

Article

The Dynamic Boundaries of the Self.

Serial Dependence In Embodied Sense of Agency

Yonatan Stern ^{a,b*}, Inbar Ben-Yehuda ^a, Danny Koren^b, Adam Zaidel^a & Roy Salomon^a

^a Gonda Brain Research Center, Bar-Ilan University, Ramat Gan, 5290002, Israel

^b Psychology Department, University of Haifa, Haifa, 3498838, Israel

* Correspondence to yoniastern@gmail.com

Abstract

The feeling of control over one's actions, termed the Sense of Agency (SoA), delineates one's experience as an embodied self. Although, this embodied experience is typically perceived as stable over time, recent theoretical accounts highlight the experience-dependent and dynamic nature of the embodied self. In this study we examined how recent experiences modulate SoA (i.e., serial dependence), and disambiguated the unique contributions of previous stimuli and choices on subsequent SoA judgments. In addition, we examined whether these effects persist across different domains of perceptual alteration. We analyzed two independent datasets of the Virtual Hand (VH) task (N = 100 participants) in which a sensorimotor conflict is introduced between the presented visual feedback and the actual movement performed. In Dataset 1, which included only temporal alterations, we found that previous stimuli recalibrate current perception, increasing the likelihood of the current choice to be different than the previous choice. Whereas previous choices induce a repetition bias increasing the likelihood to repeat choices across trials. Thus, previous external stimuli and self-generated choices exert opposing influences on SoA. We replicated these findings in Dataset 2, in which the VH task was tested with alterations in both temporal and spatial domains. In addition, we discovered that previous stimuli from a different perceptual domain exert a recalibration effect similar to stimuli from the same domain. Thus, SoA is constantly shaped by our previous subjective choices and objective stimuli experienced even across different perceptual domains. This highlights how SoA may act as unifying construct organizing our experience of the self over time and across perceptual experiences.

Keywords: sense of agency, serial dependence, virtual reality, bodily-self

1. Introduction

The sense of self is a critical construct of the human psyche, that organizes one's discrete experiences and providing a sense of continuity across time and space (Christoff et al., 2011; Damasio, 2012; R. Salomon, 2017). Despite this intuitive sense of personal continuity, questions such as "What makes me the same '*me*' across time and space?" have long fascinated philosophers (Locke, 1847), highlighting its elusiveness. Furthermore, in psychopathological conditions such as psychosis and dissociation there is a striking discontinuity in the sense of self, leading to distressful feelings of alienation from one's body and actions (Brand & Frewen, 2017; Sass & Parnas, 2003). A fundamental stratum of selfhood, coined the 'bodily-self', is that one exists in and controls his body and through it experiences the world (Blanke, 2012; Blanke et al., 2015; Blanke & Metzinger, 2009). The 'bodily-self' imbues one's diverse sensory experiences with a unique subjectivity making them *my* experiences, creating a continuous and stable sense of embodied selfhood (Gallagher, 2000; Zahavi, 2003). Yet it remains unclear what are the mechanisms that give rise to this sense of continuity.

A central component of the bodily-self is the feeling of control over one's body and actions, that is termed Sense of Agency (SoA). It enables us to delineate our bodily-self, and arises from the contingency between one's actions and their sensory outcomes. Prominent theories highlight the role of a comparator model that compares between the predicted outcome of one's intended action and the observed outcome. When the two are congruent SoA is experienced and the action is attributed to oneself, whereas when they are incongruent the outcome is likely attributed to an external cause (Frith et al., 2000; Wolpert, 1997). The two-step account of agency (Synofzik et al., 2008) distinguishes between an implicit non-conceptual *feeling* of agency that arises primarily from different perceptual processes and their processing via a comparator mechanism, and explicit propositional *judgments* of agency

derived via a belief formation process influenced by prior knowledge (e.g., probabilistic relations (Moore et al., 2009), outcome's valence (Bradley, 1978; Takahata et al., 2012) or subliminal priming (Aarts et al., 2005)). Thus, SoA arises from computational processes related both to bottom-up sensory signals as well as top-down contextual information (Haggard, 2017; Moore & Fletcher, 2012). In line with SoA's hypothesized role in maintaining a continuous sense of selfhood, here, we examined how judgments of agency are modulated by previous experiences of SoA and disambiguated the contribution of prior sensory and decision processes to this modulation.

Numerous studies have examined how prior experiences effect current perceptual processes (e.g. Fischer & Whitney, 2014; Fritsche et al., 2017; Kiyonaga et al., 2017). This has been coined *serial dependence* or *history effects*, and is experimentally examined by looking at the influence of the previous trials on the current trial's choice. Robust serial dependence been found across a range of perceptual capacities such as angle discrimination (Fischer & Whitney, 2014) and face perception (Lieberman et al., 2014). It is postulated to support perceptual stability by allowing for the efficient coding of the environment that tends to be constant over time while remaining sensitive to sudden changes (Burr & Cicchini, 2014; Kiyonaga et al., 2017). Accordingly, serial dependence relies on the task relevance of the stimuli's features and the observer's allocation of attention to them (Feigin et al., 2021; Fischer & Whitney, 2014). Recent evidence points to the contribution of two distinct superimposed processes to serial dependence that exert opposing influences (Bosch et al., 2020; Fritsche et al., 2017; Sadil et al., 2021). Prior *stimuli* (i.e., the external stimuli) bias the current trial's choice *away* from the previous trial by recalibrating the perception of the current stimuli and exerting a *repulsive* influence. Whereas the previous trial's *choice* (i.e., the self-generated judgment made) influences participants *towards* their past decision creating a 'repetition bias' and *attractive* influence. These opposing forces may affect

different stages of perception and facilitate perceptual stability by restraining and balancing each other's influence.

Serial dependence in multisensory contexts such as judging the simultaneity of auditory (e.g., hearing a voice) and visual (e.g., seeing lips move) inputs have been widely demonstrated (e.g., Van der Burg et al., 2013; Van der Burg & Goodbourn, 2015). Presumably, the previously experienced asynchrony between inputs recalibrates the current trial's temporal window of integration towards it, creating a 'lag adaptation' that modulates the current inputs' attribution to a single source (Fujisaki et al., 2004; Noel et al., 2016). Such effects are especially pertinent within the context of embodied selfhood that is continuously supported by multisensory integration. For example, simultaneous visual-tactile stimulation of a rubber-hand or a virtual avatar create an illusory sense of ownership (Botvinick & Cohen, 1998; Salomon et al., 2013), and correspondences between actions and their sensory outcomes produce SoA (Chambon et al., 2014; Hohwy, 2007; Krugwasser et al., 2019; Stern et al., 2020). Accordingly, current theoretical and computational accounts of the bodily-self emphasize the ongoing integration of multisensory signals in forming and maintaining the bodily-self and its related capacities (Legaspi & Toyoizumi, 2019; Samad et al., 2015). In line with this evidence of constant integration supporting the bodily-self, an important question is whether past experiences and serial-dependence effects modulate embodied SoA.

