levels (divided attention condition; Plaisted, Swettenham, & Rees, 1999; Pletzer et al., 2014; Pletzer et al., 2018). This observation supports the assumption that local processing is more easily inhibited than global processing, thus slowing down local processing in the selective attention condition. Accordingly, recent factor analyses show that global-local processing may not represent a uniform concept, since the global advantage effects obtained during different task instructions show little interrelation (Pletzer, Scheuringer, & Scherndl, 2017). The global advantage effect during the divided attention condition captures how much faster global processing is compared to local processing in bottom up, possibly including a certain extent of inhibition between the processes. In this case a larger global advantage effect reflects faster global than local processing and/or dominance of global over local processing. In turn, a negative global advantage effect actually reflects local advantage, that is, faster local than global processing and/or a dominance of local processing over global processing. The global advantage effect during the selective attention condition however captures which process is more prone to top-down inhibition. In this case a larger global advantage effect reflects easier suppression of local compared to global processing and vice versa in case of a negative global advantage effect. Both aspects are of relevance to and likely interact during the processing of everyday hierarchical stimuli, but may reflect distinct mechanisms. Experiments using meaningful versus meaningless stimulus material also suggest that global-local processing involves both sensory and cognitive mechanisms (Poirel, Pineau, & Mellet, 2008).

Finally, individual differences, like age (e.g., Oken, Kishiyama, Kaye, & Jones, 1999), ethnicity (e.g., McKone et al., 2010), and sex (e.g., Roalf, Lowery, & Turetsky, 2006) seem to affect the size and directionality of the global advantage effect. Various studies using different stimulus materials and instructions demonstrate a decline or even reversal of the global advantage effect during aging (Huizinga, Burack, & Van der Molen, 2010; Insch, Bull, Phillips, Allen, & Slessor, 2012; Oken et al., 1999). Using a divided attention paradigm, a stronger global advantage effect was observed in Asian compared to White participants (McKone et al., 2010). Likewise various studies using both divided and selective attention paradigms demonstrate a larger global advantage effect in men compared to women (Pletzer et al., 2014; Roalf et al., 2006; Razumnikova & Vol'f, 2011; but see Kimchi, Amishav, & Sulitzeanu-Kenan, 2009). These results suggest that individual differences affect both, sensory (bottom up) and cognitive (top-down) mechanisms involved in the processing of hierarchical stimuli.

Similar to visual hierarchical stimuli, the visual format of multidigit numbers is hierarchical, with whole number magnitudes depending on the place and value of the digits they are comprised of (e.g., $\mathbf{79} = 10^{*}\mathbf{7} + \mathbf{9}$). The triple-code model of number processing describes three different number formats: (a) a visual format represented by Arabic numerals, (b) a verbal format represented by written or spoken number words, and (c) an analogue magnitude format representing number meaning on a mental number line (Dehaene, Piazza, Pinel, & Cohen, 2003). In order to process number magnitudes, the visual format first has to be transposed into the analogue magnitude format (Dehaene et al., 2003; Dotan & Dehaene, 2013).

While the visual format clearly represents the whole number by two distinct digits, it has been debated whether the analogue magnitude format maintains the magnitudes of the individual digits in a decomposed fashion (e.g., Nuerk, Weger, & Willmes, 2001) or only represents the whole number magnitudes in a holistic fashion (e.g., Dehaene, 1989). The question of holistic versus decomposed representations of multidigit numbers obviously affects a large number of numerical processes involving the analogue magnitude format (e.g., addition, subtraction, number comparison) eliciting the related question whether these processes are performed in a holistic manner (on whole number magnitudes) or decomposed manner (utilizing single digit magnitudes). While early approaches have viewed the two representations as mutually exclusive (e.g., Dehaene, 1989; Nuerk et al., 2001), newer models assume that both single digit magnitude and whole number-magnitude representations are formed and maintained in parallel (hybrid model; Verguts & De Moor, 2005). Accordingly, number-magnitude operations can also be performed in a holistic or decomposed fashion utilizing whole number magnitudes and/or single digit magnitudes. This has the advantage of a higher flexibility in numerical operations since either single digit magnitudes or whole number magnitudes may be utilized depending on the requirements of the task. Likewise, single digit magnitude representations may be utilized for numerical operations before a holistic representation is formed.

During number comparison, detecting the larger of two two-digit numbers is harder and slower, if the larger number contains the smaller unit digit. This effect has been termed the *unit-decade compatibility effect* and has originally been discussed as evidence for decomposed number representations, since its occurrence requires the processing of unit digit magnitudes. If multidigit numbers were compared only based on holistic magnitude representations, interference by single digit magnitudes, like unit digits should not occur. Accordingly, in the discussion whether multidigit numbers are represented either holistically or decomposed, the unit-decade-compatibility effect has been used as evidence for the decomposed model. However, if holistic and decomposed representations are utilized in parallel, the decision on which number is larger can be based on either the information provided by the decomposed representations or the holistic representations or result from weighing the two types of information against each other. Supposing that it takes longer to form holistic representations than decomposed representations, basing comparisons on decomposed representations may generally lead to faster responses. However, in situations where the larger number contains the smaller unit digit (incompatible items), the separate representations of units and decades suggest conflicting decisions. In this case, a decision based on digit magnitudes is more likely to result in an incorrect response. Alternatively, the correct response may be delayed, if a response tendency elicited by unit magnitudes needs to be inhibited and information from decade or holistic magnitude representations needs to be consulted instead. Thus, in the case of incompatible items a decision based on holistic magnitude representations may be faster and is more likely to result in a correct response. Accordingly, the unit-decade compatibility effect can be viewed as a measure of how much more strongly/likely number comparison is based on the single digit magnitude representations than the holistic representations of the whole numbers in a certain individual in a certain situation. Thus, in an individual more prone to base numerical operations on single digit magnitudes or in a situation that draws particular attention to individual digits, the unit-decade compatibility effect is larger.

