It is a long-lasting debate in the number processing literature, whether the magnitudes of multi-digit numbers are processed as a whole (holistically) or in a decomposed fashion, that is, units, decades, hundreds, etc., separately.

The holistic model states, that when comparing a number pair consisting of 2 two-digit numbers, these are first represented as a whole on a mental number line, then compared to each other (Brysbaert, 1995; Dehaene, Dupoux, & Mehler, 1990). The decomposed model by Nuerk, Weger, and Willmes (2001) suggests multiple number lines. In the case of two-digit numbers, two number lines, one for units, and one for decades, are proposed. Unit and decade digits of both numbers are compared separately along these number lines. A strong argument for the theory of decomposed processing is the so-called unit-decade compatibility effect (Nuerk et al., 2001).

In compatible number comparison items, the larger number contains the larger unit digit (e.g., 65–87; 6 < 8; 5 < 7). In incompatible number comparison items, the larger number contains the smaller unit digit (e.g., 59–81; 1 < 9, but 8 > 5). The overall difference between both number pairs is 22. However, the reaction time to spot the larger number is shorter with the compatible example compared to the incompatible example. Such an effect can only occur in a decomposed model of number magnitude processing, since the mental number-line representation of the holistic model would predict equal reaction times across all two-digit number pairs with the difference of 22. If however only the whole number magnitudes were compared, a unit-decade compatibility effect should not occur at all.

It was originally argued (Poltrock & Schwartz, 1984) that such decomposed comparison occurs sequentially, that is decades are compared before units are compared. If numbers were compared decomposed, but sequentially, a decision could be made immediately after the decade comparison. This should however, elicit faster reactions in incompatible than in compatible items, since decade distance is larger in incompatible number pairs of the same distance and items with larger distance are compared faster than items with smaller distance (Nuerk et al., 2001; Pletzer, Kronbichler, Nuerk, & Kerschbaum, 2013). Thus, it is assumed that decomposed processing of units and decades occurs in parallel, which is supported by recent eye-tracking evidence (Moeller, Fischer, Nuerk, & Willmes, 2009).

However, the universality of the unit-decade compatibility effect has been challenged by two lines of research. On the one hand, interindividual differences in the compatibility effect have been reported, suggesting interindividual differences in the preferred mode of processing number magnitudes. We were recently able to demonstrate that...
sex might be one factor accounting for such interindividual differences. While men showed no compatibility effect in reaction times (RT) in a two-digit number comparison task, women did show a significant compatibility effect in RT. Since previous results suggest that men in general tend to preferably process global aspects of hierarchical stimuli, whereas women preferentially process local aspects of hierarchical stimuli (Kramer, Ellenberg, Leonhard, & Share, 1996; Pletzer, Petasis, & Cahill, 2014; Razumnikova & Vol’f, 2011; Roalf, Lowery, & Turetsky, 2006), we interpreted this as evidence that men compare the two numbers according to the holistic model, whereas women compare the two numbers according to the decomposed model (Pletzer et al., 2013).

On the other hand, it has been criticized that the compatibility effect might be elicited by the presentation mode of stimuli. Studies using comparison of numbers to a fixed standard instead of a simultaneous presentation mode usually do not find a compatibility effect (e.g., Brysbaert, 1995; Dehaene et al., 1990). In that respect, it has also been demonstrated that consecutive presentation of number pairs, as common in studies with fixed standards, does not elicit a compatibility effect (Ganor-Stern, Pinhas, & Tzelgov, 2009; Zhou, Chen, Chen, & Dong, 2008) except if a very high number of within-decade pairs (e.g., 51-57) emphasizes the importance of units for the comparison (Moeller, Fischer, Nuerk, & Willmes, 2013). Consecutive presentation prevents both parallel and sequential decomposed comparison and forces participants to process the whole number magnitude of one number before comparing it to the other number.

Furthermore, the vertical presentation of numbers above each other may visually facilitate the separate comparison of decades and units, especially since digitwise addition and subtraction of multi-digit numbers is taught in vertical presentation mode in schools. In an experiment of Nuerk, Weger, and Willmes (2004), numbers were presented diagonally above each other and they still observed a significant compatibility effect. However, it could be argued that diagonal presentation still contains a vertical element and does not fully address the issue with vertical presentation modes. No study has up to now used a completely horizontal presentation mode to study the compatibility effect. Furthermore, the previous study by Nuerk et al. (2004) did not directly compare the size of the compatibility effect between different presentation modes in the same sample but rather reported, that a significant compatibility effect could be observed with the diagonal presentation mode.

