MASTER'S THESIS – Psychology (research), *spec.* Cognitive Neuroscience

Ordering the Action Syntax: Inhibitory discrepancy drives the temporal order of action sequences

Doekemeijer, R. A.[1] roos@doekemeijer.nl

Dr. De Kleijn, R. E.[1] kleijnrde@fsw.leidenuniv.nl

[1] *Department of Cognitive Psychology, Leiden University, the Netherlands*

June 20, 2019

Abstract

The serial order of an action syntax is principal to execute complex actions successfully and is reportedly driven by inhibitory processes. These processes regulate both the preceding action segment as well as all succeeding action segments in the sequence. In our study, we propose that the unidirectionality of serial order emerges from a discrepancy within these inhibitory processes. To test this premise, we determined (1) the independent effect of the directly preceding action segment, (2) the independent effect of the directly succeeding action segment, and (3) the difference between these two inhibitory effects on the degree of trajectory curvature of an ongoing (virtual) movement.

Overall, we found a tendency of the preceding action segment to repel the ongoing trajectory relative to the tendency of the succeeding action segment to attract it. These findings ultimately support the premised inhibitory discrepancy driving the temporal order of an action sequence. In fact, our findings suggest that the preceding action segment is inhibited more than the succeeding action segment in the sequence.

Nevertheless, we heed the power of our study and we commend further research on the independent inhibitory effects of the preceding and succeeding action segments on an ongoing action segment. Furthermore, we advocate research on the role of context-dependent and context-independent individual differences on the established inhibitory discrepancy driving the serial order of an action syntax.

Keywords: action sequencing, serial order, inhibition, movement trajectories, cursor trajectories.
Word count: 5 701.

Introduction

Intuitively, humans perform complex actions by ordering them into a sequence of elementary action segments [1, 2]. For example, the abstract act of playing the piano can be viewed as a sequence of pressing particular piano keys. Fundamentally, the action segments, i.e., the so-called action syntax of the main act, is to occur in a unique temporal order to execute the main act successfully [3]. Currently, a well-known theory on the underlying mechanism driving this serial order of the action syntax proposes that action segments in the syntax are regulated by inhibitory processes [4]. These processes occur after a global excitation of all action segments, establishing the content of the action syntax, and are believed to ensure the temporal order of the sequence by (1) inhibiting all succeeding action segments and by (2) inhibiting a preceding action segment upon completion.

Both the premise of global excitation [5] as well as that of inhibition [6–8] have been observed in neuroscientific invasive studies on animals, suggesting a similar system in humans. However, this premise is hard to test due to measurement limitations accompanying human research; for ethical reasons, the invasive techniques used in the animal studies cannot be used in human studies. Nevertheless, Verschoor et al. (2015) inferred from infants' eye gazes that infants inhibit the next, unexectuted action segment in the action sequence [2]. Furthermore, Behmer et al. (2017, 2018) recently demonstrated in a behavioural study [9] and a TMS/MEP study [10] that adults inhibited both the preceding and all succeeding letters when typing, showing an inverted V-shaped pattern of motor evoked potentials around the currently being executed (i.e., ongoing) action segment. Taken together, these findings support the notion that (multiple) inhibitory processes drive the serial order of an action syntax.

However, a symmetry of the inhibition amplitudes, as suggested by the inverted V-shaped pattern found by Behmer et al. (2018), fails to completely explain the mechanism underlying serial order. That is, supposing that the neural activity of the preceding and that of the succeeding action segments are identical, inferentially, the next-to-be-executed action segment could be either the preceding or the succeeding action segment in the sequence. In other words, a symmetry of the two inhibitory processes should prompt either advancing or backtracking in the sequence, whereas a discrepancy in the inhibitory processes would drive the serial order to be unidirectional. In the current study, we test this premise of an inhibitory discrepancy driving the temporal order of an action sequence. To do so, we adapt a current action-sequencing paradigm and dynamically assess the inhibitory processes.

Assessing inhibition

Conventional behavioral measures (e.g., reaction time and task accuracy) lack the ability to capture the complexity of cognitive processes that unfold over time (i.e., the so-called dynamic processes) [11–14], whereas manual movement trajectories enable these dynamic processes to be measured accurately, non-invasively and inexpensively [14].

Particularly, the dynamic process of inhibition is revealed by the degree of curvatures in manual movement trajectories: to-be-inhibited stimuli attract movement trajectories [15], in which the degree of trajectory curvature depends on, e.g., the spatial location [16, 17] and the salience of the stimuli [18–20]. Moreover, this effect appears to be upheld for both real-time manual movements (e.g., pointing or reaching) as for virtual manual movements (e.g., directing a computer mouse) [21, 22]. In our study, we opted to establish inhibitory processes by employing the latter, due to its superior accessibility [32].

The current study

To test the premise of inhibitory discrepancy as underlying mechanism driving the temporal order of the action sequence, we captured the curvatures of virtual movement trajectories. Specifically, we adapted Nissen and Bullemer's (1987) action-sequencing task [24] to establish the inhibitory effects of (1) the directly preceding action segment and that of (2) the directly succeeding action segment on the cursor trajectory curvature of an ongoing action segment. Overall, we expect these effects to be independent and dissimilar, signifying the premised discrepancy in the inhibitory processes.

METHODS

Participants

A total of 24 participants were recruited from the Leiden University (Leiden, the Netherlands). Participants who were left-handed or incapable to freely operate a computer mouse were excluded from the study.

The remaining participants were withheld information concerning the task sequence and concerning the recordings of their cursor positions, in accordance to the ethical procedure founded by the Ethics Committee Psychology of Leiden University (CEP). At the end of the experiment, participants were debriefed about the recordings and were asked for explicit consent to use their data. Data of participants who did not consent was excluded.

Additionally, after the experiment, we excluded participants who had not explicitly learned the sequence in the action-sequencing task (i.e., participants who failed to correctly reproduce the sequence). Ultimately, we included 18 participants (5 male and 13 female; aged between 19 and 31 years old, $M = 21.0, SD = 3.36$) in our study.

Design

We implemented a single-session within-subjects design: each participant performed an action-sequencing task, a reproduction of the action sequence, and a working memory capacity test. Here, participants' cursor positions were recorded solely during the action-sequencing task.

Importantly, as working memory capacity reportedly affects an individual's ability to sequence actions [25, 26], we measured each participant's working memory capacity and included it as a covariate in our analyses. Furthermore, we counterbalanced the action-sequencing task to account for the spatial properties of the stimuli and randomly assigned the participants to either condition.

Apparatus

Computer specifications

All tasks were shown on a 17" computer monitor (LG Flatron 776 FM) with a refresh rate of 60 Hz. Moreover, the pointer acceleration, pointer trails, and enhanced pointer precision of the computer cursor were switched off.