Accordingly, the size of the unit-decade compatibility effect may well depend on individual or situational characteristics, and it has indeed been demonstrated that the unit-decade compatibility effect is affected by much the same factors as the global advantage effect. The size of the unit-decade compatibility effects depends on the spacing of numbers (Pletzer, Scheuringer, & Harris, 2016; Pletzer et al., 2018), hemifield presentation (Harris, Scheuringer, & Pletzer, 2018; Pletzer, Jäger, & Hawelka, 2019), and the sex of participants (Huber, Nuerk, Reips, & Soltanlou, 2019; Harris et al., 2018; Pletzer, Kronbichler, Nuerk, & Kerschbaum, 2013; Pletzer, Harris, & Scheuringer, 2019). Accordingly holistic versus decomposed number processing seems to share similarities with global versus local visual processing. In both fields, individual elements of a larger construct are processed independently but concurrently to that construct, resulting in potential competition between both types of information. Accordingly, in both fields the weight assigned to each type of information in a decision making process appears to be influenced by a variety of surprisingly similar external and internal factors.

So far both fields of research have been working in isolation, and the shared aspects of visual hierarchical processing and number-magnitude processing have not been investigated in depth. It has already been established that global-local processing transcends into other cognitive domains like spatial and verbal processing (Basso & Lowery, 2004; Pletzer, Scheuringer, et al., 2017). Basso and Lowery (2004) were able to relate the global advantage effect to larger spatial acuity in the line orientation task. In a recent study, we were able to extend these findings to spatial navigation strategies, demonstrating that women with a stronger global advantage effect during selective attention showed faster navigation times with allocentric compared to egocentric directions. Since the global advantage effect during selective attention conditions likely reflects how easily local information is inhibited, it is plausible that participants with an advantage in that respect also find it easier to abstract from their own body position and use a different reference frame when judging directions. More surprisingly this study also showed that a stronger global advantage effect during divided attention was related to a more holistic strategy use during verbal fluency, also only in women. The fact that these findings were only observed in women on the one hand nicely outlines how sensory (bottom-up) and cognitive (top-down) mechanisms may interact in the role global-local processing plays for other cognitive domains. On the other hand, it shows the pitfalls of ignoring sex as a relevant variable in cognitive science (compare Cahill, 2006; Pletzer, 2016). If in men bottom up processing of local information is indeed weak on average, less top-down inhibition is necessary during the selective attention condition. Accordingly, the global advantage effect during selective attention may capture different mechanisms to a different extent in men and women. A recent neuroimaging study confirms that global-local processing is on average organized differently in men and women (Pletzer & Harris, 2018).

Apart from these associations between global-local processing and spatial processing in women, we were recently able to show that the unit decade compatibility effect during number processing relates to a more landmark-oriented spatial processing style (Pletzer, Harris, et al., 2019). However, a link between global-local processing and number-magnitude processing is still missing. Linking number-magnitude processing styles to global-local processing would boost research in both fields, since many factors affecting global-local processing have not yet been considered in the number processing literature and vice versa. In the present study, we seek to investigate whether the individual or situational tendency to process or inhibit visual stimuli on a global or local level relates to a comparable tendency to process numbers in a holistic versus decomposed manner. Accordingly, we assess, whether global-advantage effects observed during different conditions when processing visual hierarchical stimuli relate to the unit-decade compatibility effect during number comparison.

To address this question, we reevaluated data from two existing data sets, taking advantage of the fact that a subset of participants from the number comparison study described in Harris et al. (2018) had also completed the paradigms to assess global-local processing described in Pletzer, Scheuringer, et al. (2017) during the same test sessions. Importantly, the participants had completed both tasks twice, which allows us to assess not only interindividual variability in the global advantage and compatibility effect but also intraindividual variability. Accordingly, we combined those data sets to assess whether the unit-decade compatibility effect as calculated in Harris et al. (2018) was related to measures of global advantage as calculated in Pletzer, Scheuringer, et al. (2017). Since global advantage presents as a multifaceted concept, previous studies on spatial and verbal processing show that the interrelation between the global advantage effect and domain-specific processing styles depends on situational characteristics (Pletzer, Scheuringer, et al., 2017). In order to explore which of these situations shows the closest association to number comparison, multiple different measures of global advantage, were considered in the present study.

Furthermore, previous studies not only show that global-local processing is affected by participant's sex (Pletzer et al., 2014; Roalf et al., 2006; Razumnikova & Vol'f, 2011; but see: Kimchi et al., 2009), but that the relationship of global advantage measures to other cognitive domains is moderated by sex (Pletzer, Harris, et al., 2019). Likewise, there is evidence that the neural networks underlying number processing are organized differently in men and women (Keller & Menon, 2009; Kucian, Loenneker, Dietrich, Martin, & Von Aster, 2005; Pletzer, 2016), and several numerical processes are affected by sex (Bull, Cleland, & Mitchell, 2013; Pletzer, 2016). For example it has been argued that men are more prone to approximate calculation, while women are more prone to exact calculation (Wei et al., 2012; Wei, Chen, & Zhou, 2016), which might also explain why the unit-decade compatibility effect is affected by participant's sex (Harris et al., 2018; Pletzer et al., 2013; Pletzer, Harris, et al., 2019). Exact calculation may require a stronger reliance on decomposed number representations than approximate calculation. In fact, sex has emerged as strongest predictor of the compatibility effect in a large-scale online study (Huber et al., 2019). Above, we discussed that the differential neural organization of global-local processing likely results in the behavioral measures of global advantage reflecting different mechanisms in men and women. It is also possible that due to the differential neural organization of number processing, the compatibility effect reflects different mechanisms to a different extent in men and women. If either is the case, one cannot expect global-advantage effects to relate to the compatibility effect in the same way in men and women. Accordingly, in the present study, we also include participant's sex as a potential moderator of the association between measures of global advantage and the unit-decade compatibility effect.

If some measures of global advantage relate to the unit-decade compatibility effect, the individual or situational tendency to process numbers in a holistic versus decomposed manner might indeed relate to the tendency to process visual stimuli on a global or local level. This could put the discussion over holistic versus decomposed number processing in a new perspective and inspire new research on factors modulating number processing.