Moreover, no study has so far addressed the question, whether different spacing between numbers in the vertical presentation mode affects the size of the compatibility effect. Spacing effects on equations suggest that it is harder to solve mathematical problems if the operands are spaced closer together than if they are spaced farther apart (Jiang, Cooper, & Alibali, 2014; Kirshner, 1989). Landy and Goldstone (2007a, 2007b, 2010) extended these works and varied the spacing according to the syntactic structure of the equations. For example, in equations involving both additions and multiplications, multiplications are supposed to be solved first. Participants tended to follow this rule more closely and made smaller errors in solving the equations, if multiplications were spaced closer together than additions. Thus, if the two numbers of a number comparison item are presented very closely together, participant may tend to compare the single digits first than to evaluate the whole number magnitudes before comparing the numbers. Furthermore, with increasing distance between numbers the similarity to multi-digit addition and subtraction should decrease and each number should be more strongly perceived as a separate entity than as part of a single item. Thus, closer spacing of numbers should increase, while wide spacing of numbers should decrease the compatibility effect.

If a different presentation mode can reduce the compatibility effect, this suggests that the processing mode can be changed either from decomposed to holistic comparison or from parallel to sequential decomposed comparison. If a different presentation mode were to reverse the compatibility effect, this would be strong evidence for a change to sequential comparison. Thus, either participants choose a processing mode (holistic vs. decomposed, sequential vs. decomposed parallel) that is most suitable for the task at hand, or holistic and decomposed processing occur simultaneously and depending on the presentation mode – influence the results to a different extent. The latter idea is consistent with the hybrid model of number processing, which attempts to unite the holistic and decomposed model and encompasses all behavioral effects during number comparison (distance, compatibility, problem size) (Nuerk et al., 2001; Verguts & De Moor, 2005). Importantly, effects of stimulus characteristics, including spacing, have also been reported for other types of hierarchical stimuli (Martin, 1979; Navon & Norman, 1983) to influence the general tendency to process stimuli at the global or local level.

In order to evaluate, whether the size of the compatibility effect is modulated by presentation mode and spacing, two studies were performed. Since our previous study demonstrated sex effects on the compatibility effect, only male participants were included in these studies.

In the first study the simultaneous vertical presentation mode was compared to a simultaneous, but horizontal presentation mode. We hypothesized a stronger compatibility effect with the vertical as opposed to the horizontal presentation mode. For purposes of validation we also compared both presentation modes to a consecutive presentation mode with numbers being presented after each other.
We expected to replicate previous findings that with a moderate amount of within-decade items, a unit-decade compatibility effect occurs only with simultaneous presentation, but not with consecutive presentation.

In the second study, number comparison stimuli were presented simultaneously, vertically above each other on the screen, but either spaced closely or spaced farther apart, similar to the spacing of local elements in hierarchical stimuli. We hypothesized a stronger compatibility effect with closer presentation modes than with more distant spacing.

### Methods

#### Participants

Thirty-two healthy men (mean age: 23.60 ± 4.29 years, range: 19–40 years) participated in Study 1 and 32 healthy men (mean age: 25.65 ± 2.77 years, range: 20–30 years) in Study 2. Participants of both studies were right-handed, had no psychological or neurological disorder according to self-reports, and were not currently on medication. All subjects gave their informed written consent to participate in the study. The experiments were conducted in accordance with the Declaration of Helsinki.

#### Stimuli

In both studies, participants completed a number comparison task with different presentation modes. Participants were presented with 2 two-digit numbers and had to decide, which number was larger. Although the instruction to identify the larger number refers to the global level (number magnitudes not digit magnitudes) it is not explicitly stated, which level to attend. Participants are free to solve the task on the global level, by comparing the magnitudes of the whole numbers, or on the local level, by comparing the magnitudes of the digits.

For each presentation mode in each study, 100 items were presented. Forty items were unit-decade compatible (C), that is, the smaller number contained the smaller unit digit (e.g., 67.43), and 40 were unit-decade incompatible (I), that is, the smaller number contained the larger unit digit (e.g., 63.47). Furthermore, 20 within-decade items, that is, items where the two numbers contained the same decade digit (e.g., 63.67), were included. Within-decade items prevent a strategy of only comparing decade digits, as they require the processing of unit digits.