Action sequencing task

Based on Nissen and Bullemer's action-sequencing task [24], we created a computer task (in Pygame, Python 3.6) in which participants were to sequentially hit six stimuli using the computer cursor. The six stimuli were located at the upper left corner (1), upper center (2), upper right corner (3), lower left corner (4), lower center (5), and lower right corner (6) of the screen (see Figure 1). The two centered stimuli were vertically offset, hence appearing above the neighbouring corner stimuli.

Stimuli. The stimuli were 60px-sized, red-coloured squares and temporarily turned

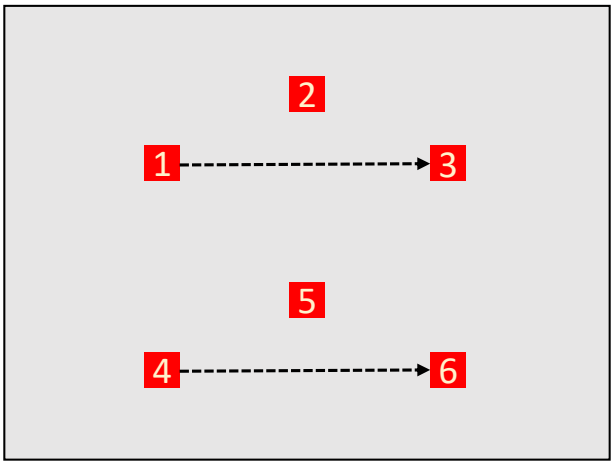

Figure 1: Lay-out of the action-sequencing task, in which the center stimuli 2 and 5 preceded or succeeded the movements from corner stimulus 1 to 3 and from corner stimulus 4 to 6, respectively.

green according to a predefined sequence. The green-coloured stimulus defined the current target and reverted to red 1.0 second after being hit by the cursor. Then, after an inter-stimulus interval (ISI) of 1.0 second the next stimulus in the sequence turned green, cueing the participant to move the cursor to this next stimulus. Upon completion of the sequence, the sequence started anew. In total, the participant performed 3 blocks of 50 consecutive sequences, separated by breaks. Finally, we asked the participant to reproduce the invoked sequence to test their mastery of the action sequence.

Sequence. The predefined sequence of the task was specifically designed to establish the effects of the preceding and the succeeding action segments on the curvature of an ongoing trajectory. To that end, the center stimuli either preceded or succeeded the left to right movement between two corner stimuli (see the dashed lines in Figure 1), invoking the effect of the preceding or that of the succeeding action segment, respectively. That is, according to Figure 1, stimulus 2 preceded or succeeded the movement from stimulus 1 to 3; stimulus 5 the movement from stimulus 4 to 6. So, the invoked sequences were $1-3-2-5-4-6$ and $4-6-5-2-1-3$.

At the end of the action-sequencing task, we asked the participant to reproduce the sequence to establish their explicit knowledge on the action sequence. As previously mentioned, participants who failed to reproduce the sequence without cues were excluded from further analyses.

Working memory capacity test

To account for the effect of working memory capacity on the participant's action sequencing performance, we measured the participants visuospatial working memory capacity using Bo, Jennet and Seidler's (2011) task [25]. In this task, the participants were shown a range of (2 to 8) coloured circles for 100 ms, followed by a 900 ms fixation point, then 2000 ms of either the same or differently coloured circles. The participants were instructed to indicate whether the images were identical or different by means of button presses. After 140 trials,

the working memory capacity w_j of each participant j was computed from all trials using each trial's number of circles n, the participant's rate of correctly identified same coloured circles (i.e., hit rates H_j), and the participant's rate of incorrectly identified differently coloured circles (i.e., false alarm rates F_j), according to

$$w_j\,(H_j, F_j) \;=\; \frac{1}{7} \cdot \sum_{n=2}^{8} (\; n \;\cdot\; [H_{j_n} - F_{j_n}]) \quad (1)$$

Procedure

Upon recruitment, participants were informed of the study (save the specifics of the task's sequence and the cursor trajectory recordings) and were requested to provide written consent to participate. Then, the participant was lead by the researcher to a secluded computer room, where the researcher launched the action-sequencing task. The instructions of the action-sequencing task were provided on the screen, indicating the participant to move the computer cursor to the target that turned green as fast and accurately as possible. During the breaks, the participants were instructed to rest their eyes and continue the task whenever they felt ready. At the end of the action-sequencing task, the participants were to reproduce the sequence without being cued. Upon completion, the researcher reentered the room to start the visuospatial working memory capacity task. Overall, the tasks took approximately 35 minutes to complete. Conclusively, participants were debriefed and were granted a (university-related) participation credit or a muffin as a reward.

Statistical analyses

To establish the inhibitory effects of the preceding action segment and that of the succeeding action segment on an ongoing cursor trajectory, we computed the degree of the trajectory curvature as the average distance from each observed point within the trajectory to its projection on the ideal trajectory, which is the straight line between a trajectory's first observed point to its last observed point. Then, we predicted this distance in three multilevel analyses: the preceding action segment (AS) analysis and succeeding AS analysis addressed the independent effect of the preceding center target and that of the succeeding center target on the computed distance, respectively; the so-called differential analysis addressed the proposed discrepancy between these two action segment effects. Overall, the first two analyses contained three multilevel models, i.e., two intercept-only models and an unconditional growth model, and the last analysis included an additional unconditional growth model. All models subsumed two levels to capture (first-level) trajectory effects and (second-level) participant effects.

Here, all analyses were conducted in a stepwise manner, so the models were nested and the previous models acted as baseline to the subsequent ones. More specifically, in all analyses, we expanded the best intercept-only model by adding the fixed effects of gender, age, and working memory capacity, thereby constituting the unconditional growth model. Then, in the differential analysis, we created a second unconditional growth model by adding the fixed effect of the center target to the previous model. Note that the majority of the inspected effects were fixed; accordingly, we employed the maximum likelihood method for all parameter estimations [27].

Conclusively, for each multilevel analysis, we determined the best model by evaluating the models' trade-offs between simplicity and goodness-of-fit using AIC scores, BIC scores and log-Likelihood ratios. We expected the (last) unconditional growth models to outperform their predecessors, ultimately reflecting the hypothesized independent and discrepant effects of the preceding action segment and the succeeding action segment on the trajectory curvature of an ongoing action segment.

Results

Preprocessing

Before conducting the stepwise multilevel analyses, the data was preprocessed. First, we excluded (6) participants who had not explicitly mastered the sequence of the action-sequencing task, thus establishing our final sample of 18 participants. Note that this indicates that we had relatively low power to detect (second-level) participant effects [28]. Second, we extracted all trajectories between stimulus 1 and 3 and between 4 and 6. Third, we removed all observations in the ISIs, and all erroneous or irregular trajectories (i.e., trajectories consisting of fewer than 14 observations or over 64 observations). Overall, we included 2298 preceding center target and 2298 succeeding center target trajectories in our analyses, each trajectory consisting of approximately 37 observed cursor positions.