Method

Participants and Procedure

The research described in the present article represents the last piece of a large-scale study with two goals: (a) to identify sex-differences in cognitive processing styles, while controlling for sex hormone fluctuations along the female menstrual cycle, and (b) to explore the link between cognitive processing styles and sex-differences therein to global-local processing. Accordingly, all participants of the present study were tested twice with test sessions for women being scheduled in different cycle phases (early follicular and midluteal cycle phase, counterbalanced) as confirmed by salivary hormone analyses. This modulation was of relevance to the first goal because previous research has suggested that the tendency toward a local-decomposed processing style might be related to progesterone (Pletzer et al., 2014). However, menstrual cycle phase and sex hormone levels are not of relevance for the second part of the study, because such a modulation was (a) assumed to occur across tasks and would thus not affect the relationship between global advantage and compatibility effect and (b) no evidence for a menstrual cycle modulation of either global advantage or compatibility effect was observed in the present sample (Harris et al., 2018; Pletzer, Harris, & Ortner, 2017). Accordingly, menstrual cycle phase and sex hormones are not considered as variables of interest in the current article. Nevertheless, the repeated measures design is particularly useful for the research question posted in the present article, since it allows to assess the association between global advantage and compatibility, not only taking into account variation across individuals but also variation within the same individual, even if the intraindividual variation was not systematically related to hormone levels.

During each test session, participants completed multiple cognitive tasks in the following order: (a) verbal fluency task (described elsewhere), (b) Navon paradigm, (c) number comparison task, (d) navigation task (described elsewhere), and (e) Kimchi-Palmer task. Results concerning the first goal, that is, sex differences and menstrual cycle modulation in each individual task, were described in Scheuringer and Pletzer (2016); Scheuringer and Pletzer (2017), as well as Harris et al. (2018). The relationship between global-local processing tasks and spatial and verbal processing styles as observed in the navigation and verbal fluency task was described in Pletzer, Harris, et al. (2017). The current article describes the relationship between global-local processing tasks and numerical processing styles.

Accordingly, participants and procedure are the same as described in Pletzer, Harris, et al. (2017). Forty-seven men and 44 women completed both the tasks on global-local processing described in Pletzer, Harris, et al. (2017) and the number comparison task described in Harris et al. (2018) during both test sessions. All participants were between 18 and 36 years old. Age was comparable between men and women ($t_{(83)} = -0.61$, $p = .54$). Participants were students of the University of Salzburg, who received course credits for their participation. They all had a comparably high level of education with a general qualification for university entrance.

Ethics Statement

All participants gave their written consent to participate in the study, and all methods conform to the Code of Ethics of the World Medical Association (Declaration of Helsinki).

The institutional guidelines of the University of Salzburg (Statutes of the University of Salzburg—see https://www.uni-salzburg.at/fileadmin/multimedia/Senat/documents/satzung-2019-07.pdf)—state in § 145 (1) that ethical approval is necessary for research on human subjects if it affects the physical or psychological integrity, the right for privacy or other important rights or interests of the subjects or their dependents. In § 145 (2), it is stated that it is the responsibility of the PI to decide whether (1) applies to a study or not. Therefore, we did not seek ethical approval for this study. Since it was noninvasive and performed on healthy adult volunteers who gave their informed consent to participate, (1) did not apply.

Navon Paradigm and Kimchi-Palmer Task

The Navon paradigm and Kimchi-Palmer task were the same as in Pletzer, Harris, et al. (2017). Both, Navon and Kimchi-Palmer stimuli were visual hierarchical stimuli with global structures made up of local parts (compare Figure 1). In the Navon paradigm stimulus material (letters vs. shapes) and attention condition (divided vs. selective) were varied in a 2 × 2 design. The participant's task was to detect predefined target letters/shapes within a time-limit of 1500 ms either at any level (divided attention con-

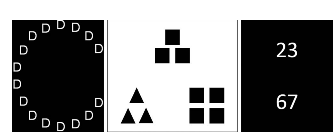

Figure 1. Example stimuli for the Navon task (left), Kimchi-Palmer-task (middle) and number comparison task (right).

dition) or at a predefined level (selective attention condition). Participants with high error rates (>50% in more than one category) were excluded from the analyses as described in Pletzer, Harris, et al. (2017). This concerned 15 men and 18 women, resulting in a remaining 58 participants (32 men, 26 women) for analysis of the Navon paradigm. Reaction times (RT) over correctly solved items were used to calculate the global advantage (GA) effect as standardized mean difference between RT to global targets and RT to local targets as described in Pletzer et al. (2014). Accordingly, for each material and attention condition, the difference in RT for global and local targets was divided by the shared standard deviation to obtain a standardized effect size for the GA effect. Accordingly, four measures of GA were obtained from the Navon paradigm.

In the Kimchi Palmer task, participants were presented three hierarchical figures, one representing the target figure (e.g., a triangle built up of squares) and two representing comparison figures (compare Figure 1). One of the comparison figures matched the target figure in its global but not its local aspects (e.g., a triangle built up of triangles), while the other comparison figure matched the target figure in its local but not its global aspects (e.g., a square built up of squares). Their task was to subjectively decide as quickly as possible, which of the two comparison figures matched the target figure more closely. Unlike in the Navon paradigm, there were no correct or incorrect responses, since decisions were solely based on participant's subjective impression. Traditionally, the number of global choices is used as a measure of the individual processing style. However, a recent study suggests that in adult participants, responses may be less spontaneous and accordingly, the processing style may be more accurately reflected in the RT difference for local and global choices (Scheuringer & Pletzer, 2016). Accordingly, RT for global and local decisions were used to calculate the GA effect in the Kimchi Palmer task as a fifth measure of global advantage. Participants, who made only global or only local choices, were excluded, because their GA effect could not be calculated. This concerned 8 men and 12 women, resulting in a remaining 71 participants (39 men, 32 women) for the Kimchi-Palmer task.

Number Comparison Task

Two two-digit numbers were presented vertically above each other (compare Figure 1). Participants had to identify the larger number. The task consisted of both a central and a hemifield presentation condition. For the present analyses, only the first condition is relevant, as it assesses number-magnitude processing unaffected by hemispheric asymmetries. In compatible number pairs, the larger number contained the larger unit digit (e.g., 52–67). In incompatible number pairs, the larger number contained the smaller unit digit (e.g., 57–62). Compatible and incompatible pairs were matched with respect to the magnitudes of numbers and the distance between numbers, which also affect RTs (compare Table 1 in Harris et al., 2018). RT to correctly solved items were used to calculate the compatibility effect as standardized mean difference between RT to compatible and incompatible items as described in Harris et al. (2018).

