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The influence of the tested item on serial dependence in perceptual decisions

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Abstract
Serial dependence in vision reflects how perceptual decisions can be biased by what we have recently perceived. Serial dependence studies test single items' effects on perceptual decisions. However, our visual world contains multiple objects at any given moment, so it's important to understand how past experiences affect not only a single object but also perception in a more general sense. Here we asked the question: What effect does a single item have when there is more than one subsequently presented test item? We displayed a single line (inducer) at the screen center, then either a single test-line or two simultaneous test-lines, varying in orientation space to the inducer. Next, participants reported test-line orientation using a left or right located response circle (to indicate which test-line should be reported). The results demonstrated that the inducer influenced subsequent perceptual judgments of a test-line even when two test-lines were presented. Distant items caused repulsive serial dependence, while close items caused attractive serial dependence. This shows how a single inducer can influence test-line judgments, even when two test-lines are presented, and can produce attractive and repulsive serial dependence biases when the item to report is revealed after it has disappeared.

Keywords
serial dependence, perceptual decisions, visual attention, perceptual bias

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Despite all the noise in our sensory input, we perceive a seamless and stable visual world around us whenever we open our eyes. How does the visual system achieve this stability? Studies of serial dependence (Cicchini et al., 2017, 2018; Fischer & Whitney, 2014; Fornaciai & Park, 2018) suggest that perceptual history is used to construct a continuous visual world and to compensate for noise in the visual information from factors such as changes of viewpoint from eye movements or self-motion, changes in lighting or shading or because of occlusion.

Fischer and Whitney (2014) showed that following an oriented Gabor patch inducer, perceptual decisions related to the orientation of a subsequent test Gabor were serially dependent upon the inducer's orientation (see Burr & Cicchini, 2014; Cicchini & Kristjánsson, 2015; Kiyonaga et al., 2017; Pascucci et al., 2023). Fischer & Whitney (2014) argued that such serial dependence results from a spatiotemporal integration window that they called the continuity field, where stimuli seen a few seconds ago interact with the perception of current visual stimuli (Collins, 2019; Fritsche et al., 2020; Gekas et al., 2019). Further studies have shown that judgments of numerosity (Fornaciai & Park, 2018), eye gaze (Alais et al., 2018), shape (Manassi et al., 2019), motion coherence (Suarez-Pinilla et al., 2018), facial identity (Liberman et al., 2014), gaze direction (Alais et al., 2018), or emotional expressions (Liberman et al., 2018) are also serially dependent on perceptual history.

Typically, these studies of serial dependence have investigated the effects of serial dependence from single items upon perceptual judgments. However, our visual world contains many objects at any given time, and it is, therefore, important to understand how what we have seen in the past influences not only a single object but also how serial dependence affects perception in a more general sense. Rafiei et al. (2021b) used attended targets and ignored distractors in a visual search task as inducers finding that the attentional role of the inducers played a crucial role in determining the direction and amplitude of serial dependence. Utilizing the feature distribution learning method (Chetverikov et al., 2016, 2017a, 2017b, 2019, 2020; Hansmann-Roth et al., 2019, 2021; Tanrikulu et al., 2020) to ensure that participants learned the distractor distributions, during mini-blocks, participants completed a few odd-one-out visual search trials. At the end of each mini-block, participants were asked to report the orientation of the last target in the block (target on trial N). The target in the visual search task on trial N-1 caused an attractive bias upon perceptual decisions about the target orientation on the last trial (trial N), while the learned distractors from trial N-1 produced a repulsive bias. Later, Rafiei et al. (2021a) tested serial dependence effects of visual search items upon a task-irrelevant test-line (rather than a target), with similar results, showing that these biases from visual search are more general, not limited to visual search targets.