Problem size (size of larger and smaller number), absolute distance, decade distance (the absolute distance between the decade digits of the two numbers), unit distance (the absolute distance between the unit digits of the two numbers), and parity were matched across presentation modes; problem size and absolute distance were furthermore matched between compatible and incompatible items (Table 1). In each condition (Presentation Mode × Compatibility), half of the items had small decade distance (1–4), the other half large decade distance (>4). All items had large unit distance (>4). Numbers ranged from 21 to 98. Except for within-decade items, all four digits of an item were different. All items were presented for 2 s, preceded by a 1 s fixation period.

#### Study 1

The 2 two-digit numbers were presented blockwise in three different presentation modes.

(i) Vertically above each other in the middle of the screen (Figure 1A).

(ii) Horizontally next to each other in the middle of the screen (Figure 1B). The vertical and horizontal distance between the numbers extended a visual angle of 11.5°.

(iii) Consecutively, that is, the first number appeared at the center of the screen for 1 s, disappeared and was followed by the second number appearing on the screen for 1 s (Figure 1C).

#### Study 2

The 2 two-digit numbers were displayed above each other in the middle of the screen (Figure 1D). In half of the items, the two numbers were presented close to each other, extending a visual angle of 11.5°. In the other half of the
items, the two numbers were presented distant to each other, extending a visual angle of 22°. Presentation modes were randomized. In half of the items of each condition, the upper number was larger, in the other half, the lower number was larger.

Analyses
Statistical analysis was carried out using software JASP 0.7.5.5 (https://jasp-stats.org). The impact of vertical spacing and presentation modes (vertical vs. horizontal; simultaneous vs. consecutive) on the compatibility effect in number comparison were assessed with ANOVA was run with presentation mode on the compatibility effect, a main effect of presentation mode, a BF of anecdotic evidence for the null hypothesis, that is, that the compatibility effect was of equal size for vertical and horizontal presentation (Figure 2A).

Error Rates
A large and significant main effect of compatibility, $F(1,31) = 24.89$, $MSE = 40.81$, $p < .001$, $\eta_p^2 = .45$, was observed. Participants made more errors on incompatible as compared to compatible items. However, no significant main effect of presentation mode, $F(1, 31) = 0.86$, $MSE = 16.28$, $p = .36$, $\eta_p^2 = 0.03$, was observed on error rates and no significant interaction between Compatibility × Presentation Mode, $F(1,31) = 0.54$, $MSE = 25.96$, $p = .47$, $\eta_p^2 = 0.02$. For the main effect of presentation mode, a BF of 5.20 suggests anecdotic evidence for the null hypothesis, that is, participants made a comparable amount of errors with the vertical and horizontal presentation. For the interaction between Compatibility × Presentation Mode, a BF of 4.62 suggests anecdotic evidence for the null hypothesis, that is, that the compatibility effect was of comparable size with the vertical and horizontal presentation (Figure 2B).

Results
Effects of Horizontal versus Vertical Presentation Mode on the Compatibility Effect (Study 1)
In order to determine the effect of horizontal versus vertical as presentation mode on the compatibility effect, a $2 \times 2$ ANOVA was run with “compatibility” (compatible vs. incompatible) and “presentation mode” (horizontal vs. vertical) as within-subject factors on both RT and ER (Error Rate).

Reaction Times
Large and significant main effects of both compatibility, $F(1,31) = 35.61$, $MSE = 3,059.27$, $p < .001$, $\eta_p^2 = .54$, and presentation mode, $F(1,31) = 10.62$, $MSE = 2,637.75$, $p = .003$, $\eta_p^2 = .26$, were observed. Responses were slower to incompatible as compared to compatible trials and to vertically spaced as opposed to horizontally spaced trials. However, no significant interaction between Compatibility × Presentation Mode, $F(1,31) = 0.18$, $MSE = 1,973.41$, $p = .68$, $\eta_p^2 = .006$, was observed. A BF of 4.60 suggests anecdotic evidence for the null hypothesis, that is, that the compatibility effect was of equal size for vertical and horizontal presentation (Figure 2A).
ANOVA were run with “compatibility” (compatible vs. incompatible) and “presentation mode” (simultaneous vs. consecutive) as within-subjects factors. For the simultaneous condition, once reactions to the horizontally and once reactions to the vertically presented numbers were used.