We examined serial dependence effects of embodied SoA, in two datasets of the '*Virtual Hand*' (VH) task (Krugwasser et al., 2019; Stern et al., 2020). The VH task is a VR-based paradigm in which participants judge the congruence between their self-generated movements and a realistic VH that mimics their movement. SoA is assessed by judgments of congruence between the real hand's and the virtual hand's movements. We examined two central questions: First, whether prior stimuli and choice influence embodied SoA. In line with recent findings in unimodal perceptual tasks that found opposing influences of the two

(Bosch et al., 2020; Fritsche et al., 2017; Sadil et al., 2021), we predicted that prior stimuli would recalibrate the perception of the current trial's alteration causing it to be perceived in light of the previous alteration (or lack of alteration), thus increasing the likelihood of the current choice to be different than the previous choice and exerting a *repulsive* serial dependence effect. Whereas prior choice would exert an *attractive* effect causing the participant to repeat his previous response. In the second dataset we examined whether these results replicate. Second, we also examined in this dataset whether serial dependence effects of previous stimuli are present across different domains (i.e., a temporal or spatial) of alteration between trials. Such a finding would provide novel evidence for a domain-general centralized processing of SoA that is modulated across different aspects of sensory inputs.

2. Methods

2.1. Participants

We reanalyzed data from four VH experiments (Krugwasser et al., 2019; Stern et al., 2020) some of which are novel and some have been previously published, resulting in a total of 100 participants. The experiments differed only in minor changes to the VH task and in additional tasks that were administered following the VH task. All participants provided written informed consent, and received payment or academic credit in return for their participation. The experiments were approved by the Internal Review Board of Bar-Ilan University. To increase statistical power, we aggregated the four experiments into two datasets. Dataset 1 includes experiments in which only temporal alterations were administered (N= 44, 25 females, mean \pm SD age = 24.51 \pm 3.48). Whereas Dataset 2 includes experiments in which both temporal and spatial alterations were administered (N= 56, 31 females, mean \pm SD age = 24.13 \pm 2.65). All participants were right-handed, with normal or corrected to normal vision and self-reported no neurological or psychiatric history.

Participants with less than 80% valid trials or that failed to comply with experiment instructions were excluded from the analysis (see Supplemental Material (SM) Methods for further details).

2.2. Procedure

During the VH task, the participant's right hand was hidden from their view, while a Leap Motion controller (Leap Motion Inc., San Francisco, CA) visually tracked the hand's movement. On a screen positioned in front of the participant a realistic VH that mimicked the real hand's position and movement was presented (see Figure 1A for set-up, further technical details are described in Krugwasser et al., (2019) and Stern et al., (2020)). In each trial, participants were first presented with a fixation cross (1.5 s) followed by the presentation of the VH (2 s). During presentation of the VH participants were instructed to bend only their index finger, while maintaining the rest of their hand stationary. A sensorimotor conflict was introduced in some trials by presenting the VH with an alteration either in the temporal or spatial domain (75% trials), while in other trials no conflict was introduced. Alterations in both domains were not presented simultaneously. Within each domain, four magnitudes of alteration were employed. In the temporal domain, one of four delays (0/100/200/300 ms) between the actual and the VH's movement was inserted. In the spatial domain, one of four magnitudes of angular deviation in the bending movement of the VH's index finger was presented (0°, 6°, 10°, 14°). Across all experiments an equal number of trials for each magnitude of alteration were presented. Following presentation of the VH, participants responded to a two-alternative forced-choice (2AFC) question "Was the movement of the VH identical to my movement?" (i.e., agency question, presented in Hebrew; see Figure 1B for trial flow), and rated their confidence on a scale ranging from 1 (i.e. "not at all") to 7 (i.e. "completely").

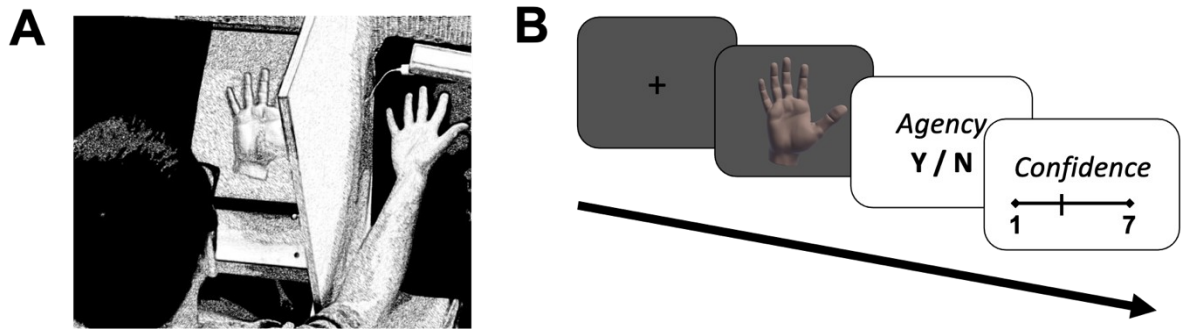


Figure 1. Experimental set-up and trial flow of the VH task. (A) Experimental set-up. The participant's hand is hidden from view by a barrier, and a camera tracks hand movement and presents it on the VH. (B) Trial flow. In each trial, a fixation cross was followed by a VH that moved with or without an alteration. Following the VH's presentation, the participant judged whether the movement presented was congruent with that made, and rated his confidence. Note, that the agency question included no explicit mention of the word 'agency'.

2.3. Data analysis

Data were processed using custom in-house Matlab version R2019a (MathWorks, 2019) scripts. Trials in which participants did not respond, reaction time was over 4 seconds, or the hand tracking camera malfunctioned (as reported in the camera logs) were excluded from the analysis. SoA was operationalized as the proportion of responses in which the real and VH's actions were judged to be identical, indicating that the self-generated real movement and VH's movement were judged as congruent and perceived as corresponding to one's *actual* movements.