Statistical Analyses

Statistical analysis was carried out in R 3.3.2. Since all participants completed two test sessions, this nestedness of data needed to be accounted for by using linear mixed effects models. These models were, implemented using the *lme* Function of the *nlme* package (Pinheiro et al., 2017). All models enter participant number as a random factor to control for repeated measurements and are described in detail in the results section. Since we previously demonstrated that global advantage does not represent a uniform concept but is dependent on task conditions (Pletzer, Harris, et al., 2017), the five GA effects (four from the Navon paradigm + one from the Kimchi-Palmer task) were not averaged but entered as separate independent variables in linear mixed effects models on the compatibility effect in the number comparison task. In order to obtain standardized effect sizes, dependent and independent variables were scaled in all analyzes. That way, the estimate b represents an effect size based on standard deviations similar to Cohen's *d*. Data and scripts are openly available at http://webapps.ccns.sbg.ac.at/OpenData/.

Results

In the number comparison task, faster responses with compatible as compared to incompatible items, that is, the compatibility effect, are indicative of stronger decomposed or less holistic processing of multidigit numbers. To be used as dependent variable, the compatibility effect was calculated as standardized mean difference over RTs. In order to assess, whether the compatibility effect was affected by global-local processing, it was subjected to a linear mixed effects model with the fixed effects session, as well as the interactive effects of sex and GA, separately for the four Navon task conditions and the Kimchi-Palmer task (compatibility ~ 1|PNr + session + sex × GA).

The compatibility effect was significantly negatively related to the GA effect in the letters selected and shapes divided conditions (letters selected: $b = -0.42$, $SE_b = 0.15$, $t_{(55)} = -2.90$, $p = .005$; shapes divided: $b = -0.26$, $SE_b = 0.12$, $t_{(55)} = -2.14$, $p = .04$), with a trend also in the shapes selected condition ($b = -0.27$, $SE_b = 0.14$, $t_{(55)} = -1.88$, $p = .07$), that is, the larger the GA, the more holistic or the less decomposed were numbers processed. This relationship was significantly modulated by sex in two conditions (letters selected: $b = 0.39$, $SE_b = 0.18$, $t_{(55)} = 2.10$, $p = .04$; shapes divided: $b = 0.38$, $SE_b = 0.18$, $t_{(55)} = 2.13$, $p = .04$) and showed a trend modulation by sex in the third (shapes selected: $b = 0.32$, $SE_b = 0.19$, $t_{(55)} = 1.68$, $p = .09$). These interactions indicate a stronger association in women (letters selected: b = −0.38, $p = .01$; shapes divided: b = −0.27, $p = .05$; shapes selected: b = −0.27, $p = .06$) compared to men (letters selected: b = −0.04, $p = .75$; shapes divided: b = 0.12, $p = .34$; shapes selected: b = 0.05, $p = .70$; Figure 2). There was no significant association between the compatibility effect and the GA in the letters divided condition ($b = -0.14$, $SE_b = 0.12$, $t_{(55)} = -1.12$, $p = .27$).

Furthermore, there was a significant negative association between the compatibility effect and the GA in the Kimchi Palmer task ($b = -0.31$, $SE_b = 0.13$, $t_{(68)} = -2.36$, $p = .02$; Figure 3) that was by trend modulated by sex ($b = 0.32$, $SE_b = 0.17$, $t_{(68)} = 1.86$, $p = .07$). A significant association was observed only in

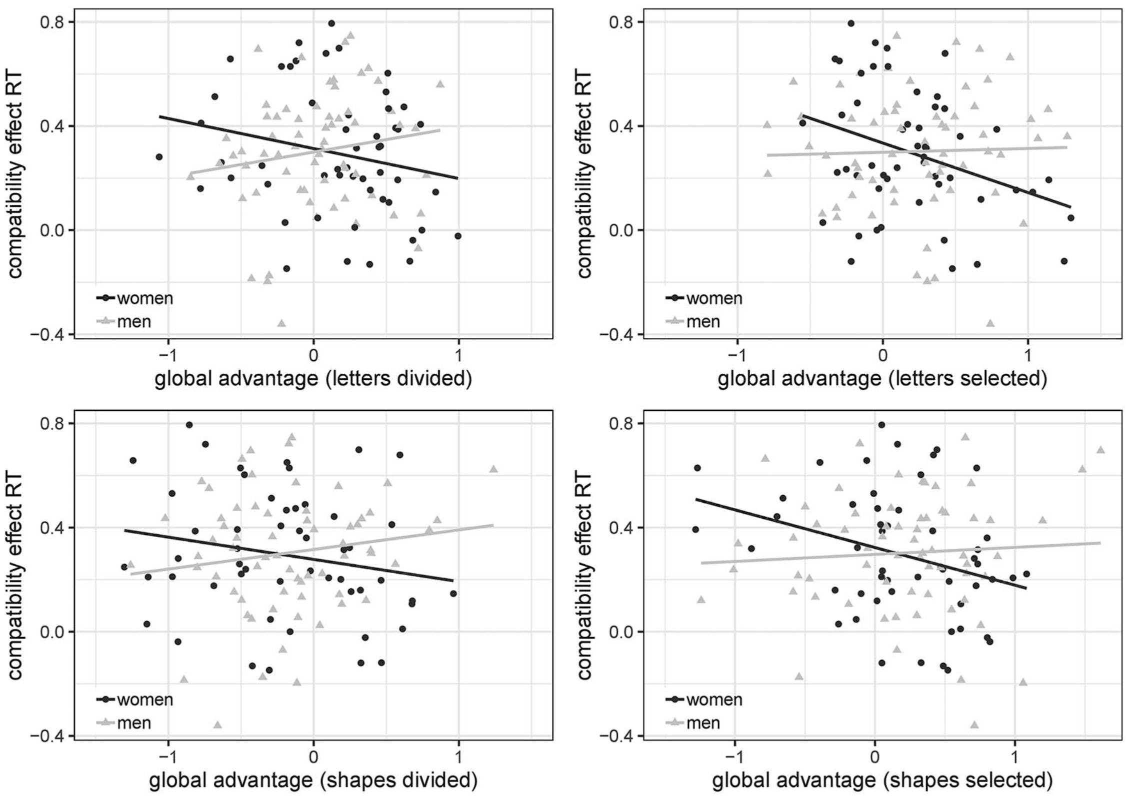

Figure 2. Relationship of the global advantage (GA) effects in the Navon paradigm to the compatibility effect during number comparison. A larger GA effect in the letters selected and shapes divided condition was significantly related to a smaller compatibility effect, that is, less decomposed/more holistic number processing in women, but not in men. A similar trend was observed in the shapes selected condition.

women (b = −0.29, p = .03), but not in men (b = −0.05, p = .67).