Subsequently, we calculated the perpendicular distance from each cursor position p in the form $[x_p, y_p]$ to its projection on the ideal trajectory. Recall that this ideal trajectory was defined as the shortest line between the cursor's starting position and its position upon hitting the target stimulus. So, for each trajectory i, we determined its corresponding ideal line of the form $ax + by + c = 0 : b = -1$, and established each observed point's distance given its trajectory d_{pi},

$$d_{pi}([x_p, y_p], a_i, c_i) = \frac{a_i \cdot x_p - y_p + c_i}{\sqrt{a_i^2 + (-1)^2}} \tag{2}$$

This approach allowed the computed distance to be both positive as well as negative, indicating observations positioned above and below the ideal trajectory, respectively.

Stepwise multilevel analyses

The parameter estimates and fit indices of all models within the conducted analyses are listed in Table 1 and Table 2, respectively. In this section, we first outline the encompassed models' compositions, then we discuss each model's relative goodness-of-fit, according to a Likelihood Ratio Test (LRT), in turn. We conclude this section by visually examining the assumptions of the final models.

Model compositions

We established a fixed-intercept model (I),

$$\overline{d_{ij}} = \gamma_{00} + \epsilon_{ij} \tag{3}$$

a subsequent random-intercept model (II),

$$\begin{aligned} \overline{d_{ij}} &= \gamma_{0j} + \epsilon_{ij} \\ \gamma_{0j} &= \gamma_{00} + u_{0j} \end{aligned} \tag{4}$$

and an unconditional growth model (III) by adding the covariates gender g_j, age a_j, and working memory capacity w_j,

$$\begin{aligned} \overline{d_{ij}} = \gamma_{0j} + \ \gamma_{10} \cdot g_j + \ \gamma_{20} \cdot a_j \\ + \ \gamma_{30} \cdot w_j + \ \epsilon_{ij} \end{aligned} \tag{5}$$

Furthermore, in the differential analysis, we created a second unconditional growth model (IV) by adding the fixed effect of the center target ct_{ij} to the previous unconditional growth model,

$$\begin{aligned} \overline{d_{ij}} = \gamma_{0j} + \ \gamma_{10} \cdot g_j + \ \gamma_{20} \cdot a_j + \ \gamma_{30} \cdot w_j \\ + \gamma_{40} \cdot ct_{ij} + \ \epsilon_{ij} \end{aligned} \tag{6}$$

Overall, $\overline{d_{ij}}$ represents the estimated average distance from point to ideal line of each trajectory i within a participant j, γ_n the model's estimate of parameter n, ϵ_{ij} the error, and u_{nj} the residual between γ_{nj} and a participant's observed parameter value.

Preceding and succeeding AS analyses

The independent effect of the preceding center target and that of the succeeding center target were first analyzed. We found a

Table 1: Parameter estimates of the models within each multilevel analysis, predicting the average distance from each observed point in a trajectory to its projection on the ideal trajectory.

Model[1]		(Intercept)	Gender[2]	Age	Working memory	Center target[3]
Preceding AS analysis	I	-0.51** (0.12)				
	II	-0.54* (0.22)				
	III	-2.01 (1.78)	-0.40 (0.48)	0.05 (0.07)	0.26 (0.26)	
Succeeding AS analysis	I	0.29* (0.14)				
	II	0.24 (0.44)				
	III	3.69 (3.41)	-1.63 (0.91)	-0.06 (0.13)	-0.87 (0.49)	
Differential analysis	I	-0.11 (0.09)				
	II	-0.15 (0.27)				
	III	0.83 (2.17)	-1.01 (0.58)	-0.00 (0.08)	-0.31 (0.31)	
	IV	0.43 (2.17)	-1.01 (0.58)	-0.00 (0.08)	-0.31 (0.31)	0.80** (0.18)

[1] I : Intercept
Ⅱ : I + (Intercept | Participant)
Ⅲ : Ⅱ + Gender + Age + Working memory
Ⅳ : Ⅲ + Center target
[2] base: female.
[3] base: preceding center target.
* $p < 0.05$, ** $p < 0.001$.

Table 2: Fit indices of the models within each multilevel analysis.

Model[1]		DoF	Log-Likelihood	AIC	BIC
Preceding AS analysis	I	2	-7214.27	14432.54	14444.02
	II	3	-7203.45	14412.91	14430.12
	III	6	-7202.21	14416.42	14450.85
Succeeding AS analysis	I	2	-7555.83	15115.67	15127.15
	II	3	-7488.53	14983.05	15000.27
	III	6	-7486.11	14984.21	15018.65
Differential analysis	I	2	-14805.40	29614.79	29627.66
	II	3	-14754.51	29515.01	29534.31
	III	6	-14752.70	29517.40	29556.00
	IV	7	-14742.39	29498.78	29543.81

[1] I : Intercept
Ⅱ : I + (Intercept | Participant)
Ⅲ : Ⅱ + Gender + Age + Working memory
Ⅳ : Ⅲ + Center target

nonzero intercept both in the preceding p as well as in the succeeding s fixed-intercept model (I), $t_p(2297) = -4.37, p < 0.001; t_s(2297) = 2.14, p < 0.05$. Particularly, the preceding center target was associated with a negative distance, indicating the average trajectory to be repelled by (i.e., curve away from) the center target. On the contrary, the succeeding center target was associated with a positive distance, thus indicating the average trajectory to be attracted to (i.e., curve toward) the center target. In Figure 2, the (generalized) independent effects of the preceding and succeeding action segments on the ongoing cursor trajectories are illustrated.

The effect of the succeeding center target fell to non-significance in the random-intercept model (II), indicating that this effect did not uphold for all participants, $t(2280) = 0.55, p = 0.58$. This non-significance was similarly found in the following unconditional growth model (III), $t(2280) = 1.08, p = 0.28$. Additionally, this unconditional growth model estimated the contributions of gender g (base: female), age a, and working memory capacity w to be insignificant, $t_g(14) = -1.80, p = 0.09; t_a(14) = -0.46, p = 0.65; t_w = -1.79, p = 0.09$. Ultimately, we concluded from two LRTs that the latter two models performed similarly, $\chi^2(3) = 4.84, p = 0.18$, and better than the first model, $\chi^2(1) = 134.62, p < 0.001$. Accordingly, the unconditional growth model (III) was uphold in the succeeding AS analysis.