2.3.1. Analysis of current stimuli's effect on SoA

To assess the effects of the current trial's magnitude and domain of alteration on SoA, a within-subject repeated-measures ANOVA was computed in R (R Core Team, 2019) using the *afex* package (Singmann et al., 2020). When the assumption of sphericity was violated, Greenhouse-Geisser correction was applied. In Dataset 2 that includes both temporal and spatial alterations, trials with no alteration (i.e. magnitude 0) were randomly split and assigned a domain. In addition, for each domain of alteration we conducted a separate

ANOVA because we cannot assume that the levels of alteration across the domains are equivalent (this was corroborated by significant main effects of Domain described in SM Results). Post-hoc comparisons were Bonferroni corrected.

2.3.2. Analysis of serial dependence effects on SoA

To examine the influence of serial dependence on SoA we individually fitted each participant's data to a series of logistic regression models that examine the contribution of previous choice and previous stimuli on SoA (See Figure 2 for schematic representation of this approach). These models calculate the probability of making a “self” response in the current trial according to the follow equation:

$$p_t = \frac{1}{1 + e^{-z_t}} \quad (\text{Equation 1})$$

Where z_t values are linear combinations of predictors, that differed between models. Parameter estimation of the logistic regression was performed using the Bayesian adaptive direct search (BADs; (Acerbi & Ji, 2017)) toolbox to optimize the log likelihood of each model (see SM Methods for further details of the implementation of the BADs toolbox). After obtaining estimates of parameters for each participant, group-level significance was tested via a one-sample t-test comparing the group's parameter estimates to a mean of zero, while Cohen's d was used to assess the effect size. It should be noted that our model approach considered alteration magnitude as a continuous variable. While this is parsimonious in the parameters used (and a baseline bias parameter was included), it implicitly assumes that the choices are well-described by a sigmoid function vs. magnitude that was corroborated by visual inspection of model fits (see SM Results).

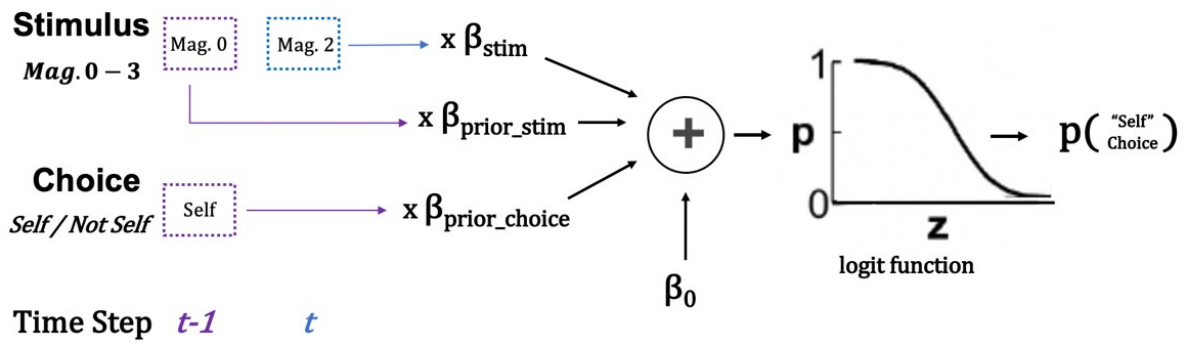


Figure 2. SoA model schematic. Logistic regression models examined four predictors and their associated beta parameters influencing SoA judgments and the contribution of history effects. (1) Current trial’s (trial *t* in blue) magnitude of alteration (e.g., Magnitude 2) and its associated parameter β_{stim} , (2) previous trial’s (trial *t-1* in purple) magnitude of alteration (e.g., Magnitude 0) and its associated parameter β_{prior_stim} , (3) SoA judgment made on previous trial (e.g. “Self”) and its associated parameter β_{prior_choice} , and (4) baseline bias β_0 . The sum of the product of the predictors and their associated coefficients (*z*) were entered into a logit function to return a probability of making a “self” judgment on the current trial. Models included different combination of predictors. Stimuli ranged from Magnitude 0 (i.e., no alteration) to Magnitude 3.

In light of our theoretical interest in serial dependence we focus on two models whose comparison tests these effects. A “No-History” model which does not include information regarding the previous trial and assesses the probability of a ‘self’ response only by the current trial’s stimulus magnitude and a baseline bias. In contrast, a “Full-History” model that incorporates both the previous trial’s stimulus magnitude and choice as predictors of the current trial’s judgment (in addition to the two standard predictors: the current trial’s stimulus magnitude and baseline bias). In addition, two intermediary models were tested that included only the previous trial’s stimulus magnitude (i.e., “Stimulus History Model”) or the previous trials choice (i.e., “Choice History Model”) in addition to the two standard predictors (see SM Methods for their full description).

The “No-History” model in Dataset 1 (that included only temporal alterations) was modeled as:

$$z_t \cdot \beta_0 + \beta_{stim} s_t \quad (\text{Equation 4.1})$$

β_0 represents the baseline bias, and s_t is the magnitude of alteration presented in the current trial. In Dataset 2, stimulus alterations in the temporal and spatial domain were modeled with two separate (mutually exclusive) stimulus parameters $s_{t_{temp}}$ and $s_{t_{spat}}$, respectively, such that only one could be non-zero on each trial:

$$z_t \cdot \beta_0 + \beta_{stim_{temp}} s_{t_{temp}} + \beta_{stim_{spat}} s_{t_{spat}} \quad (\text{Equation 4.2})$$

The “Full-History” model also includes the previous trial’s stimulus and choice as predictors, allowing us to simultaneously examine the contribution of each of these predictors. In Dataset 1 this was modeled via:

$$z_t \cdot \beta_0 + \beta_{stim} s_t + \beta_{prior_{stim}} s_{t-1} + \beta_{prior_{choice}} c_{t-1} \quad (\text{Equation 5.1})$$

s_{t-1} represents the stimulus in the previous trial and c_{t-1} the choice made in the previous trial.

In Dataset 2, to account for the two domains of alteration this was modeled as:

$$z_t \cdot \beta_0 + \beta_{stim_{temp}} s_{t_{temp}} + \beta_{stim_{spat}} s_{t_{spat}} + \beta_{prior_{temp}} s_{t-1} + \beta_{prior_{spat}} s_{t-1} + \beta_{prior_{choice}} c_{t-1} \quad (\text{Equation 5.2}).$$

Previous stimuli were split according to whether they were from the same domain as the current trial (i.e., $\beta_{prior_{temp}}$) or different (i.e., $\beta_{prior_{spat}}$), and for each trial at least one of these term’s value was zero. This method of coding was used to reduce the number of parameters given the limited number of trials. It implicitly assumes that a transition between temporal to spatial and vice versa have similar influences (see SM Methods for further discussion).