**Reaction Times**

For both comparisons, a large and significant effect of compatibility (vertical: $F(1, 31) = 6.38$, $MSE = 1.86109$, $p < .01$, $\eta_p^2 = 0.17$; horizontal: $F(1, 31) = 4.81$, $MSE = 3.42502$, $p < .05$, $\eta_p^2 = 0.13$), as well as a significant effect of presentation mode (vertical: $F(1, 31) = 10.85$, $MSE = 36.14511$, $p = .001$, $\eta_p^2 = 0.26$; horizontal: $F(1, 31) = 5.89$, $MSE = 35.73002$, $p < .05$, $\eta_p^2 = 0.16$) were observed. Responses were slower for incompatible compared to compatible as well as for simultaneous versus consecutive presentation. Furthermore, for both comparisons, a highly significant interaction of Compatibility × Presentation Mode (vertical: $F(1, 31) = 13.61$, $MSE = 2.99224$, $p = .001$, $\eta_p^2 = 0.31$; horizontal: $F(1, 31) = 35.05$, $MSE = 1.39397$, $p < .001$, $\eta_p^2 = 0.53$) was observed. No significant compatibility effect was observed, when numbers were presented consecutively (Figure 2A). However, a BF$_{01}$ of 2.82 fails to provide evidence for the null hypothesis of no compatibility effect with consecutive presentation.

**Error Rates**

For both comparisons, large and significant main effects of both compatibility (vertical: $F(1, 31) = 10.87$, $MSE = 23.36$, $p = .002$, $\eta_p^2 = 0.26$; horizontal: $F(1, 31) = 10.37$, $MSE = 37.40$, $p = .003$, $\eta_p^2 = 0.25$), as well as presentation mode (vertical: $F(1, 31) = 11.59$, $MSE = 59.04$, $p = .002$, $\eta_p^2 = 0.27$; horizontal: $F(1, 31) = 6.09$, $MSE = 80.79$, $p < .05$, $\eta_p^2 = 0.16$) were observed. Participants made more errors on incompatible as compared to compatible trials and when numbers were presented consecutively, as when numbers were presented simultaneously. Furthermore, a large and significant interaction was observed between Compatibility × Presentation Mode (vertical: $F(1, 31) = 5.16$, $MSE = 28.77$, $p = .03$, $\eta_p^2 = 0.14$; horizontal: $F(1, 31) = 9.21$, $MSE = 27.59$, $p < .05$, $\eta_p^2 = 0.23$). The compatibility effect in error rates was larger, when numbers were presented simultaneously, than when they were presented consecutively (Figure 2B). No significant compatibility effect was observed, when numbers were presented consecutively, $F(1, 31) = 3.16$, $p = .08$. A BF$_{01}$ of 4.42 provides anecdotic evidence for the null hypothesis of no compatibility effect with consecutive presentation.

**Effects of Vertical Spacing on the Compatibility Effect (Study 2)**

To determine the impact of vertical spacing on the compatibility effect, a $2 \times 2$ ANOVA was run with the within-subjects factors, compatibility (compatible vs. incompatible), and, vertical spacing (close vs. distant) on both reaction times (RT) and error rates (ER).

**Reaction Times**

Large and significant main effects of both compatibility, $F(1, 31) = 26.98$, $MSE = 2.44370$, $p < .001$, $\eta_p^2 = 0.47$, and vertical spacing, $F(1, 31) = 42.73$, $MSE = 1.61078$, $p < .001$, $\eta_p^2 = 0.58$, were observed. Responses were slower for incompatible compared to compatible items and for large vertical spacing compared to small vertical spacing. Furthermore, a large and significant interaction effect of Compatibility × Vertical Spacing was observed, $F(1, 31) = 13.53$, $MSE = 1.04463$, $p = .001$, $\eta_p^2 = 0.30$. The compatibility effect was larger with close spacing compared to distant spacing (Figure 3A). However, the compatibility effect was still significant with the more distant spacing, $F(1, 31) = 6.19$, $MSE = 1.53664$, $p < .05$, $\eta_p^2 = 0.17$.