With respect to the preceding AS analysis, we found the significance of the intercept as established in the fixed-intercept model (I) to be uphold in the random-intercept model (II), $t(2280) = -2.49, p < 0.05$. Nevertheless, both the intercept and the covariates appeared insignificant in the subsequent unconditional growth model (III), $t_0 = -1.13, p = 0.26; t_g(14) = -0.84, p = 0.42; t_a(14) = 0.74, p = 0.47; t_w = 1.02, p = 0.33$. Overall, the random-intercept model outperformed its predecessor, $\chi^2(1) = 21.64, p < 0.001$, and was not outperformed by its successor, $\chi^2(3) = 2.49, p = 0.48$; so, we opted to retain the unconditional growth model (III) in the preceding AS analysis.

Differential analysis

From the fixed-intercept model (I) and the random-intercept model (II) of the differential analysis, we determined that the distance between the observed and ideal trajectory was negligible for all subjects, $t_{\text{I}}(4595) = -1.23, p = 0.22$; $t_{\text{II}}(4578) = -0.56, p = 0.57$; $\chi^2 = 101.78, p < 0.001$. Furthermore, in neither the first unconditional growth model (III) nor the second one (IV), we found any of the covariates to significantly contribute to their respective model's fit, III : $t_0(4577) = 0.20, p = 0.84, t_g(14) = -1.76, p = 0.10, t_a(14) = -0.06, p = 0.96, t_w(14) = -0.99, p = 0.34, \chi^2 = 1.171, p = 0.19$; IV : $t_0(4578) = 0.38, p = 0.70, t_g(14) = -1.76, p = 0.10, t_a(14) = -0.06, p = 0.96, t_w(14) = -0.99, p = 0.34, \chi^2 = 1.90, p = 0.39$. However, in the second unconditional growth model, the center target (base: preceding center target) appeared to be positive and highly significant, $t_{ct}(4577) = 4.54, p < 0.001$. In other words, the succeeding center target invoked the distance to be more positive compared to the preceding center target. Overall, we found this final model superior over all preceding models, $\chi^2 = 101.78, p < 0.001$.

This effect of the center target may indicate that (1) the succeeding center target invokes a smaller negative distance than the preceding center target, ultimately suggesting a main repelling effect of the preceding center target, or that (2) the succeeding center target induces a greater positive distance than the preceding center target, thus implying a main attracting effect of the succeeding center target. Figure 3 shows that both propositions are supported by our data.

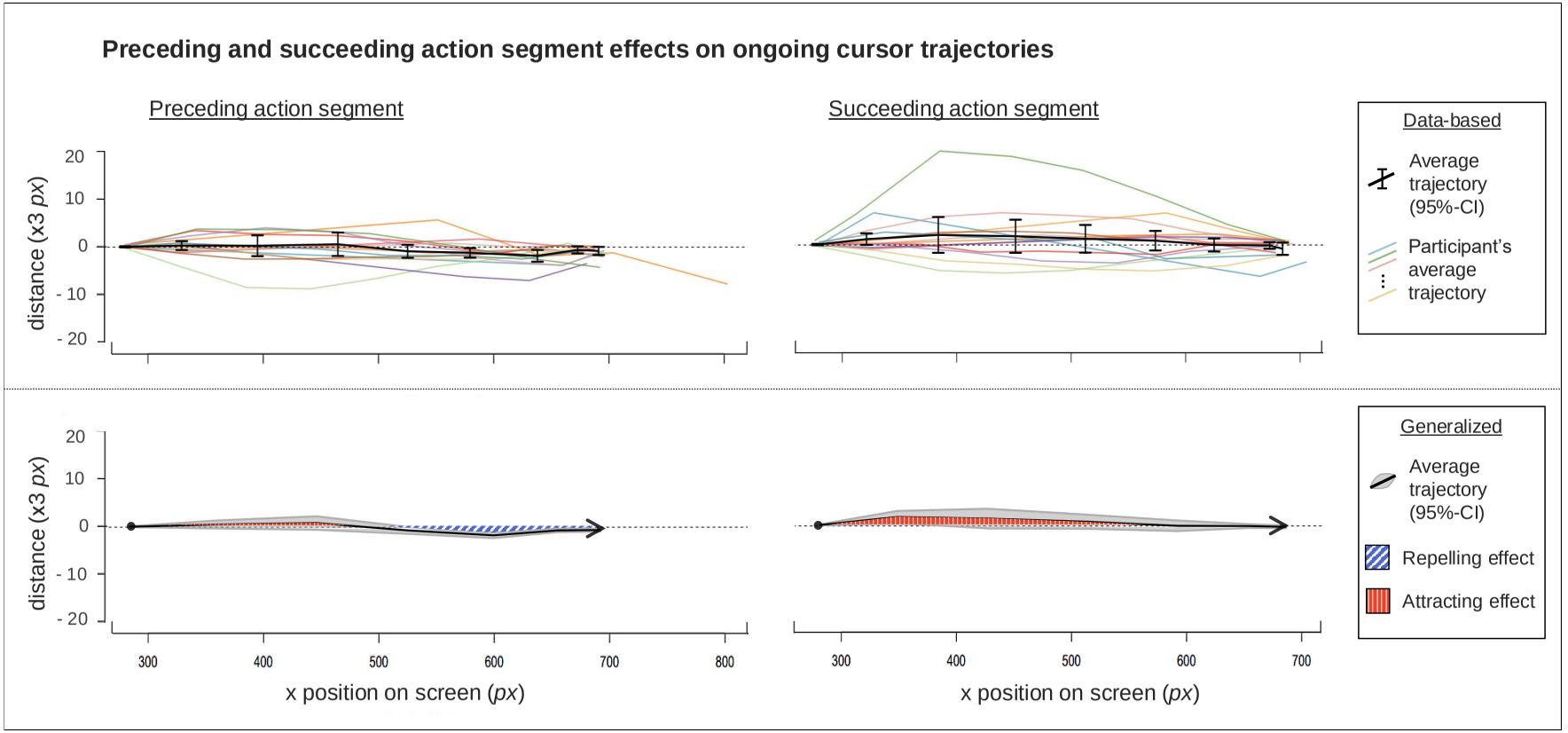

Figure 2: The effects of the preceding center target (left) and succeeding center target (right) on the cursor trajectory of an ongoing action segment as found in our data (top) and as generalized to a main repelling or attracting effect (bottom).