Models were compared using the Akaike Information Criterion (AIC), defined for a given model (M_i) as:

$$AIC_{M_i} = 2k - 2 \ln(L_i) \quad (\text{Equation 3})$$

With k being the number of parameters in a given model, and L_i its maximum-likelihood.

AIC rewards goodness of fit while also penalizing for the addition of parameters to avoid overfitting. When comparing two models, the model with the lower AIC score indicates the more likely model. Δ AIC values between 2 and 6, between 6 and 10 and > 10 are considered positive, strong and very strong evidence (respectively) for the model with the lower value (Kass & Raftery, 1995). In addition, models' goodness-of-fit were evaluated for each subject using McFadden's pseudo-R-squared (see SM Methods).

3. Results

3.1. SoA decreases as stimulus alteration magnitude increases

We examined the effect of current alteration magnitude on judgments of SoA in each of the four experiments separately. As noted above, participants were pooled from four different experiments, and aggregated into two datasets. We conducted a repeated measures ANOVA for Experiments 1 and 2 (that included only temporal alterations), to examine the effects of alteration *Magnitude* (0/1/2/3) on SoA and the proportion of “same” responses. As alteration magnitude increased SoA decreased (Fig. 3), in line with the results previously reported (Krugwasser et al., 2019; Stern et al., 2020). A significant main effect for *Magnitude* was found (Experiment 1: $F_{(1.7,39.5)} = 131.9, p < 0.001, \eta_p^2 = 0.85$, Fig. 3A; Experiment 2: $F_{(2.1,40.4)} = 102.5, p < 0.001, \eta_p^2 = 0.84$, Fig. 3B; all post-hoc comparisons $p < .05$), reflecting a reduction

in SoA as magnitude of alteration increases. In Experiments 3 and 4 that included both temporal and spatial alterations, we found a significant main effect of *Magnitude* in the temporal (Experiment 3: $F_{(2,3,92.5)} = 187.5, p < 0.001, \eta_p^2 = 0.82$; Experiment 4: $F_{(2,1,29.3)} = 49.5, p < 0.001, \eta_p^2 = 0.78$) and the spatial (experiment 3: $F_{(2,1,83)} = 182.2, p < 0.001, \eta_p^2 = 0.82$; experiment 4: $F_{(2,2,30.9)} = 88, p < 0.001, \eta_p^2 = 0.86$) domains. These results across the four experiments demonstrate, as predicted, a strong and consistent effect of the magnitude of alteration on SoA. As seen in Fig. 3, as magnitude increases judgments of SoA decrease, for both alterations in the temporal and spatial domains.

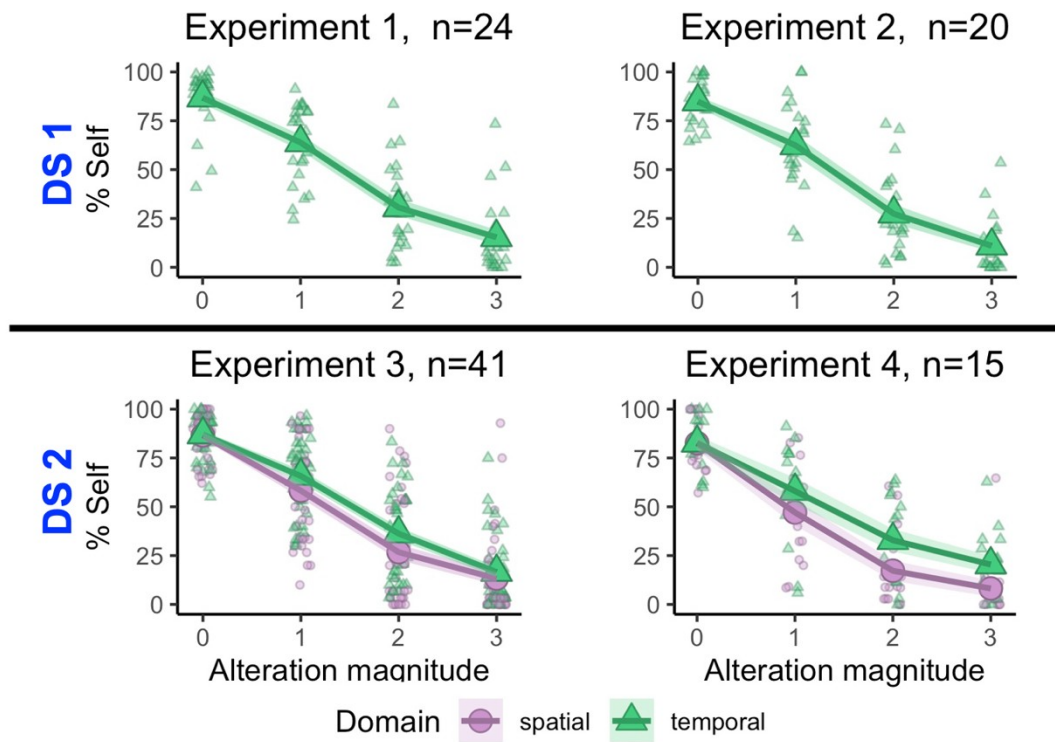


Figure 3. SoA as a function of alteration magnitude, in each of the four experiments. X-axis represents the magnitude of the sensorimotor conflict in the temporal (green; delay of 0/100/200/300 ms) or spatial (purple; deviation of 0°/6°/10°/14°) domain. Y-axis represents the proportion of trials participants reported that the VH's movement and their movement were congruent. Individual subject's means are presented as small triangles (temporal) or small circles (spatial), while group means as large triangles/circles, and SEM is shaded ribbons.

3.2.1 Prior stimuli and choices modulate SoA in opposite directions

We examined serial dependence via the comparison of four logistic regression models: (1) no-history, (2) stimulus history, (3) choice history, (4) full-history (Fig. 2). Comparing the models' performance via their AIC averaged across participants, we found that all of the models with history parameters performed moderately better in comparison to the no-history model ($\Delta AIC_{\text{Stim. History}} = -12.4$; $\Delta AIC_{\text{Choice History}} = -13.6$; $\Delta AIC_{\text{Full History}} = -14$; Fig. 4). Thus, history models explain the data better than a no-history model, although there is no significant difference between the different history models (see SM Results for converging results with the models' pseudo R^2). Due to our theoretical interest in the contribution of both prior choice and stimuli, we focus on the “full-history” model's parameters that dissociates these effects and examines them simultaneously (see SM Results for a full report of the other models' parameter's significance).