The Role of Similarity in Feature Space

Notably, the attractive serial dependence effect found in Rafiei et al. (2021a) decreased in amplitude with decreasing similarity of the test and inducer. Fritsche et al. (2017) reported similar results, showing that these opposing effects on perceptual decisions might result from the different goals of perception and decision-making processes: perception may be optimized for detecting environmental changes, whereas decision processes may integrate over longer time periods to produce stable outcomes. Subsequently, Fritsche & de Lange (2019) also showed that the orientation difference between the inducer and test affected the direction of the bias. The participants in Rafiei et al. (2021a) completed 4–5 odd-one-out visual searches, locating an oddly oriented target among distractors, followed by a briefly presented test-line, and participants then reported the orientation of the test-line by rotating a line located in the middle of the screen. The proximity in orientation space between the target orientation, the average distractor orientation, and the test-line orientation was manipulated. The distractors produced an attractive bias when the test-line orientation was close to the distractor orientation. However, when the target orientation was far from the test-line orientation, it did not produce any serial dependence upon the test-line. Rafiei et al. argued that both proximity in feature space and the attentional role of a particular item (whether a visual search target or distractor) play a crucial role in determining the direction and amplitude of biases in perceptual decisions.

Current Aims

In these previous studies, we investigated the influence of a set of items upon the perceptual decision related to a subsequent single item (Rafiei et al., 2021a, 2021b). Here, we addressed the opposite question—what serial dependence biases are induced by a single item upon perceptual decisions regarding more than one test item when observers only learn which item to report after they disappear? We compare this to when only one test item appears. This question is also essential from the perspective of the issue of proximity in feature space since, unlike in the studies of Rafiei et al. (2021a, 2021b), the inducer does not have an explicit task role (is neither a target nor a distractor). Our observers viewed an inducer (an oriented line) on the screen, and subsequently, two lines with different orientations appeared, where one of them was close to the inducer's orientation, while the other was far from its orientation.

To summarize, our previous investigations revealed that inducers (visual search targets and distractors) produce attractive or repulsive bias upon perceptual decisions depending on their attentional role. Here we asked whether similar biases upon a set of lines would occur from a single inducer and whether this inducer causes both attractive and repulsive biases. We also assessed the effects of proximity in feature space between the inducer and test lines.

Method

Participants

Twenty students or staff members at the University of Iceland (11 females, average age = 26.31 years; 9 males, average age = 25.75) participated after signing informed consent forms. A participant group of 20 has been shown to be of sufficient size for reliable results in previous studies of serial dependence. All participants had normal or corrected to normal vision. All participated in a training session which was held at least one day before the experimental session. The training and experimental sessions were identical (350 trials each). The task was challenging and this long training procedure ensured that observers were able to perform the task well after practice.

Stimuli and Procedure

The stimuli appeared on a grey background on a 24-inch Asus monitor with a 1,920×1,080-pixel resolution at a viewing distance of approximately 70 cm. Psychopy 3 (Peirce et al., 2019) was used to generate the stimuli and control their presentation. Trials were defined by the combination of the number of lines on the test screen (One or Two) and the similarity of the test line to the post-cued inducer (Similar or Dissimilar, see Figure 1). There were 350 trials in each session, selected randomly from the four conditions.

Each trial had four parts (Figure 1). Firstly, participants were asked to pay attention to the orientation of a 2.5 deg *inducer* line presented at the screen center for 500 ms (orientations selected randomly from 0–180). Subsequently, the *test* display was presented, which involved either one line on the left or right side of fixation or two lines on either side of fixation (10 degrees away from the fixation point displayed for 500 ms). One key manipulation was how the orientation of these