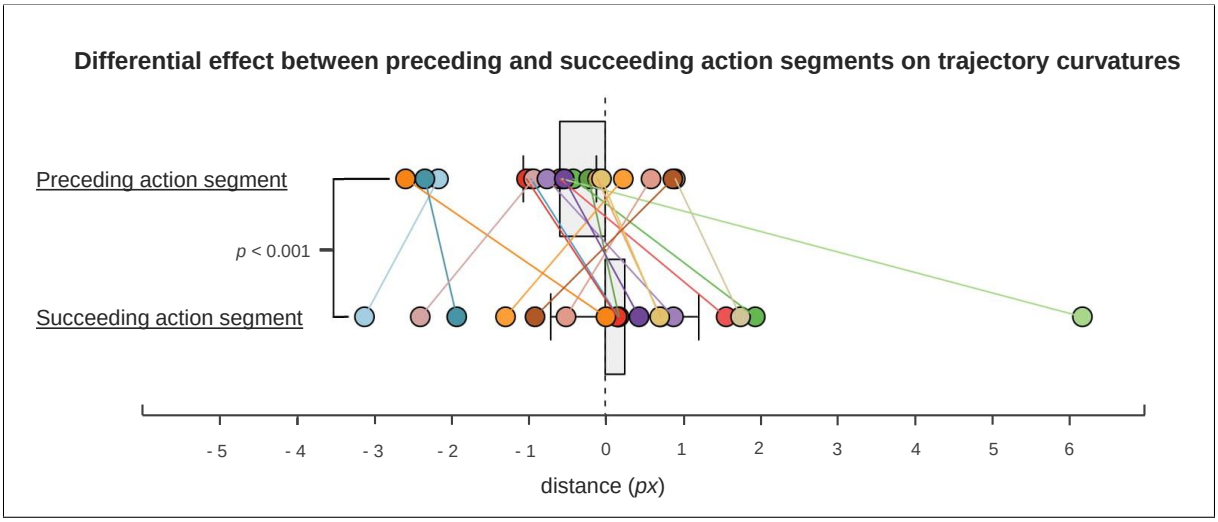

Figure 3: The relative effects of the preceding and succeeding action segments on the ongoing trajectory's curvature, as measured by the averaged distance from the observed points within the trajectory to their projections on the ideal trajectory, for each participant separately (colored circles) and combined (grey bars, 95%-CI).

Assumptions of the final models

All final models assumed normality and homoscedasticity; accordingly, we employed Q-Q plots and scatter plots to visually test each model for any major assumption violations (see Appendix A and Appendix B, respectively). Although our sample size restricted our ability to identify violations, we determined that all final models solely exhibited slight non-normality.

Discussion

We examined virtual movement trajectories to test the premise that an discrepancy within the inhibitory processes drives the temporal order of an action sequence. Specifically, we examined the effect of (1) the preceding action segment, that of (2) the succeeding action segment, and (3) the inferential discrepancy between these two effects on the cursor trajectory curvature of an ongoing action segment. Overall, we tested each proposition in its corresponding multilevel analysis, assessing the degree of the trajectory curvature of the ongoing action segment as the average distance from the observed trajectory to the ideal trajectory. Ultimately, we found a tendency for the preceding action segment to repel the ongoing cursor trajectory and a tendency for the succeeding action segment to attract it. Furthermore, we established the premised discrepancy between the effects of the preceding and succeeding action segments. We discuss each of these findings in turn, followed by our limitations and we conclude with our suggestions for future research.

We established a tendency of the preceding action segment to repel the ongoing trajectory and a contrary tendency of the succeeding action segment to attract it, but lacked power to statistically detect them after accounting for individual differences (i.e., gender, age, and working memory capacity). Nevertheless, the tendency of the succeeding action segment to attract the ongoing trajectory is consistent with previous research, which has repeat-

edly demonstrated inhibited stimuli to attract ongoing trajectories [15, 21, 22]. The independent (repelling) effect of the preceding action segment on the ongoing action segment had, to our knowledge, thus far been unexplored, electing our finding as pioneering yet preliminary.

Furthermore, the discrepant tendencies of the preceding and succeeding action segments to respectively repel and attract the ongoing trajectory signify the expected discrepancy within the inhibitory processes that drive serial order. More particularly, the repelling effect of the preceding action segment indicated that the preceding action was considered relatively nonsalient, while the attracting effect of the succeeding action segment indicated that the succeeding action was considered salient in the sequence [29]. Then, as inhibitory processes suppresses the salience of of stimuli [30], we presume that the preceding action segment in the sequence was inhibited more than its succeeding counterpart.

Taken together, our findings support the notion of an inhibitory discrepancy between preceding and succeeding action segments in the sequence. Particularly, we believe that this inhibitory discrepancy allows an individual to successfully execute an action sequence while being cognitively offline, i.e., without any information from the environment. Tubau, Hommel, and Moliner (2007) noted that individuals either adopt stimulus-based control (i.e., relying on external prompts) or plan-based control (i.e., using an internally-generated plan of execution) to execute an action sequence [31]; based on the current findings, we propose that the internal mechanism enabling this plan-based control is the discrepancy between the inhibitory processes of preceding and succeeding action segments.

Limitations and future directions

We note the limited power of our study to establish individual-level effects and we advocate further research to scrutinize the independent inhibitory effects of the preceding and succeeding action segments on the ongoing action segment by, e.g., increasing the sample size to over 50 [28]. To do so, we suggest the use of online experiment environments, such as Amazon Mechanical Turk (MTurk).

Next, with respect to research using cursor trajectories, we advocate the implementation of a baseline measure (e.g., a cursor trajectory unaffected by any stimuli) and/or the implementation of a training session. These implementations reportedly account for context-independent individual differences, such as an individual's familiarity with directing the computer mouse, that may affect an individual's cursor trajectories [32, 33].

Lastly, we regard the generalizability of our findings; our sample consisted of individuals who mastered the untold sequence in the task, i.e., those who adopted plan-based control, and we specifically propose that our findings may differ for individuals who employ stimulus-based control. Simply, the preceding and succeeding action segments can only be properly inhibited if the individual is aware of the fact that they are the preceding and succeeding action segments in the sequence. Accordingly, we believe that our action segment effects depend on the individual's cognitive control mode employed during the action-sequencing task. Overall, we recommend further research on the dependency of our findings on context-dependent individual differences, such as employed control mode.

REFERENCES

[1] Kennerley, S. W., Sakai, K., & Rushworth, M. F. S. (2004). Organization of Action Sequences and the Role of the Pre-SMA. *Journal of Neurophysiology, 91,* 978-993. DOI: 10.1152/jn.00651.2003.

[2] Verschoor, S. A., Paulus, M., SpapÃľ, M., Biro, S., & Hommel, B. (2015). The Developing Cognitive Substrate of Sequential Action Con-

trol in 9- to 12-month-olds: Evidence for concurrent activation models. *Cognition, 138,* 64-78. DOI: http://dx.doi.org/10.1016/j.cognition.2015.01.005.

[3] Lashley, K. S. (1951). The Problem of Serial Order in Behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior; the Hixon Symposium.* New York, NY: Wiley, 112-146.

[4] Estes, W.K. (1972). *An associative basis for coding and organization in memory.* Washington, DC: V.H. Winston & Sons, 161-190.