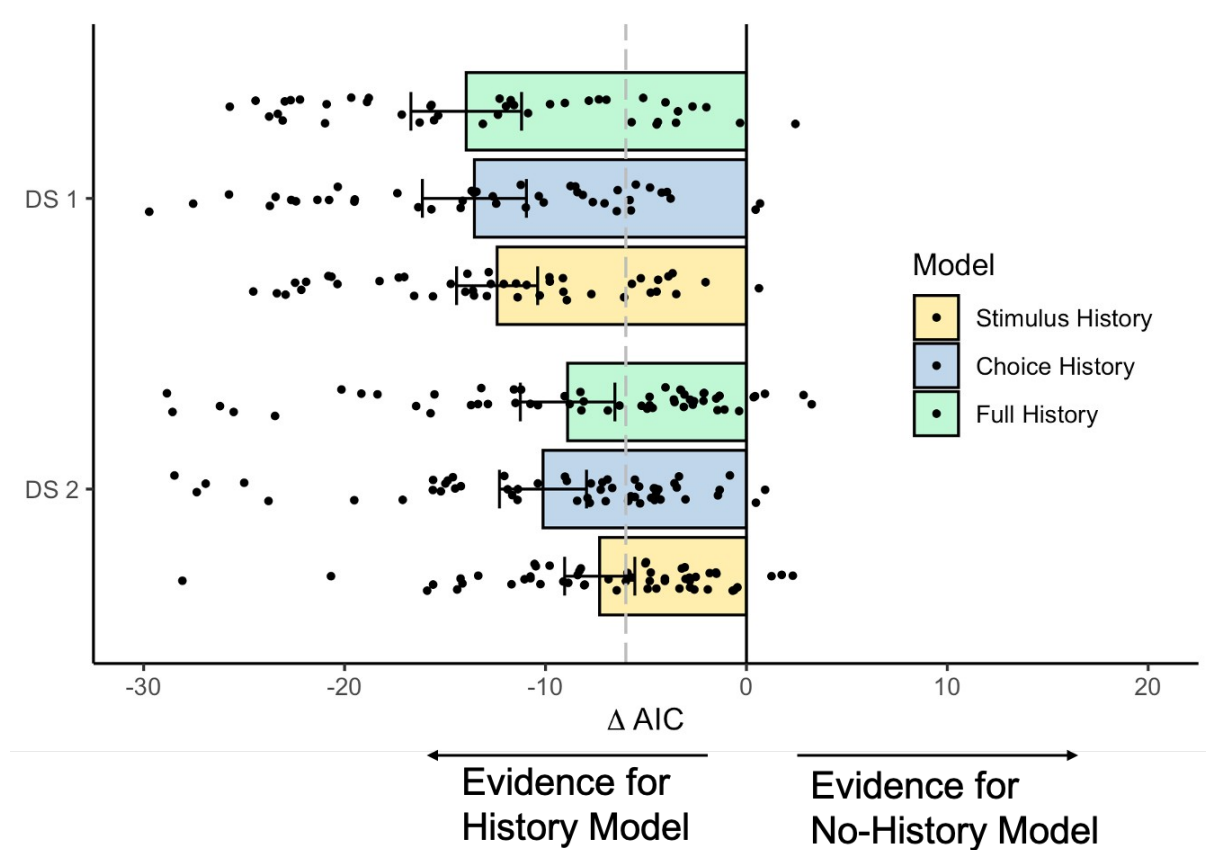


Fig. 4. Comparison of History Models. The delta AIC of the three history models, that is calculated as the model's AIC from which we subtracted the no-history model's AIC. Dots represent the AIC for a given participant, and bars represent the group means (errorbars mark \pm SEM). Δ AIC < -6 is considered strong evidence for the history model (the vertical dashed line marks Δ AIC = -6). Across all three history models in both data sets we found strong evidence in favor of the history models.

Examining the full-history model's parameters we did not find collinearity between the predictors (all Variance Inflation Factors (VIF) < 1.8). In line with the ANOVA results reported above (section 3.1.), the contribution of the current trial's alteration (i.e., β_{stim}) significantly differed from zero (mean \pm SEM = -3.87 ± 0.55 , $t_{43} = -7.03$, $p < .001$, Cohen's $d = 1.06$), such that as alteration magnitude increased, the probability of a "self" response decreased, hence the negative beta value. Examining the contribution of prior stimuli, we found that after a greater conflict (i.e., greater magnitude) in the previous trial, the current trial's probability of a "self" response was increased (see Figure 5). This is considered a *repulsive* effect as it repels the perceptual decision *away* from the previous stimulus, and reduces the tendency to perceive the current stimulus as the previous one. Accordingly, in the full-history model the distribution of $\beta_{prior_{stim}}$ was significantly different than zero and in the opposite direction of the current trial's stimuli's effect (M = 0.32, SEM = 0.09, $t_{43} = 3.59$, $p < .001$, Cohen's $d = 0.54$; see Fig. 6A). A complementary approach using a repeated measures ANOVA corroborated the significant influence of previous stimuli (see SM Results).