Discussion

The present analysis set out to investigate whether the individual tendency to base number processing on holistic or decomposed representations of multidigit numbers was dependent on the individual processing style for visual hierarchical stimuli, that is, global-local processing. We furthermore wanted to address whether this association was moderated by global-local processing condition and sex of participants. Assuming that holistic and decomposed number processing occur in parallel, the unit-decade compatibility effect can be seen as a measure of how much more strongly number comparison is based on the single digit magnitude representations than the holistic representations of the whole numbers. Likewise, during the processing of visual hierarchical stimuli, the global advantage effect represents how much faster global processing is compared to local processing (in the bottom up divided attention condition) or how much easier local information can be inhibited compared to global information (in the top down selective attention condition). Accordingly, we assessed whether the compatibility effect during number comparison was negatively related to the global advantage effects in the divided and/or selective attention condition of the Navon paradigm or the global advantage effect in the Kimchi-Palmer task, and sex was considered a potential moderator.

Results indicate that the compatibility effect is indeed negatively related to the global advantage effect in various conditions in women, while no evidence for such a relationship was observed in men. The larger women's global advantage effects, the smaller their compatibility effect during number comparison; that is, the more global their visual processing style, the less likely they were to base their numerical processing on decomposed number representations. These results are in line with the hypothesis that global-local processing transcends to representations of multidigit numbers, which are hierarchical in nature. Like spatial and verbal processing (Pletzer, Harris, et al., 2017), number processing relates, at least partially, to basic visual processing. However, two aspects about these results require special attention: (a) The fact that unlike for spatial and verbal processing, multiple measures of global advantage related to the compatibility effect, and (b) the fact that the relationship between the compatibility effect and global advantage was only observed in women.

Regarding (a), it is noteworthy that unlike for spatial and verbal tasks, the compatibility effect during number comparison was significantly predicted by three out of five global advantage measures with similar trends visible for the nonsignificant predictors. In our previous analysis, spatial and verbal processing were only

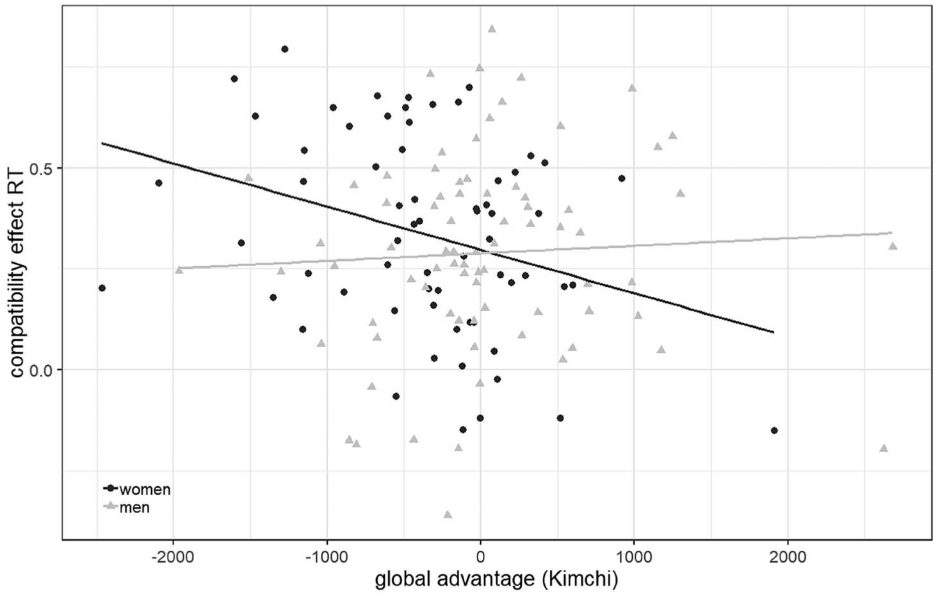

Figure 3. Relationship of the global advantage effect in the Kimchi paradigm to the compatibility effect during number comparison. A larger GA in the Kimchi-Palmer task was related to a smaller compatibility effect, that is, less decomposed/more holistic number processing in women, but not in men.

related to some aspects of global-local processing (Pletzer, Scheuringer, et al., 2017), suggesting that for spatial perspective taking, it is more important how much easier local information is subjected to top down inhibition compared to global information, while for verbal fluency it is more important how much faster global stimulus aspects are processed bottom up compared to local stimulus aspects. For the unit-decade compatibility effect, which likely indicates whether number comparison is more strongly based on mental representations of the individual digits than the whole number, several aspects of global-local processing appear to be important.

First, the global advantage during divided attention using shape stimuli was related to the unit-decade compatibility effect in women. This suggests that either faster processing of local or slower processing of global information relates to a stronger reliance on single digit magnitude representations during number comparison. This may be due to the faster formation of strong single digit magnitude representation or the slower formation of a holistic representation of whole number magnitudes.

Second, irrespective of stimulus material, the global advantage during selective attention emerged as predictor of the unit-decade compatibility effect in women. This suggests that more inhibition toward local or less inhibition toward global information is related to a reduced tendency to base number comparison on mental representations of single digit magnitudes rather than whole number magnitudes. In the case of incompatible items, correct decisions require the inhibition of single digit, that is, unit digit, magnitudes (compare Macizo, 2017). The faster this local level information is inhibited, the faster reactions to incompatible items can occur and the smaller is the unit-decade compatibility effect. Vice versa, less inhibition toward local or more inhibition toward global information in hierarchical stimulus processing is related to the tendency toward decomposed magnitude processing. Accordingly, like in the case of divided attention, it is also possible that less inhibition toward local information simply leads to stronger or faster representations of single digit magnitudes or that more inhibition toward global information delays the formation of a holistic magnitude representation, which in turn leads to a stronger reliance on single digit magnitude representations during number comparison. In line with this, a recent study was able to show that both unit and decade digit magnitudes are processed automatically, even if irrelevant to the task, for example, during parity judgments (Cipora, Soltanlou, Smaczny, Göbel, & Nuerk, 2019).