**Error Rates**

A large and significant main effect of compatibility, $F(1, 31) = 14.47$, $MSE = 20.41$, $p = .001$, $\eta_p^2 = 0.32$, was observed. Participants made significantly more errors on incompatible trials as compared to compatible trials. However, no significant main effect of vertical spacing on error rates, $F(1, 31) = 1.54$, $MSE = 14.31$, $p = .23$, $\eta_p^2 = 0.05$, was observed and only a trend for a Compatibility × Vertical Spacing interaction was observed, $F(1, 31) = 3.69$, $MSE = 7.66$, $p = .06$, $\eta_p^2 = 0.11$. For the main effect of presentation mode, a BF$_{01}$ of 4.21 provides anecdotic evidence for the null hypothesis, that is, participants made a comparable amount of errors with close and distant spacing of the numbers. However, for the interaction of Compatibility × Spacing, a BF$_{01}$ of 2.31 fails to provide evidence for the null hypothesis, that the compatibility effect does not differ between close and distant spacing condition (Figure 3B).
The present studies were designed to assess the effects of different presentation modes on the compatibility effect during number comparison in men. According to Bayesian analyses, the compatibility effect was of comparable size between the horizontal and the traditional vertical presentation format. However, the compatibility effect was significantly smaller with the consecutive presentation format than with both simultaneous presentation formats. Furthermore, we found that as expected, the compatibility effect was larger, if numbers were spaced closer together than when spaced closer apart.

The fact that simultaneous presentation leads to a comparable compatibility effect, irrespective of whether numbers are presented vertically, horizontally (this study), or diagonally (Nuerk et al., 2004), provides support for decomposed processing of number magnitudes. The compatibility effect is not enhanced if presented vertically in a mode which is taught for digitwise addition and subtraction in school. However – as demonstrated previously (Ganor-Stern et al., 2009; Zhou et al., 2008) the compatibility effect is nonsignificant with consecutive presentation of numbers, which compares to a large number of studies using fixed standards for number comparison that did not find a compatibility effect. This suggests that with consecutive presentation, the whole number magnitudes are processed before comparison. However, Bayesian analyses did not allow the conclusion of a null effect of compatibility with the consecutive presentation mode. This compares to recent results of Moeller et al. (2013), that a compatibility effect can be elicited with consecutive presentation if a large number of within-decade trials is used.

The effect of vertical spacing shows strong similarities to previous effects of stimulus spacing on mathematical processes (Landy & Goldstone, 2007a, 2007b, 2010). If numbers are spaced closely together, it is more likely that the magnitudes of their constituting digits are compared before the magnitudes of the whole numbers. The close spacing furthermore supports parallel comparison of decade and unit magnitudes as reported by Moeller et al. (2009), since all digits can be viewed at once. If numbers are spaced further apart, two scenarios are possible. Either, the whole numbers are processed before comparison or participants resort to a more sequential, but decomposed comparison, since the distant spacing prevents parallel comparison of decades and units. While the present study design does not allow a definite decision on which processing mode was used by participants, both, theoretical considerations, as well as individual subject data rather support the assumption of holistic than sequential processing. First, with the distant spacing, the two digits of one number are much more close together than the decade or unit digits of the different numbers. Based on the results of Landy and Goldstone (2010), more narrow spaced problems tend to be solved first, suggesting that in the distant spacing condition participants would more likely first process the whole number magnitude of one number before comparing it to the second number. Second, sequential comparison should elicit a reversed compatibility effect. However, the compatibility effect is still significant in the original direction in the distant spacing condition. When analyzing compatibility effects over items for each participant individually, only 13 participants show a negative compatibility effect in the distant spacing condition, 11 of which are of small effect size. For participants with a positive compatibility effect, effect sizes are on average in the medium range.

In summary, we found no effect of presentation mode on the compatibility effect as long as numbers are presented simultaneously on the screen, but the compatibility effect...
is influenced by the distance between the numbers, such that more distant spacing results in a smaller compatibility effect. Together, these results suggest that presentation mode and spacing can change the processing mode for multi-digit numbers (e.g., from decomposed to holistic or from parallel to sequential). Thus, information on number size and distance between numbers should be reported in studies on the unit-decade compatibility effect.

Acknowledgments

We thank Simon Hotinceanu, Michael Huemer, Isabelle Weber, and Nina Rheinthaler for their help with data acquisition, Thomas Scherndl for statistical advice, and all participants for their time and willingness to contribute to this study. The studies reported in this manuscript were funded by the Austrian Science Fund (P28261).

Electronic Supplementary Materials

The electronic supplementary material is available with the online version of the article at http://dx.doi.org/10.1027/1618-3169/a000326

ESM 1. Raw data (sav).
Raw data for Study 1.
ESM 2. Raw data (sav).
Raw data for Study 1.

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195

Received December 29, 2015
Revision received April 12, 2016
Accepted April 15, 2016
Published online June 29, 2016

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Experimental Psychology (2016), 63(3), 189–195