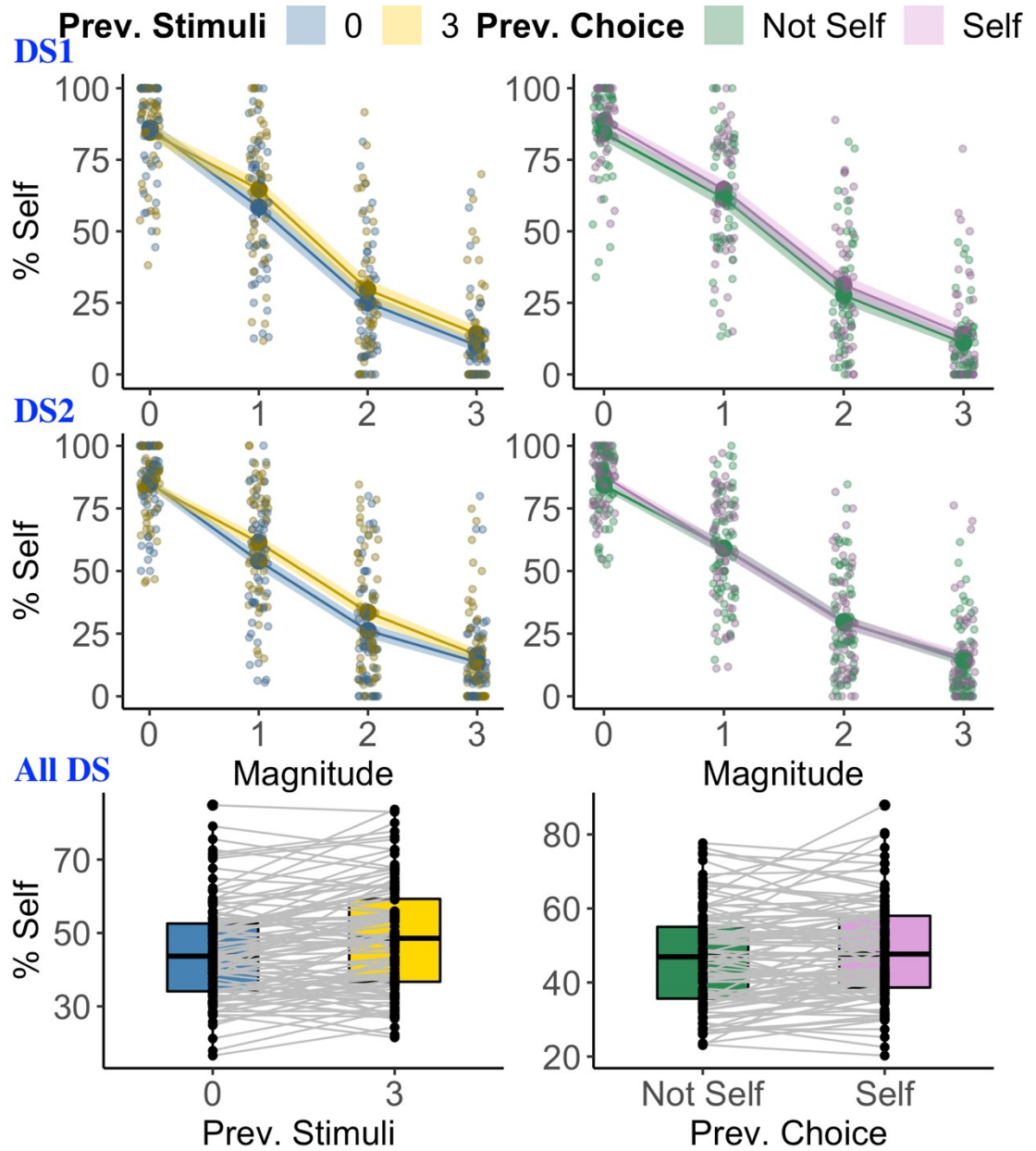


Fig. 5. Effect of previous stimulus magnitude and previous choice across datasets. Across both datasets (top two left panels), following a large magnitude of alteration (prev. mag 3; yellow) the tendency to respond “self” was increased in comparison to trials following no alteration (prev. mag 0; blue). Large circles are group mean, ribbons are SEM and smaller circles are individual subjects. For visualization purposes we display only the effect of previous magnitude 0 & 3, whereas in the logistic regression previous magnitude was a continuous variable ranging from 0-3. Bottom left panel shows mean proportion of “self” responses collapsed across magnitude of current trial and with all subjects from both datasets, with grey lines showing difference for

individual subjects following previous magnitudes. Previous choice (top two right panels) showed an opposite effect with an increased tendency to repeat the previous response. Bottom right panel show this effect collapsed across magnitude of current trial and combining data from both datasets.

Examining the contribution of previous choice, we found that following a “self” response, the probability for a “self” response in the current trial was increased and vice versa (see Figure 5). This is considered an *attractive* effect, as this repetition effect biases the perceptual decision *towards* the previous choice. Accordingly, $\beta_{prior\ choice}$ was significantly different than zero ($M = -0.21$, $SEM = 0.062$, $t_{43} = 3.44$, $p = .001$, Cohen’s $d = 0.52$; see Fig. 6A), and in the same direction as current trial’s stimuli’s effect (i.e., negative). A complementary approach using a repeated measures ANOVA corroborated the significant influence of previous choice (see SM Results).

In the “full-history” model both previous choice and previous stimuli exhibit significant history effects in opposite directions. Previous stimuli exhibit a *repulsive* bias, shifting the current judgment *away* from the previous judgment. Whereas previous choice exhibits an *attractive* bias, shifting the current judgment *towards* the previous judgment. These opposing influences are in line with our findings in the models in which we examined only a single history predictor (i.e., “Stimulus History” Model or “Choice History” model) and the history effects were mitigated and borderline significant (see SM Results). Presumably, this results from the interaction between prior choice and stimuli, and modeling the influence of only one results in its underestimation due to the unaddressed impact of the other predictor that influences in the opposite direction.