The fact that both bottom up and top down mechanisms involved in hierarchical stimulus processing show the same pattern of results with regards to the unit decade compatibility effect may simply be attributed to the fact that holistic magnitude representations require the visual processing of individual digits, while the recognition of the form of local elements is not necessary for the recognition of global configurations in hierarchical visual scenes. Therefore, any mechanism that delays the formation of a holistic magnitude representation will lead to a stronger compatibility effect. Accordingly, even the global advantage effect in the Kimchi Palmer task, which reflects participant’s subjective choices, relates to the compatibility effect. This likely shows that even the conscious decision to focus or not focus on certain digits to solve the number comparison task has the same effect as highly automatized processing mechanisms. A strong visual focus on individual digits, fast visual processing of these digits or neglecting the global configuration of these digits, all delay holistic magnitude representations and require number comparison to be based on decomposed digit representations, which leads to a disadvantage in incompatible items.

Regarding (b), the fact that the relationship between global advantage and compatibility was stronger in women than in men compares to previous findings for spatial and verbal processing, where the relationship of global-local processing was also stronger in women compared to men (Pletzer, Scheuringer, et al., 2017). For spatial and verbal processing, we originally assumed that the moderation by sex was the result of the global advantage effects in different conditions reflecting different mechanisms for men and women. However, since almost all measures of global advantage show an association to the unit-decade compatibility effect in women, this explanation seems unlikely. In fact, as argued above, several mechanisms presumably involved in global-local processing may affect number-magnitude processing in the same way. Accordingly, it is more likely that the moderation by sex signifies different mechanisms involved in the unit-decade compatibility effect for men and women.

This is entirely possible since, according to the hybrid model, a two-digit number forms three different magnitude representations in the brain: decades, units, and whole number magnitudes. Accordingly, one can solve number comparison items by balancing the comparison of decomposed versus holistic magnitude representations. However, one can also ignore holistic magnitude representations altogether and balance the comparison of decade and unit magnitude representations. In that case the compatibility effect would not reflect how fast local information is processed or how easily local information can be inhibited altogether but how easily specific local information can be selected while inhibiting other types of local information. In the case of within-decade trials (e.g., 52 vs. 56), decade information is noninformative and needs to be ignored, while unit information needs to be selected. In the case of compatible items (e.g., 52 vs. 86), both digit representations yield the same result and nothing needs to be inhibited, though formally only the decade information is needed to solve the trial. In the case of incompatible items (e.g., 56 vs. 82) on the other hand, only decade information is informative, and unit information needs to be ignored. For participants who do solve the task via balancing information from decade and unit representations rather than information from decomposed versus holistic representations, the unit-decade compatibility would be a general measure of selective attention rather than a measure of global-local processing. Accordingly, no association to the global advantage effect is to be expected.

Following this reasoning, the results of the present study suggest that on average men solve the number comparison task without or before forming a holistic magnitude representation. This idea is supported by the repeated observation of faster overall RTs in men compared to women for numerical tasks (Bull et al., 2013; Pletzer, 2016). If that is indeed the case, the sex difference in the unit-decade compatibility effect needs to be interpreted differently than previously assumed (Harris et al., 2018; Pletzer et al., 2013; Pletzer, Harris, et al., 2019). Rather than signifying that men rely more strongly on holistic magnitude representations than women, it may in fact indicate that in this task, men do not form a holistic magnitude representation at all since it is not necessary to solve the task at hand. Nevertheless, the extent to which holistic magnitude representations do play a role in number comparison for men and women may be modulated by stimulus characteristics like the spatial distance between numbers or the presentation mode (Pletzer et al., 2016). If the compatibility effect does indeed reflect different processing mechanisms in men and women, it is hard to compare between the sexes, though it does suggest that men can more easily suppress specific visual information. This assumption is supported by some studies on sex differences in visual attention (Pletzer, Harris, et al., 2017; Stoet, 2017).

Beyond the current study, this observation gives rise to the idea, that executive resources may be more strongly directed toward input inhibition in men but toward output inhibition in women since several studies indicate that women are better at inhibiting a prepotent response tendency in various self-control tasks (Chapple, Vaske, & Hope, 2010; Mansouri, Fehring, Gaillard, Jaberzadeh, & Parkington, 2016; Sjoberg & Cole, 2018). If that's the case and visual scenes are more fully processed by women compared to men, it is possible that basic visual processing plays a stronger role for higher cognitive processing in women compared to men. This may explain the overall stronger attention to stimulus-details in women (Handa & McGivern, 2015; Pletzer et al., 2014), resulting in a stronger requirement for integrated processing of global and local stimulus aspects across a variety of tasks.

In summary, the findings of the present study provide evidence for a missing link between the processing of visual hierarchical stimuli and the processing of multidigit numbers. At least in women, the unit-decade compatibility effect in number comparison is partly affected by the individual visual processing style due to the hierarchical nature of the visual number format. These results may help to put the discussion on holistic versus decomposed number processing in a new framework. The parallel representations of whole number and single digit magnitudes as proposed in hybrid models may not be an isolated phenomenon during number processing, but simply arise from the hierarchical nature of the stimulus material by utilizing the parallel processing mechanisms already implemented for other visual hierarchical stimuli. Furthermore, this new link between global-local processing and number processing may foster new research in both areas since several factors that have repeatedly been shown to affect global-local processing have not been investigated in the number processing literature and vice versa. Finally, the present findings highlight the importance of addressing sex differences in cognitive science since the assumption of one behavioral parameter reflecting the same cognitive process in men and women may in fact mask important associations that could otherwise shed light on cognitive processing in both men and women.