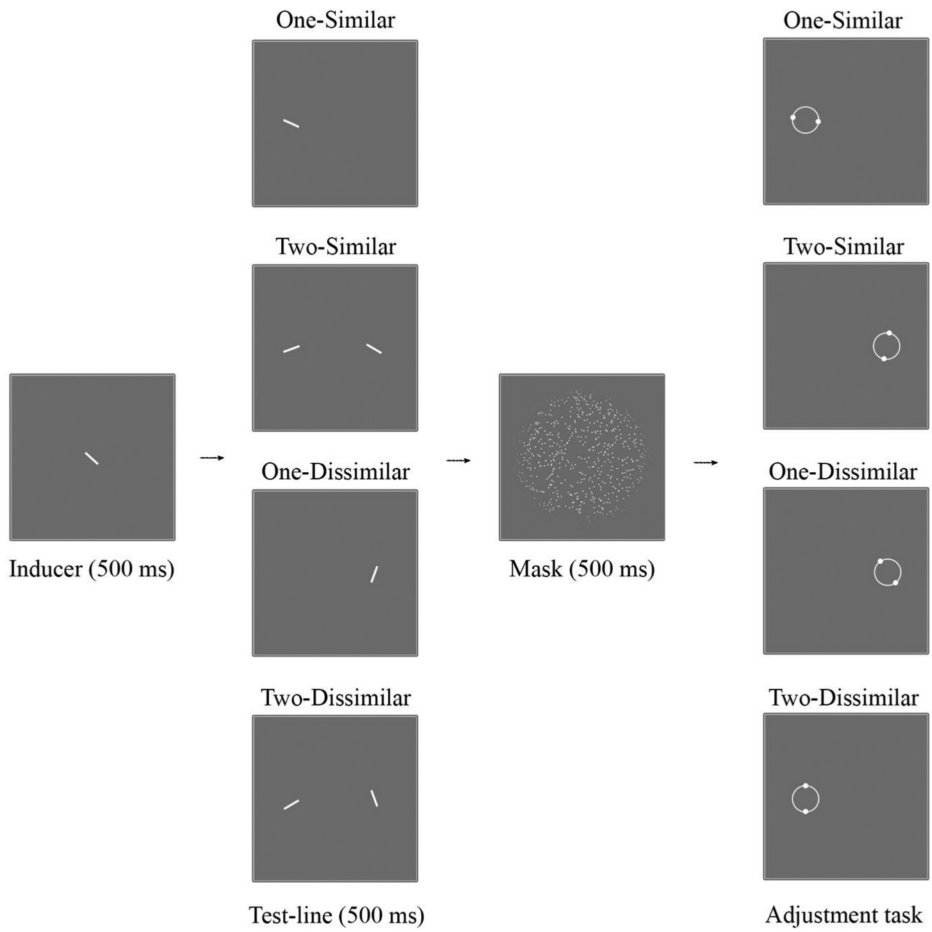

Figure 1. Design of a single trial in the experiment. Participants were asked to pay attention to the inducer's orientation and the orientation of the test-line(s) presented on the following screen on each trial. Subsequently, participants had to report the orientation of the line from the previously viewed screen (second screen), using the response circle positioned either on the left or right side (to indicate which line should be reported), where they used the "Right" and "Left" keys to rotate the answer circle so that the two disks on the circle were at the ends of an imaginary line corresponding to the orientation of the test line that observers were reproducing.

test-lines differed relative to the inducer's orientation. There were four different test displays: In the *One-Similar* condition, only one test line appeared either on the left or right side of the screen, oriented similarly to the inducer (−15 to 15 in 5-degree steps, excluding 0 degrees). In the *One-Dissimilar* condition, the orientation of the presented line on the left or right side of the screen was ± 50 to 80 degrees away from the inducer's orientation. In both these conditions, the orientations were randomly clockwise or counter-clockwise relative to the inducer. Two lines were displayed on the left and right sides of the screen for 500 ms in the *Two-Similar* and *Two-Dissimilar* conditions. The orientation of one of the lines was close to the inducer's orientation (as in the One-Similar condition), while the other line's orientation was far from the inducer's orientation (as in the One-Dissimilar condition). Which line to report on was then indicated by the response circle's location (which served as a post-cue, see Figure 1).

A mask was then presented in the middle of the screen for 500 ms (covering the locations of the lines). Finally, participants were asked to report the orientation of the line from the previously seen display using the response circle by aligning an imaginary line between the two disks with the orientation of the test-line (by pressing the "left" or "right" keys). They confirmed their response with the "Up" key and proceeded to the subsequent trial. The response circle appeared either on the left or the right, and its location served as a post-cue about which line should be reported. Therefore, participants did not know which line from the Two-Similar and Two-Dissimilar conditions should be reported until the response screen appeared. In the One-similar and One-dissimilar conditions, the response circle always appeared behind the presented test-line.

Data Analysis

Before the formal data analysis, we removed the outliers from the data, and to do that, we first determined the direction of the biases (whether they were attractive or repulsive) for each participant. To accomplish that, we compared the fits of two models: The first model assumes an attraction for cardinal orientations and that the mean error for each observer is a function of two fourth-degree polynomials centered on cardinal orientations (0, 90), with each polynomial spanning a 90-degree range (so one range from −45 to 45 and the other range from 45 to 135). The second model presupposes repulsive biases and comprises two polynomials with their centers in oblique orientations (45, 135). Both models presuppose that the response variance can change linearly as a function of the distance to the polynomial's center. Whichever model fits the data better is chosen for the subsequent analyses. Following that, the best-fitting model was used to compute the bias-corrected responses by removing the mean predicted error, or in other words, computing the model's residuals. Finally, bias-corrected errors greater than or equal to +/−3 predicted standard deviations were considered outliers and excluded from subsequent analyses.