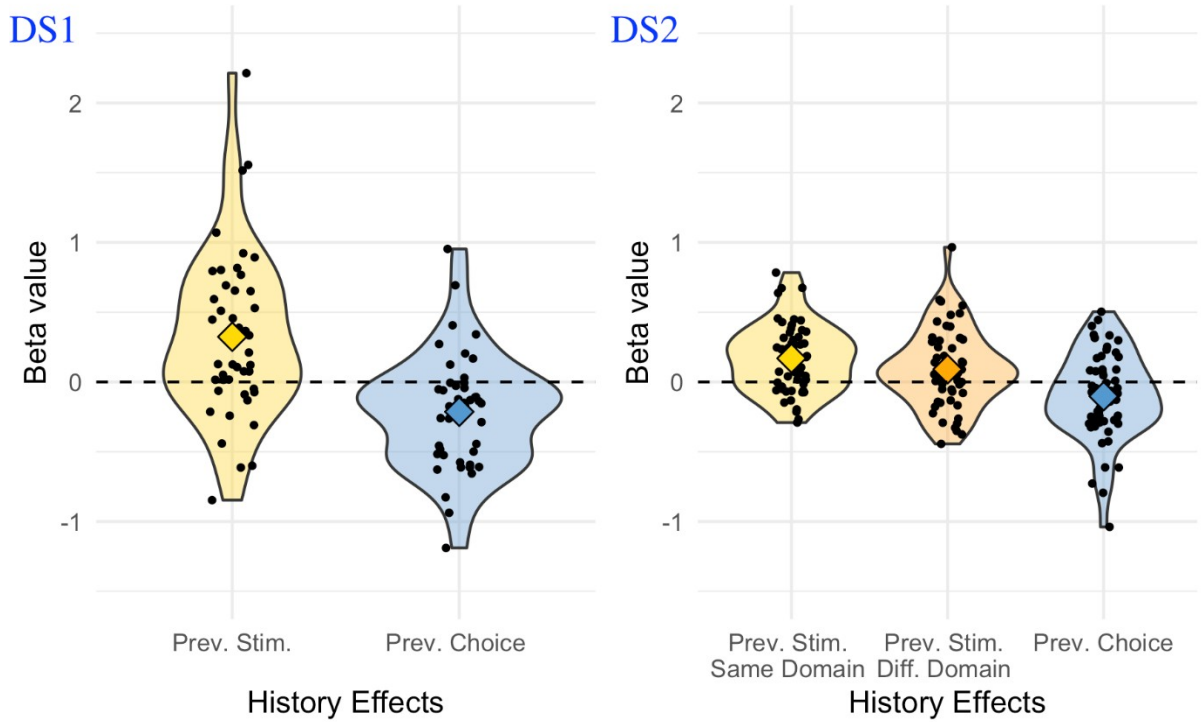


Fig. 6. Distribution across participants of history betas in “full-history” model. In Dataset 1 we found that previous stimuli (yellow) were significantly greater than zero, and their effect was opposite that of the current stimuli. Whereas previous choice (blue) was significantly smaller than zero and in the same direction as the current stimuli’s effect on SoA. In Dataset 2, we replicated these findings, such that both previous stimuli from the same domain (*Prev. Stim. Same Domain*) and different domain (*Prev. Stim. Diff. Domain*) were significantly greater than zero, while previous choice was significantly smaller than zero.

3.2.2 Replicating opposing influences of previous stimuli and choices in Dataset 2

In Dataset 2 we sought to: (1) replicate Dataset 1’s findings that both previous stimuli and choice are significant predictors and that they influence the current trial’s judgment in opposite directions, and (2) examine whether there is an across-domain effect of previous stimuli on SoA judgments. As noted above, Dataset 2 included both temporal and spatial alterations and its models included a separate predictor for each domain of alteration in the current trial. Previous stimuli were split into two predictors depending on whether they are from the same (i.e., β_{prior_s}) or a different domain (i.e., β_{prior_d}) than the current trial’s alteration.

Comparing the models' performance via their AIC, as in Dataset 1, we found that all of the models with history parameters performed moderately better than the no-history model ($\Delta AIC_{\text{Stim. History}} = -7.3$; $\Delta AIC_{\text{Choice History}} = -10.1$; $\Delta AIC_{\text{Full History}} = -8.9$; see Figure 4).

Examining the full-history model's parameters we did not find collinearity between the predictors (all VIF < 2). Examining the contribution of the current trial's stimuli, as magnitude increased the likelihood of making a "self" judgment decreased, such that β_{stim} was negative and significantly differed from zero in both the temporal and spatial domains ($M = -1.57$, $SEM = 0.11$, $t_{56} = 14.6$, $p < .001$, Cohen's $d = 1.95$, $M = -2.07$, $SEM = 0.16$, $t_{56} = 13$, $p < .001$, Cohen's $d = 1.73$, for temporal and spatial respectively). Replicating our results from Dataset 1, previous stimuli from the same domain exhibited an opposite effect than the current stimuli's influence (hence the positive value), that was significant ($M = 0.17$, $SEM = 0.03$, $t_{55} = 5.23$, $p < .001$, Cohen's $d = 0.7$; see Figure 6). Thus, previous stimuli from the same domains exhibit a *repulsive* effect on SoA. In contrast, previous choice exhibited an *attractive* effect increasing the tendency to repeat one's previous response, that was significant ($M = -0.10$, $SEM = 0.04$, $t_{55} = 2.44$, $p = .02$, Cohen's $d = 0.36$). Thus, replicating the results of Dataset 1, in Dataset 2 previous choice and stimuli exhibited significant history effects whose influence is in opposite directions.

3.2.3 Prior stimuli's influence spans across domains of alteration

Regarding our second question pertaining to serial dependence across-domains of perceptual alteration, we found that previous stimuli from a different domain exhibited a significant *repulsive* effect on the current trial ($M = 0.09$, $SEM = 0.04$, $t_{55} = 2.45$, $p = .017$, Cohen's $d = 0.33$; see Figure 6). Thus, previous stimulus' influence is not limited to the same perceptual domain, rather it spans across domains. This cross-domain effect's direction is also repulsive, similar to the effect of previous stimuli from the same domain. The current

finding supports a centralized, domain-general component in the processing of SoA and its associated sensory input. Comparing same and different domain effects via a paired t-test, the influence of previous stimuli from the same domain was significantly greater than those from a different domain ($t_{55} = 2.75, p = .008$, Cohen's $d = 0.37$), highlighting also the significant contribution of within-domain perceptual processes.

To summarize, in Dataset 2 we replicated our finding that both previous stimuli and choices significantly influence SoA in opposite directions. In addition, we found that previous stimuli from a different domain also exhibit a significant effect on SoA.

4. Discussion

SoA is supported by the ongoing integration of sensorimotor signals, and is a central component of the bodily-self. Using a VR-based task of embodied SoA, we found robust serial dependence effects in Dataset 1 that were replicated in Dataset 2. Dissociating the contribution of prior stimuli and choice, we found that both exert significant and opposite influences on the current trial's judgment. Finally, in Dataset 2 that included both temporal and spatial alterations, we found that prior stimuli with an alteration from a different perceptual domain influence the current trial, providing novel evidence that SoA is a domain-general unifying construct.