References

Basso, M. R., & Lowery, N. (2004). Global-local visual biases correspond with visual-spatial orientation. *Journal of Clinical and Experimental Neuropsychology, 26,* 24–30. http://dx.doi.org/10.1076/jcen.26.1.24.23939

Bull, R., Cleland, A. A., & Mitchell, T. (2013). Sex differences in the spatial representation of number. *Journal of Experimental Psychology: General, 142,* 181–192. http://dx.doi.org/10.1037/a0028387

Cahill, L. (2006). Why sex matters for neuroscience. *Nature Reviews Neuroscience, 7,* 477–484. http://dx.doi.org/10.1038/nrn1909

Chapple, C. L., Vaske, J., & Hope, T. L. (2010). Sex differences in the causes of self-control: An examination of mediation, moderation, and gendered etiologies. *Journal of Criminal Justice, 38,* 1122–1131. http://dx.doi.org/10.1016/j.jcrimjus.2010.08.004

Cipora, K., Soltanlou, M., Smaczny, S., Göbel, S. M., & Nuerk, H.-C. (2019). Automatic place-value activation in magnitude-irrelevant parity judgement. *Psychological Research*. Advance online publication. http://dx.doi.org/10.1007/s00426-019-01268-1

Dehaene, S. (1989). The psychophysics of numerical comparison: A reexamination of apparently incompatible data. *Perception & Psychophysics, 45,* 557–566. http://dx.doi.org/10.3758/BF03208063

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

Dotan, D., & Dehaene, S. (2013). How do we convert a number into a finger trajectory? *Cognition, 129,* 512–529. http://dx.doi.org/10.1016/j.cognition.2013.07.007

Fink, G. R., Halligan, P. W., Marshall, J. C., Frith, C. D., Frackowiak, R. S. J., & Dolan, R. J. (1996). Where in the brain does visual attention select the forest and the trees? *Nature, 382,* 626–628. http://dx.doi.org/10.1038/382626a0

Handa, R. J., & McGivern, R. F. (2015). Steroid hormones, receptors, and perceptual and cognitive sex differences in the visual system. *Current Eye Research, 40,* 110–127. http://dx.doi.org/10.3109/02713683.2014.952826

Harris, T., Scheuringer, A., & Pletzer, B. (2018). Sex differences and functional hemispheric asymmetries during number comparison. *Biology of Sex Differences, 9,* 3. http://dx.doi.org/10.1186/s13293-017-0162-6

Heinze, H. J., Johannes, S., Münte, T. F., & Mangun, G. R. (1994). The order of global-and local-level information processing: Electrophysiological evidence for parallel perceptual processes. In H. J. Heinze, T. F. Münte, & G. R. Mangun (Eds.), *Cognitive electrophysiology* (pp. 102–123). Boston, MA: Birkhäuser. http://dx.doi.org/10.1007/978-1-4612-0283-7_4

Huber, S., Nuerk, H. C., Reips, U. D., & Soltanlou, M. (2019). Individual differences influence two-digit number processing, but not their analog magnitude processing: A large-scale online study. *Psychological Research, 83,* 1444–1464. http://dx.doi.org/10.1007/s00426-017-0964-5

Huberle, E., & Karnath, H. O. (2006). Global shape recognition is modulated by the spatial distance of local elements—Evidence from simultanagnosia. *Neuropsychologia, 44,* 905–911. http://dx.doi.org/10.1016/j.neuropsychologia.2005.08.013

Huizinga, M., Burack, J. A., & Van der Molen, M. W. (2010). Age-related change in shifting attention between global and local levels of hierarchical stimuli. *Journal of Cognition and Development, 11,* 408–436. http://dx.doi.org/10.1080/15248371003700031

Insch, P. M., Bull, R., Phillips, L. H., Allen, R., & Slessor, G. (2012). Adult aging, processing style, and the perception of biological motion. *Experimental Aging Research, 38,* 169–185. http://dx.doi.org/10.1080/0361073X.2012.660030

Keller, K., & Menon, V. (2009). Gender differences in the functional and structural neuroanatomy of mathematical cognition. *NeuroImage, 47,* 342–352. http://dx.doi.org/10.1016/j.neuroimage.2009.04.042

Kimchi, R., Amishav, R., & Sulitzeanu-Kenan, A. (2009). Gender differences in global-local perception? Evidence from orientation and shape judgments. *Acta Psychologica, 130,* 64–71. http://dx.doi.org/10.1016/j.actpsy.2008.10.002

Kucian, K., Loenneker, T., Dietrich, T., Martin, E., & Von Aster, M. (2005). Gender differences in brain activation patterns during mental rotation and number related cognitive tasks. *Psychology Science, 47,* 112–113.

Luna, D., Merino, J. M., & Marcos-Ruiz, R. (1990). Processing dominance of global and local information in visual patterns. *Acta Psychologica, 73,* 131–143. http://dx.doi.org/10.1016/0001-6918(90)90075-Q

Macizo, P. (2017). Conflict resolution in two-digit number processing: Evidence of an inhibitory mechanism. *Psychological Research, 81,* 219–230. http://dx.doi.org/10.1007/s00426-015-0716-3

Mansouri, F. A., Fehring, D. J., Gaillard, A., Jaberzadeh, S., & Parkington, H. (2016). Sex dependency of inhibitory control functions. *Biology of Sex Differences, 7,* 11. http://dx.doi.org/10.1186/s13293-016-0065-y

Martin, M. (1979). Local and global processing: The role of sparsity. *Memory & Cognition, 7,* 476–484. http://dx.doi.org/10.3758/BF03198264

McKone, E., Aimola Davies, A., Fernando, D., Aalders, R., Leung, H., Wickramariyaratne, T., & Platow, M. J. (2010). Asia has the global advantage: Race and visual attention. *Vision Research, 50,* 1540–1549. http://dx.doi.org/10.1016/j.visres.2010.05.010

Milner, A. D., & Goodale, M. A. (2008). Two visual systems re-viewed. *Neuropsychologia, 46,* 774–785. http://dx.doi.org/10.1016/j.neuropsychologia.2007.10.005

Müller-Oehring, E. M., Schulte, T., Raassi, C., Pfefferbaum, A., & Sullivan, E. V. (2007). Local-global interference is modulated by age, sex and anterior corpus callosum size. *Brain Research, 1142,* 189–205. http://dx.doi.org/10.1016/j.brainres.2007.01.062

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9,* 353–383. http://dx.doi.org/10.1016/0010-0285(77)90012-3

Navon, D., & Norman, J. (1983). Does global precedence really depend on visual angle? *Journal of Experimental Psychology: Human Perception and Performance, 9,* 955–965. http://dx.doi.org/10.1037/0096-1523.9.6.955