[5] Jin, X., Tecuapetla, F., & Costa, R. M. (2014). Basal Ganglia Subcircuits Distinctively Encode the Parsing and Concatenation of Action Sequences. *Nature Neuroscience, 17 (3),* 423-430. DOI: 10.1038/nn.3632.

[6] Aldridge, J. W. & Berridge, K. C. (1998). Coding of Serial Order by Neostriatal Neurons: A "natural action" approach to movement sequence. *The Journal of Neuroscience, 18 (7),* 2777-2787. DOI: https://doi.org/10.1523/JNEUROSCI.18-07-02777.1998.

[7] Tanji, J. & Shuma, K. (1994). Role for Supplementary Motor Area Cells in Planning Several Moments Ahead. *Nature, 371,* 413-416. DOI: 10.1038/371413a0.

[8] Shima, K. & Tanji, J. (1998). Both the Supplementary and the Presupplementary Motor Areas are Crucial for the Temporal Organization of Multiple Movements. *Journal of Neurophysiology, 80 (6),* 3247-3260. DOI: 10.1152/jn.1998.80.6.3247.

[9] Behmer, L. P. & Crump, M. J. (2017). The Dynamic Range of Response Set Activation During Action Sequencing. *Journal of Experimental Psychology: Human Perception and Performance, 43 (3),* 537-554. DOI: 10.1037/xhp0000335.

[10] Behmer, L. P., Jr., Jantzen, K. J., Martinez, S., Walls, R., Amir-Brownstein, E., Jaye, A., Leytze, M., Lucier, K., & Crump, M. J. C. (2018). Parallel Regulation of Past, Present, and Future Actions During Sequencing. *Journal of Experimental Psychology: Human Perception and Performance, 44 (8),* 1147-1152. DOI: 10.1037/xhp0000507.

[11] Roznowski, M., Dickter, D. N., Hong, S., Sawin, L. L., & Shute, V. J. (2000). Validity of Measures of Cognitive Processes and General Ability for Learning and Performance on Highly Complex Computerized Tutors: Is the g factor of intelligence even more general? *Journal of Applied Psychology, 85 (6),* 940-955. DOI: 10.1037//0021-90I0.85.6.940.

[12] Jakobsen, L. H., Sorensen, J. M., Rask, I. K., Jensen, B. S., & Kondrup, J. (2011). Validation of Reaction Time as a Measure of Cognitive Function and Quality of Life in Healthy Subjects and Patients. *Nutrition, 27,* 561-570. DOI: 10.1016/j.nut.2010.08.003.

[13] Dutilh, G., Annis, J., Brown, S. D., Cassey, P., Evans, N. J., Grasman, R. P. P. P., Hawkins, G. E., Heathcote, A., Holmes, W. R., Krypotos, A.-M., Kupitz, C. N., Leite, F. P., Lerche, V., Lin, Y.-S., Logan, G. D., Palmeri, T. J., Starns, J. J., Trueblood, J. S., Van Maanen, L., Van Ravenzwaaij, D., Vandekerckhove, J., Visser, I., Voss, A., White, C. N., Wiecki, T. V., Rieskamp, J., & Donkin, C. (2018). The Quality of Response Time Data Inference: A blinded, collaborative assessment of the validity of cognitive models. *Psychonomic Bullitin & Review.* DOI: 10.3758/s13423-017-1417-2.

[14] Song, J. H. & Nakayama, K. (2009). Hidden Cognitive States Revealed in Choice Reaching Tasks. *Trends in Cognitive Sciences, 13 (8),* 360-366. DOI: 10.1016/j.tics.2009.04.009.

[15] Welsh, T. N., Elliott, D., & Weeks, D. J. (1997). Hand Deviations towards Distractors: Evidence for response competition. *Experimental Brain Research, 127 (2),* 207-212. DOI: https://doi.org/10.1007/s002210050790.

[16] Tipper, S. P., Howard, L. A., & Houghton, G. (1998). Action-based Mechanisms of Attention. *Philosophical Transactions of the Royal Society B, 353,* 1385-1393. DOI: 10.1098/rstb.1998.0292.

[17] Welsh, T. N., Pacione, S. M., Neyedli, H. F., Ray, M., & Ou, J. (2015). Trajectory Deviations in Spatial Compatibility Tasks with Peripheral and Central Stimuli. *Psychological Research, 79,* 650-657. DOI: 10.1007/s00426-014-0597-x.

[18] Chang, S. W. C. & Abrams, R. A. Hand Movements Deviate Toward Distractors in the Absence of Response Competition. *The Journal of General Psychology, 131 (4),* 328-344.

[19] Welsh T. N. (2011). The Relationship between Attentional Capture and Deviations in Movement Trajectories in a Selective Reaching Task. *Acta Psychologica, 137,* 300-308. DOI: 10.1016/j.actpsy.2011.03.011.

[20] Dignath, D., Pfister, R., Eder, A. B., Kiesel, A., & Kunde, W. (2014). Something in the Way She Moves: Movement trajectories reveal dynamics of self-control. *Psychonomic Bulletin and Review, 21,* 809-816. DOI: 10.3758/s13423-013-0517-x.

[21] Spivey, M. J., Grosjean, M., & Knoblich, G. (2005). Continuous Attraction toward Phonological Competitors. *Proceedings of the National Academy of Sciences, 102 (29), 10393-10398.* DOI: 10.1073/pnas.0503903102.

[22] Cranford, E. A. & Moss, J. Mouse-Tracking Evidence for Parallel Anticipatory Option Evaluation. *Cognitive Processing, 19 (3),* 327-250. DOI: 10.1007/s10339-017-0851-4.

[23] Fischer, M. H. & Hartmann, M. (2014). Pushing Forward in Embodied Cognition: May we mouse the mathematical mind? *Frontiers in Psychology, 5 (1315),* 1-4. DOI: 10.3389/fpsyg.2014.01315.

[24] Nissen, M. J. & Bullemer, P. (1987). Attentional Requirements of Learning: Evidence from Performance Measures. *Cognitive Psychology, 19,* 1-32. DOI: 10.1016/0010-0285(87)90002-8.

[25] Bo., J., Jennet, S., & Seidler, R. D. (2011). Working Memory Capacity Correlates with Implicit Serial Reaction Task Performance. *Experimental Brain Research, 214,* 73-81. DOI: 10.1007/s00221-011-2807-8.

[26] Kikumoto, A. & Mayr, U. (2018). Decoding Hierarchical Control of Sequential Behavior in Oscillatory EEG Activity. *eLife, 7,* 1-36. DOI: 10.7554/eLife.38550.

[27] Field, A., Miles, J., & Field, Z. (2012). *Discovering Statistics Using R.* Thousand Oaks, CA: SAGE Publications.