After excluding the outliers, to assess how proximity in feature space between the inducer and current stimulus orientations affected the biases produced by the inducer, we calculated the adjustment error for the reported orientation by subtracting the actual orientation from the reported orientation.

A hierarchical Bayesian linear model was then used to estimate the effects of the inducer's orientation on the perceptual judgments of the test-lines. The model integrates all the data in a single model and evaluates the uncertainty of parameter estimates. The bias caused by the inducer was modelled by employing the Bayesian model as a function of the proximity in feature space between the inducer and the test line, the number of line(s) presented on the screen, and the intercept (all modeled as fixed effects). The number of line(s), the proximity in feature space between the inducer and the test line, and the intercept were also modeled as random effects. The model is a mixture of two different distributions of behavioral responses, denoted by the variable x. Each of these distributions represented a distinct response on the adjustment task. The Gaussian distribution (with probability density $f_N(x;\, \mu,\, \sigma^2)$) represents variability and biases in adjustment errors, whereas the uniform distribution, ranging orientation space with probability density $f_U(x) = 1\, /\, 180$ represents the random guesses of the participants (Zhang & Luck, 2008). The probability of an observation coming from a Gaussian distribution is used to combine the two distributions:

$$f(x;\, \theta,\, \mu,\, \sigma^2) = \lambda f_N(x;\, \mu,\, \sigma^2) + (1 - \lambda) f_U(x)$$

Results

Figure 2 shows the biases from the inducers upon the perceptual judgments of the test lines. When the orientations of the test-line and the inducer were similar, there was a strong attractive bias upon perceptual judgments of the test-line, ($b = -0.71$, 95% HPDI = [−1.01, −0.40], BF = 1,999, the calculated BF is for both the One-Similar and Two-Similar conditions).

We next tested the condition where the inducer and test-line(s) orientations were dissimilar. The results showed that the inducer produced a repulsive serial dependence bias upon perceptual judgments of the test line ($b = 0.29$, 95% HPDI = [0.54, 0.03], BF = 24.64, for both One-Dissimilar and Two-Dissimilar together), independently of the number of lines shown on the test-line screen (see Figure 2).

To test how the number of simultaneous test-lines affected serial dependence effects upon perceptual judgments of the test lines, we compared the biases on the trials where one line was shown on the screen against trials with two lines presented on the screen in the "Similar" condition. For this, we used a Bayesian paired *t*-test, and the results showed that the number of lines presented on the screen did not affect the bias produced by the inducer (BF = 0.90). We also adopted a similar analysis for the "Dissimilar" trials and compared the biases on the trials where one line versus two lines appeared on the screen; the results showed that the number of lines presented on the screen did not modulate the serial dependence effects (BF = 0.38).

Discussion

Most serial dependence studies have investigated the role of a single preceding stimulus on the perception of a subsequent single item. In the real world, however, we usually perceive many stimuli simultaneously, raising the question of how information from our perceptual history affects the multitude of items we see at a given moment. Our earlier studies (Rafiei et al., 2021a, 2021b)