Nuerk, H. C., Weger, U., & Willmes, K. (2001). Decade breaks in the mental number line? Putting the tens and units back in different bins. *Cognition, 82,* B25–B33. http://dx.doi.org/10.1016/S0010-0277(01)00142-1

Oken, B. S., Kishiyama, S. S., Kaye, J. A., & Jones, D. E. (1999). Age-related differences in global-local processing: Stability of laterality differences but disproportionate impairment in global processing. *Journal of Geriatric Psychiatry and Neurology, 12,* 76–81. http://dx.doi.org/10.1177/089198879901200207

Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., Heisterkamp, S., Van Willigen, B., & Maintainer, R. (2017). Package 'nlme'. *Linear and Nonlinear Mixed Effects Models* (version 3.1–148). Retrieved from https://cran.uib.no/web/packages/nlme/nlme.pdf

Plaisted, K., Swettenham, J., & Rees, L. (1999). Children with autism show local precedence in a divided attention task and global precedence in a selective attention task. *Journal of Child Psychology and Psychiatry, 40,* 733–742. http://dx.doi.org/10.1111/1469-7610.00489

Pletzer, B. (2016). Sex differences in number processing: Differential systems for subtraction and multiplication were confirmed in men, but not in women. *Scientific Reports, 6,* 39064. http://dx.doi.org/10.1038/srep39064

Pletzer, B., & Harris, T. (2018). Sex hormones modulate the relationship between global advantage, lateralization, and interhemispheric connectivity in a Navon paradigm. *Brain Connectivity, 8,* 106–118. http://dx.doi.org/10.1089/brain.2017.0504

Pletzer, B., Harris, T. A., & Ortner, T. (2017). Sex and menstrual cycle influences on three aspects of attention. *Physiology & Behavior, 179,* 384–390. http://dx.doi.org/10.1016/j.physbeh.2017.07.012

Pletzer, B., Harris, T., & Scheuringer, A. (2019). Sex differences in number magnitude processing strategies are mediated by spatial navigation strategies: Evidence from the unit-decade compatibility effect. *Frontiers in Psychology, 10,* 229. http://dx.doi.org/10.3389/fpsyg.2019.00229

Pletzer, B., Jäger, S., & Hawelka, S. (2019). Sex hormones and number processing. Progesterone and testosterone relate to hemispheric asymmetries during number comparison. *Hormones and Behavior, 115,* 104553. http://dx.doi.org/10.1016/j.yhbeh.2019.07.001

Pletzer, B., Kronbichler, M., Nuerk, H. C., & Kerschbaum, H. (2013). Sex differences in the processing of global vs. local stimulus aspects in a two-digit number comparison task—An fMRI study. *PLoS ONE, 8,* e53824. http://dx.doi.org/10.1371/journal.pone.0053824

Pletzer, B., Petasis, O., & Cahill, L. (2014). Switching between forest and trees: Opposite relationship of progesterone and testosterone to global-local processing. *Hormones and Behavior, 66,* 257–266. http://dx.doi.org/10.1016/j.yhbeh.2014.05.004

Pletzer, B., Scheuringer, A., & Harris, T. (2016). Spacing and presentation modes affect the unit-decade compatibility effect during number comparison. *Experimental Psychology, 63,* 189–195. http://dx.doi.org/10.1027/1618-3169/a000326

Pletzer, B., Scheuringer, A., & Scherndl, T. (2017). Global-local processing relates to spatial and verbal processing: Implications for sex differences in cognition. *Scientific Reports, 7,* 10575. http://dx.doi.org/10.1038/s41598-017-11013-6

Poirel, N., Pineau, A., & Mellet, E. (2008). What does the nature of the stimuli tell us about the global precedence effect? *Acta Psychologica, 127,* 1–11. http://dx.doi.org/10.1016/j.actpsy.2006.12.001

Razumnikova, O. M., & Vol'f, N. V. (2011). Selection of visual hierarchical stimuli between global and local aspects in men and women. *Fiziologiia Cheloveka, 37,* 14–19.

Roalf, D., Lowery, N., & Turetsky, B. I. (2006). Behavioral and physiological findings of gender differences in global-local visual processing. *Brain and Cognition, 60,* 32–42. http://dx.doi.org/10.1016/j.bandc.2005.09.008

Robertson, L. C., & Lamb, M. R. (1991). Neuropsychological contributions to theories of part/whole organization. *Cognitive Psychology, 23,* 299–330. http://dx.doi.org/10.1016/0010-0285(91)90012-D

Scheuringer, A., & Pletzer, B. (2016). Sex differences in the Kimchi-Palmer task revisited: Global reaction times, but not number of global choices differ between adult men and women. *Physiology & Behavior, 165,* 159–165. http://dx.doi.org/10.1016/j.physbeh.2016.07.012

Scheuringer, A., & Pletzer, B. (2017). Sex differences and menstrual cycle dependent changes in cognitive strategies during spatial navigation and verbal fluency. *Frontiers in Psychology, 8,* 381. http://dx.doi.org/10.3389/fpsyg.2017.00381

Sjoberg, E. A., & Cole, G. G. (2018). Sex differences on the go/no-go test of inhibition. *Archives of Sexual Behavior, 47,* 537–542. http://dx.doi.org/10.1007/s10508-017-1010-9

Stoet, G. (2017). Sex differences in the Simon task help to interpret sex differences in selective attention. *Psychological Research, 81,* 571–581. http://dx.doi.org/10.1007/s00426-016-0763-4

Verguts, T., & De Moor, W. (2005). Two-digit comparison: Decomposed, holistic, or hybrid? *Experimental Psychology, 52,* 195–200. http://dx.doi.org/10.1027/1618-3169.52.3.195

Wei, W., Chen, C., & Zhou, X. (2016). Spatial ability explains the male advantage in approximate arithmetic. *Frontiers in Psychology, 7,* 306. http://dx.doi.org/10.3389/fpsyg.2016.00306

Wei, W., Lu, H., Zhao, H., Chen, C., Dong, Q., & Zhou, X. (2012). Gender differences in children's arithmetic performance are accounted for by gender differences in language abilities. *Psychological Science, 23,* 320–330. http://dx.doi.org/10.1177/0956797611427168

Received February 18, 2019
Revision received May 29, 2020
Accepted June 1, 2020 ■