[28] Maas, C. J. M., & Hox, J. J. (2005). Sufficient Sample Sizs for Multilevel Modeling. *Methodology, 1 (3),* 86-92. DOI: 10.1027/1614-1881.1.3.86.

[29] Carr, S. M, Philips, J. G., & Meeham, J. W. (2008). Non-target Flanker Effects on Movement in a Virtual Action Centred Reference Frame. *Experimental Brain Research, 184,* 95-102. DOI: 10.1007/s00221-007-1078-x.

[30] Gaspelin, N. & Luck, S. J. (2018). The Role of Inhibition in Avoiding Distraction by Salient Stimuli. *Trends in Cognitive Sciences, 22 (1),* 79-92. DOI: 10.1016/j.tics.2017.11.001.

[31] Tubau, E., Hommel, B., & LÃşpez-Moliner, J. (2007). Modes of Executive Control in Sequence Learning: From stimulus-based control to plan-based control. *Journal of Experimental Psychology: General, 136 (1),* 43-63. DOI: 10.1037/0096-3445.136.1.43.

[32] Fischer, M. H. & Hartmann, M. (2014). Pushing Forward in Embodied Cognition: May we mouse the mathematical mind?. *Frontiers in Psychology, 5*, 1-4. DOI: 10.3389/fpsyg.2014.01315.

[33] Verwey, W. B. (1994). Evidence for the Development of Concurrent Processing in a Sequential Keypressing Task. *Acta Psychologica, 85 (3),* 245-262. DOI: 10.1016/0001-6918(94)90038-8.

Appendices

A Assumption tests for normality

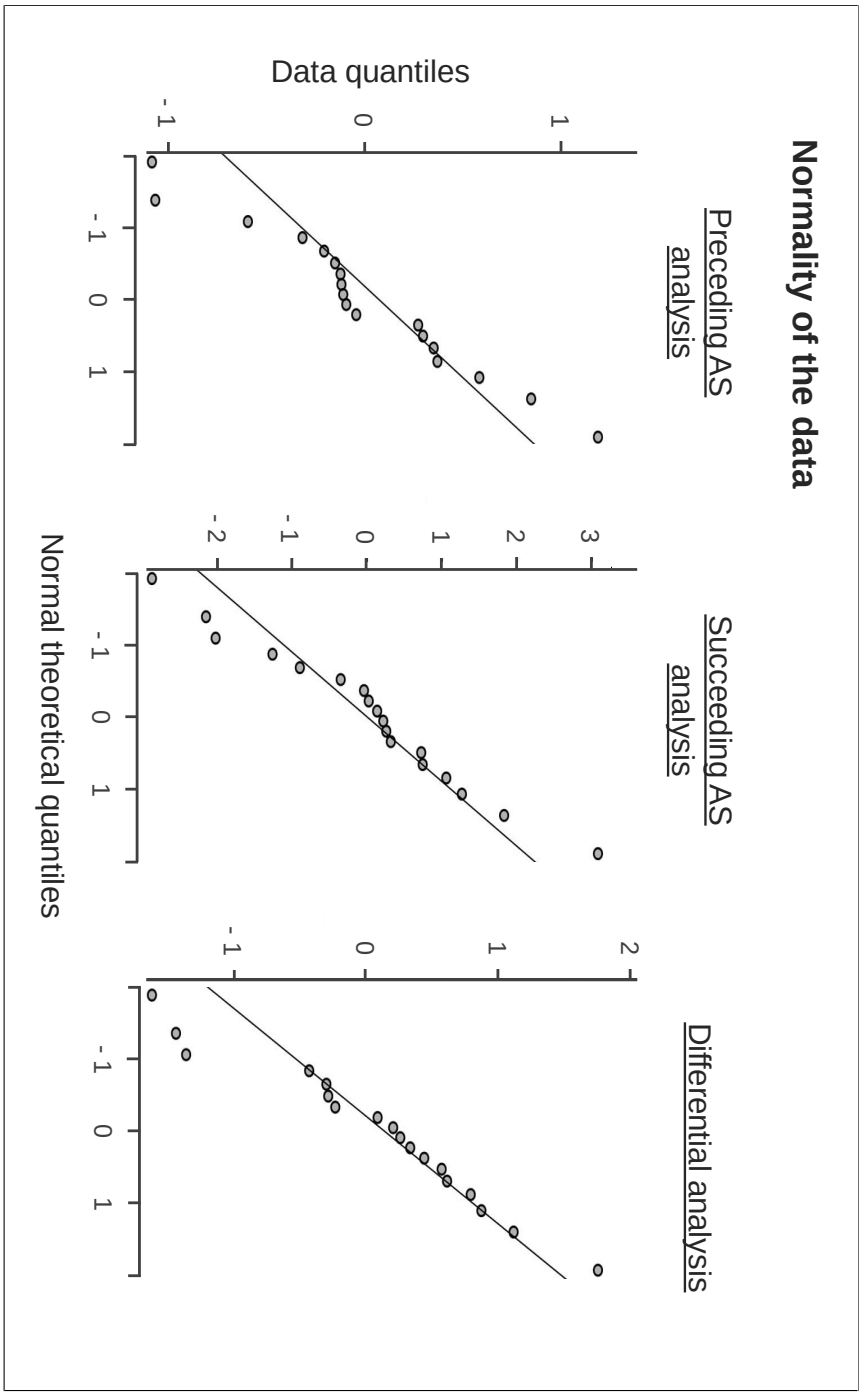

Figure 4: Normality of the second-level data as employed in the preceding action segment analysis (left), succeeding action segment analysis (middle), and differential analysis (right).