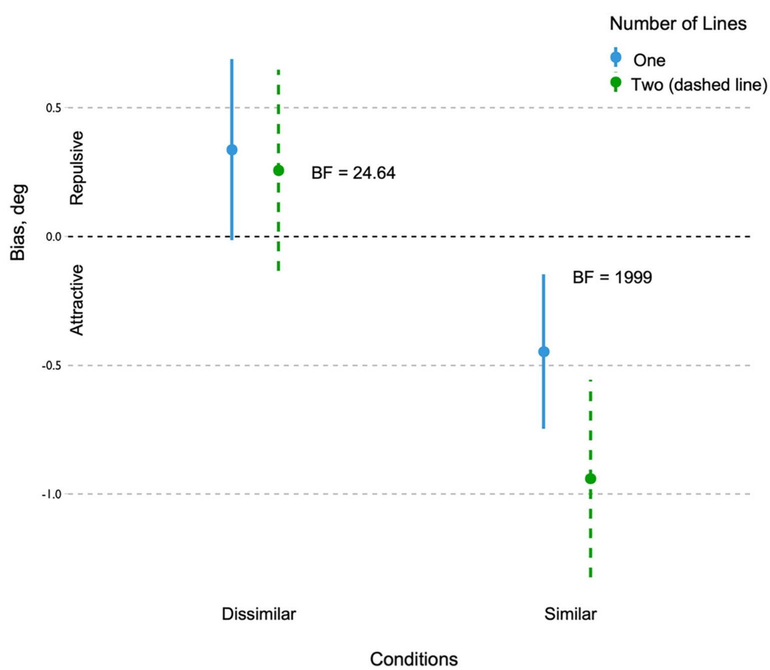

Figure 2. The biases produced by the inducer upon the perceptual judgments of similar and dissimilar test-lines as a function of whether one or two test-lines were presented. The results showed that the inducer caused opposing serial dependence that was determined by the similarity between the inducer and the test-line. When the inducer and test-line(s) were dissimilar, the inducer produced a repulsive bias. However, the inducer produced an attractive serial dependence bias when they were similar. The bars here represent the confidence interval of the biases produced by the inducer.

showed that distractors and targets could act as two sources of biases from perceptual history, introducing opposing biases upon the perceptual decisions related to a single test item.

Here we investigated whether similar biases would occur from a single line upon a set of test-lines, as we found from a set of lines upon a single test-line in Rafiei et al. (2021a, 2021b). Secondly, we further assessed the effects of proximity in feature space between the inducer and the test items. A third question was whether a single inducer could cause both attractive and repulsive serial dependence upon perceptual judgments of a subsequent test item depending on which item is to be reported.

We first presented a single inducer and later showed either one or two oriented test-lines on the screen. In half of the trials, participants needed to report the orientation of the only test line, while in the rest of the trials, they were asked to report the orientation of one of two test lines (they did not know which one to report until the report display appeared). This question is interesting from the perspective of the proposal of the continuity field in perception (Fischer & Whitney, 2014; Liberman et al., 2016) since when two potential tests appear, the continuance is uncertain, a version of the well-known correspondence problem seen in many contexts in visual perception (e.g., Ullman, 1979). The results showed that a single inducer introduced opposing serial dependence biases upon perceptual decisions of the two subsequently presented items: The direction of the biases depended on their relations in feature space.

Is Serial Dependence Altered by Having Two Potential Test-Lines?

Serial dependence has been assumed to *smooth* perception to maintain perceptual continuity to deal with noise in the visual input from sources such as shifts in gaze, eye-blinks, occlusion, or changes in lighting (Burr & Cicchini, 2014; Cicchini & Kristjánsson, 2015; Collins, 2019; Fritsche et al., 2020; Gekas et al., 2019). Information about recently appearing items in the visual environment is used to maintain this under the assumption of continuity and autocorrelation in the world (Cicchini et al., 2017; Fischer & Whitney, 2014; Liberman et al., 2016; Pascucci et al., 2023; Rafiei et al., 2021a, 2021b).

Nevertheless, how does the visual system figure out the continuity, in other words, determine what follows what? While our results do not directly address this question, they show that an inducer influenced judgments of a test-line even when two test-lines were presented, which is in line with the results reported by Manassi et al. (2017). Note that Fischer et al. 2020 (experiments 3 and 4): presented two differently colored dot fields simultaneously at different spatial positions, finding serial dependence between trials modulated by the color of the dots. They did not, however, try to address the question that we address here of differences between one and two items, nor did they assess the effects of a single task-irrelevant inducer line upon subsequent test-lines.

Note that our results are agnostic regarding whether the serial dependence effects we observe upon perceptual judgments involve effects upon perception, decisional processes, or even some combination of those. Furthermore, our data cannot distinguish between whether the perception of the two lines is affected per se or just the subsequent decision. Providing decisive answers to questions like this has proved to be difficult within research on serial dependence in vision, and this is a highly controversial issue that cannot be resolved here (see Pascucci et al., 2023).