Consistent with evidence from unimodal and multimodal perceptual processes, we found that embodied SoA, the feeling of control over one's body's actions (Stern et al., 2020), exhibits robust serial dependence effects. Presumably, these effects enable a stable and resource efficient perception of the embodied self that is adaptive to minor alterations while also sensitive to sudden changes (Burr & Cicchini, 2014; Cicchini et al., 2014). The current experimental study complements theoretical and computational accounts that highlight the ongoing integration of internal and external signals supporting a dynamic embodied selfhood

whose perceived physical boundaries are constantly updated (Allen & Tsakiris, 2018; Apps & Tsakiris, 2014; Samad et al., 2015). Our results converge with previous findings that multisensory cues involved in self-motion perception recalibrates each other allowing for an accurate representation of oneself (Zaidel et al., 2011) and the environment (Zaidel et al., 2013). A recent study of peri-personal space (Noel et al., 2020), also found that the multisensory perception of nearby space as belonging to oneself is also recalibrated based on previous trials. Our finding of serial dependence and the cumulative influence of past trials are in line with a recent study (Wang et al., 2018) that examined the effects of response selection on SoA in an auditory Simon Task (i.e., auditory stimuli and the response button are spatially congruent or incongruent). They found that only in trials preceded by a congruent trial did response fluency significantly modulate SoA, demonstrating that response fluency's modulation of SoA is similarly a cumulative process also dependent on prior trial's congruency.

Theoretical accounts of the self posit a hierarchy of computational processes integrating low-level perceptual and interoceptive signals as well as higher-level prior beliefs and expectations (Apps & Tsakiris, 2014; Legaspi & Toyoizumi, 2019; Samad et al., 2015). Dissociating the contribution of prior choice and stimuli, we found that the two exert opposing influences. Specifically, previous choices exert an *attractive* influence that induces a 'repetition bias' increasing the tendency to repeat one's previous choice (Arrington & Logan, 2005; Samuelson & Zeckhauser, 1988). This influence may stem from top-down processing, that within a two-stage theoretical framework of SoA (Synofzik et al., 2008), may be related to higher level explicit *judgments* of agency that incorporate top-down contextual information that is based on past decisions (Moore et al., 2009). This enables the formation of a coherent representation of the Self that is consistent with previous decisions. Previous choice's mechanism of influence remains unclear and may result from a shift in the initial

starting point of the decision process prior to stimulus perception (Leite & Ratcliff, 2011; Zhang et al., 2014), or via an increase in the evidence accumulation rate via a top-down modulation of attention (Urai et al., 2019).

In contrast, prior stimuli recalibrate the perception of the current stimuli in relation to the previous, exerting a *repulsive* influence, shifting *away* the tendency to repeat one's judgment (i.e., following a large alteration a minor alteration is perceived as small, and the trial is more likely to be judged as congruent). Presumably this reflects bottom-up influences related to the perceptual features of the stimuli, and may be related to lower-level *feelings* of agency that arise from implicit processing of sensory and motor signals. Thus, prior choice and stimuli's influence may reflect distinct cognitive processes of SoA that exert opposing influences that are integrated into a stable representation (Bosch et al., 2020; Fritsche et al., 2017).

Self-initiated actions and the subsequent SoA are powerful means through which we can actively test and delineate our internal model of the bodily-self (Leptourgos & Corlett, 2020; Salomon, 2017; Pacherie, 2008). The current study's finding that prior stimuli from a different domain than the current trial exert a significant influence on SoA, demonstrates that serial dependence is not solely based on the modulation of domain-specific perceptual processes such as the recalibration of spatial perception and angle discrimination rather entails a domain-general component. In line with serial dependence's reliance on attentional processes and perceived relevance (Feigin et al., 2021; Fischer & Whitney, 2014), stimuli may be encoded as a 'self' or 'not-self' action, irrespective of the type of sensorimotor conflict, and subsequently exert a domain-general influence. Thus, SoA is a unifying construct that organizes across perceptual domains the perceived sensory outcomes of our actions. This finding complements our group's previous findings that SoA's sensitivity,

criteria and metacognition are highly correlated across perceptual domains (Krugwasser et al., 2019; Stern et al., 2020), supporting embodied SoA's role as a unifying intermediate process between domain-specific perceptual capacities (i.e., spatial or temporal sensorimotor processing) and higher-level metacognitive beliefs (Constant et al., 2021).

In psychopathological conditions such as psychosis there is an impairment of SoA (Frith, 2014) that causes an unstable sense of self (Nelson et al., 2014; Sass & Parnas, 2003). It remains unclear at what level of the hierarchy these aberrant processes occur (Fletcher & Frith, 2009; Sterzer et al., 2018), and whether patients exhibit overly strong priors (Corlett et al., 2019; Powers et al., 2017) or diminished sensory precision and weak corollary discharge (Thakkar et al., 2017). Furthermore, different experimental paradigms have found conflicting evidence for over- (Franck et al., 2001; Haggard et al., 2003) and under-attribution of agency in schizophrenia (Blakemore et al., 2000; Shergill et al., 2005). In an attempt to explain these conflicting findings, it has been suggested that the over-attribution is found in tasks measuring explicit *judgments* of agency, whereas under-attribution is found in implicit measures relating to feelings of agency. Over-attribution of explicit judgments of agency may attempt to compensate for diminished lower-level feelings of agency in implicit tasks (Leptourgos & Corlett, 2020; Synofzik et al., 2010). The current study provides potential tools to test such a hypothesis by identifying impairments at different levels by dissociating the contribution of prior choice and stimuli. It is hypothesized that patients will exhibit an overweighting of prior choice that is in line with widespread impairments of perseverance and strong priors (Corlett et al., 2019; Heathcote et al., 2015), while there will be an underweighting of prior stimuli that together create an unstable sense of self.

The current study has a number of limitations. First, the experiments analyzed were not designed for serial dependence analyses. On the one hand this further supports the robustness

of our findings, but on the other hand the number of trials did not provide optimal statistical power. Furthermore, serial dependence is typically strongest with minor alterations (Fischer & Whitney, 2014), whereas the current experiments included also large magnitudes of alteration that may not fully capture the extent of serial dependence's influence due to ceiling effects. Second, due to limited statistical power the current study did not examine the effects of serial dependence on explicit judgments of confidence nor implicit measures such as reaction time. Finally, although the current study dissociated the contribution of previous choice and stimuli, it does not provide an explicit computational account of how these processes are integrated. Future studies will employ experimental designs with a larger number of trials and magnitudes of alteration tailored per participant's perceptual sensitivity to address these questions.

5. Conclusion

The current study analyzed data from VR-based experiments of embodied SoA to examine how it is modulated by serial dependence and dissociate the contributions of prior stimuli and choice. The current study found robust serial dependence in SoA that was replicated across two datasets. These effects were driven by opposing influences, with prior stimuli exerting a repulsive effect and prior choice exerting an attractive effect. Furthermore, we found that the effect of prior stimuli's persists across different perceptual alterations. Thus, SoA is a dynamic process that is influenced by prior experience and thus may serve as a unifying construct organizing our experience across time and perceptual domains.

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