B Assumption tests for homoscedasticity

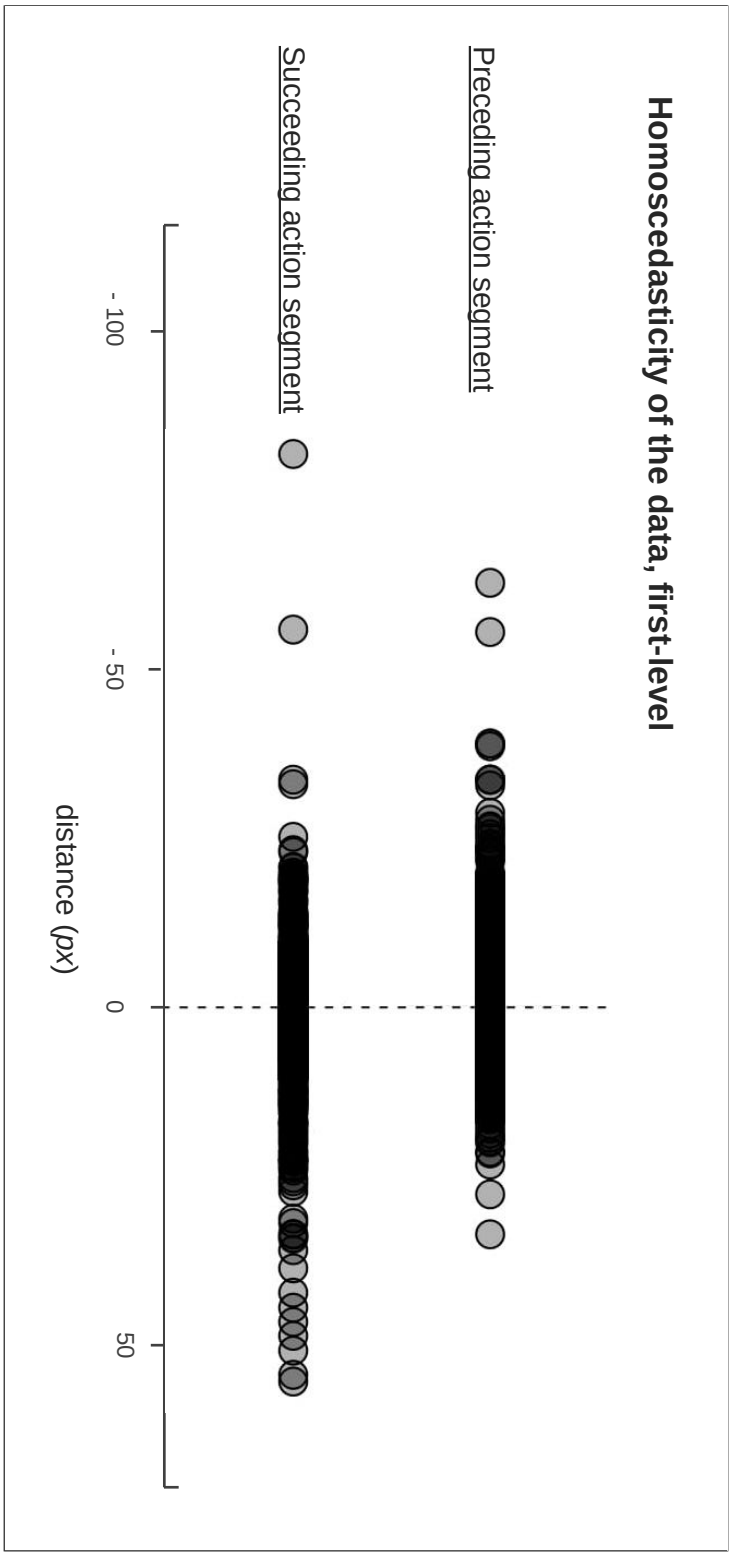

Figure 5: Homescedasticity of the (first-level) trajectory data as employed in the differential analysis.

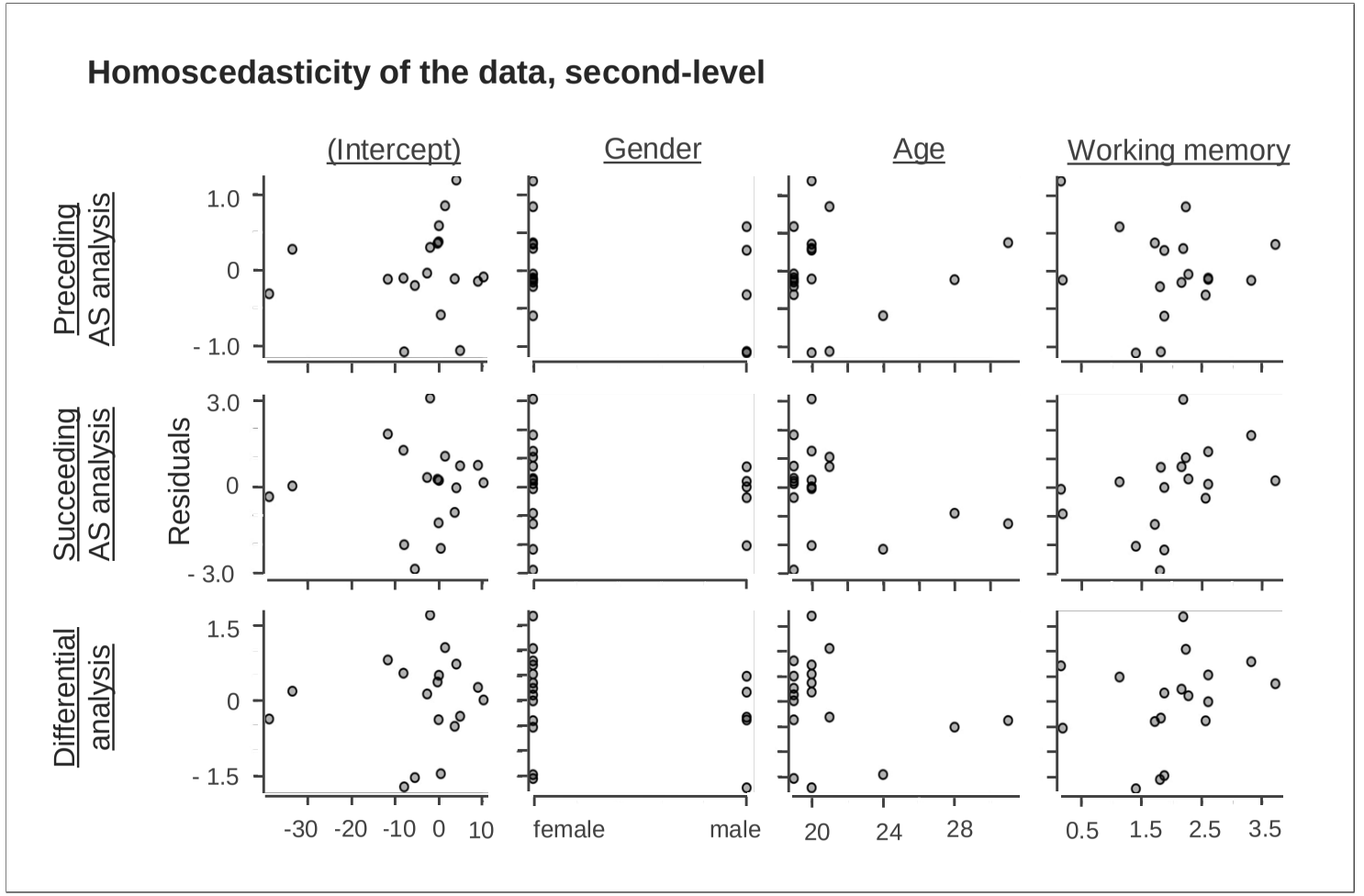

Figure 6: Homescedasticity of the (second-level) participant data as employed in the preceding action segment analysis (top), succeeding action segment analysis (middle), and differential analysis (bottom).