The Effects of Proximity in Feature Space

Proximity in feature space between the inducers and test items has been found to affect the direction of serial dependence biases (Rafiei et al., 2021a, 2021b; as shown previously by Fritsche & de Lange, 2019; Fritsche et al. 2017). However, in previous studies, two factors potentially affected the biases; their attentional role (whether they were a target or a distractor) or the proximity in orientation space between the inducer and the current stimulus. Here, the inducer did not play any differential attentional role (it was not attended like a target among distractors or actively ignored like a distractor), and our results, therefore, confirm that when the inducer and the current item are similar (close in orientation space), there is an attractive bias from the inducer line upon perceptual judgments of the test-line (in line with Fischer & Whitney, 2014 and Rafiei et al., 2021a, 2021b). However, if the inducer and the current item are dissimilar (far from each other in orientation space), the inducer introduces a repulsive bias. These results align with our previous findings in Rafiei et al. (2021a, 2021b), Fritsche et al. (2017) and Fritsche and de Lange (2019). Proximity in feature space, therefore, plays a crucial role in determining whether biases produced by an inducer line are attractive or repulsive. However, importantly this bias is not specific to a single test-line but occurs for two potential test items, where which one to report is only revealed after they were presented.

Serial Dependence Occurs at Multiple Levels

It seems likely that serial dependence occurs at a number of different levels of perceptual processing. For example, adjustment tasks like the one we use here most likely also involve visual working memory, as the stimulus must be reproduced when it is no longer on screen and presumably has to be briefly memorized. The biases we observed may partly be due to interference between the previous and current memory traces of the stimuli. Notably, Fischer & Whitney (2014) showed that serial dependence occurs independently of any explicit memory of prior stimuli. However, in other studies (Bliss et al., 2017; Fritsche et al., 2017), biases towards prior stimuli have been found to increase the longer retention time before the adjustment response. Visual working memory therefore seems to modulate the strength of serial dependence.

Fornaciai and Park (2018) argued that serial dependence is simply a form of memory interference and that the order of events may not be crucial. They reported that a future stimulus could cause systematic biases in judgments of a preceding stimulus, biases that were quite similar to serial dependence effects. In Czoschke et al. (2019), participants memorized two consecutively presented clouds of drifting dots, and a subsequent cue then indicated whether they were to report the drift direction of the first or second cloud. They observed attractive serial dependence biases from drift directions memorized on preceding trials while there were repulsive biases from the drift direction memorized within trials. Czoschke et al. argued that this demonstrated repulsive interference between simultaneous working memory representations. Concerning our results, it is likely that working memory plays a role in our results, given the nature of the task.

Recently, Pascucci et al. (2019) proposed that perception is shaped by two oppositional temporal biases: previous decisions and sensory adaptation. They argued that stimuli themselves create repulsive biases through adaptation-like effects, pushing perception away from previously perceived stimuli. On the other hand, past perceptual decisions create attractive biases. These biases distort current sensory data so that it appears more like preceding visual input than it actually is, thereby compensating for sensory adaptation. However, the similarity effect that was observed in the current study is somewhat orthogonal to this distinction. We found that the inducer produced an attractive bias upon the perceptual decision of the line that needed to be reported if it was similar to it, and on the other hand, the inducer produced a repulsive bias while the line that needed to be reported was dissimilar to the inducer. The direction of the biases was, in other words, based on the degree of similarity between the two stimuli.

Conclusion

In Rafiei et al. (2021a, 2021b), we showed how serial dependence from arrays of visual search stimuli affects the perceived orientation of a single test-line. However, what is the effect of a single item upon more than one subsequent test item? Our results show that an inducer influenced a line's report even when two test-lines were presented. Secondly, we assessed the effects of proximity in feature space between the inducer and the visual search items finding that proximity in feature space affects the direction of the biases produced by the inducer. The same inducer causes an attractive bias if it is similar to the test but a repulsive bias if they are dissimilar. Since observers do not know until after the tests-items disappear which one to report, this suggests that a single inducer produces both attractive and repulsive serial dependence biases upon subsequent perceptual decisions.

Author Contribution(s)

Mohsen Rafiei: Conceptualization; Data curation; Formal analysis; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing.

Sabrina Hansmann-Roth: Conceptualization; Validation; Writing – review & editing.

Árni Kristjansson: Formal analysis; Methodology; Project administration; Resources; Supervision; Writing – original draft; Writing – review & editing.

Andrey Chetverikov: Conceptualization; Formal analysis; Methodology; Software; Validation; Writing – review & editing.

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